Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Thermoplastic stiffened wing skin made by advanced fibre placement

Problem area
New opportunities for cost effective structural airframe components can be realized by using thermoplastic materials in combination with advanced fibre placement machines. Thermoplastic components can be welded or co-consolidated which can result in new structural concepts with a high level of structural efficiency. In combination with advanced fibre placement machines, products can be made repeatedly within tight dimensional tolerances, with low material scrap rates and with a high level of automation. Hence offering huge potential in complying with the ambitious cost and weight targets defined by the major aerospace industries.

Description of work
In the framework of a European program, ALCAS (Advanced Low Cost Aircraft Structures), the National Aerospace Laboratory NLR has developed a thermoplastic stiffened wing skin together with Stork Fokker AESP and Atkins-Nedtech. The skin with local reinforcements and the stiffeners with integrated joggles are made by advanced fibre placement of PEKK/AS4D. The components are consolidated in an autoclave and finally bonded together. The skin is bolted on a thermoset wing box by Stork Fokker and mechanically tested statically and in fatigue at VZLU.

Results and conclusions
The main target was to develop a highly integrated composite wing box to reduce the assembly costs while maintaining the advantages of composites. A good concept is found, which can be further developed to a skin with integrated stiffeners and co-consolidation, to meet this target.

Applicability
Stiffened structures like aircraft fuselages, wing skins, stabilisers, control surfaces.

Report no.
NLR-TP-2009-220

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Report classification
UNCLASSIFIED

Date
June 2009

Knowledge area(s)
Lucht- en Ruimtevaart
Constructie- en Fabricagetechnologie

Descriptor(s)
Advanced Fibre Placement
PEKK
ALCAS
Skin

This report is based on a presentation which was given on the Sampe '09 conference, Baltimore, May 19, 2009.

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

Customer	European Union
Contract number	----
Owner	National Aerospace Laboratory NLR
Division NLR	Aerospace Vehicles
Distribution	Unlimited
Classification of title	Unclassified
	June 2009

Approved by:

Author	Reviewer	Managing department
26/6	29-6-09	29/6 '09

Summary

New opportunities for cost effective structural airframe components can be realized by using thermoplastic materials in combination with advanced fibre placement machines. Thermoplastic components can be welded or co-consolidated which can result in new structural concepts with a high level of structural efficiency. In combination with advanced fibre placement machines, products can be made repeatedly within tight dimensional tolerances, with low material scrap rates and with a high level of automation. Hence offering huge potential in complying with the ambitious cost and weight targets defined by the major aerospace industries.

In the framework of a European program, ALCAS (Advanced Low Cost Aircraft Structures), The National Aerospace Laboratory NLR has developed a thermoplastic stiffened wing skin together with Stork Fokker AESP and Atkins-Nedtech.

The skin with local reinforcements and the stiffeners with integrated joggles are made by advanced fibre placement of PEKK. The components are consolidated in an autoclave and finally bonded together. The skin is assembled by Stork Fokker on a thermoset wing box and mechanically tested statically and in fatigue at VZLU. The main target was to develop a highly integrated composite wing box to reduce the assembly costs while maintaining the advantages of composites. A good concept is found, which can be further developed to a skin with integrated stiffeners and co-consolidation, to meet this target.

In this paper the manufacturing process of the skin and stringers is reported. The tooling concepts, the manufacturing results and a brief overview of the mechanical test results are given.

Contents

1 Introduction

Nowadays, composites are commonly used on new generation aircrafts, like the Boeing 787 and Airbus 380. Most composite aircraft components are made of thermoset materials. New opportunities for cost effective products can be found in the use of thermoplastic materials in combination with advanced fibre placement machines. A thermoplastic material like PEKK is very tough (high allowable strains), has good mechanical properties even at higher temperatures (up to 120 °C) and is excellent chemical resistant. Thermoplastic components can be welded or co-consolidated. In combination with advanced fibre placement machines, products can be made accurately, with low scrap rates and cost effective.

In the framework of several technology programs, the Structures Technology department of NLR has developed technologies to place PEKK and PEEK UD tapes at high speeds followed by autoclave consolidation or to place tapes at lower speeds with in-situ consolidation. These programs were carried out in close collaboration with Dutch and European industries. One of these programs is the European ALCAS project, in which Advanced Low Cost Aircraft Structures are developed (Ref. 1). Within the business jet wing platform of this program, four types of wing box concepts are developed and compared. Within this platform, NLR has developed a thermoplastic stiffened wing skin together with Stork Fokker AESP and Atkins-Nedtech. The main target was to develop a highly integrated composite wing box to reduce the assembly costs while maintaining the advantages of composites.

The skin with local reinforcements and the stiffeners with joggles are made by advanced fibre placement of PEKK. The components are consolidated in an autoclave and finally bonded together. The skin is assembled by Stork Fokker on a thermoset wing box and mechanical tested at VZLU.

In this paper the manufacturing processes of the skin and stringers are reported. The tooling concepts and the manufacturing results will be described and a brief overview of the mechanical test results is given.

2 Manufacturing

2.1 Production philosophy and small panel demonstration

As mentioned in the introduction, the main target was to develop a highly integrated wing box. For the stiffened upper skin, which had to be removable from the wing box, a complete integrated design was chosen with local reinforcements and blade stringers made by advanced fibre placement. The basic principle and an overview of the AFP machine are given in figure 2. By using an AFP machine, costs can be saved on labour and material (low scrap rates), thermoplastic material can be laid-down in curved shapes (stringer joggle) and local reinforcements can be made very accurate (drop off positioning).

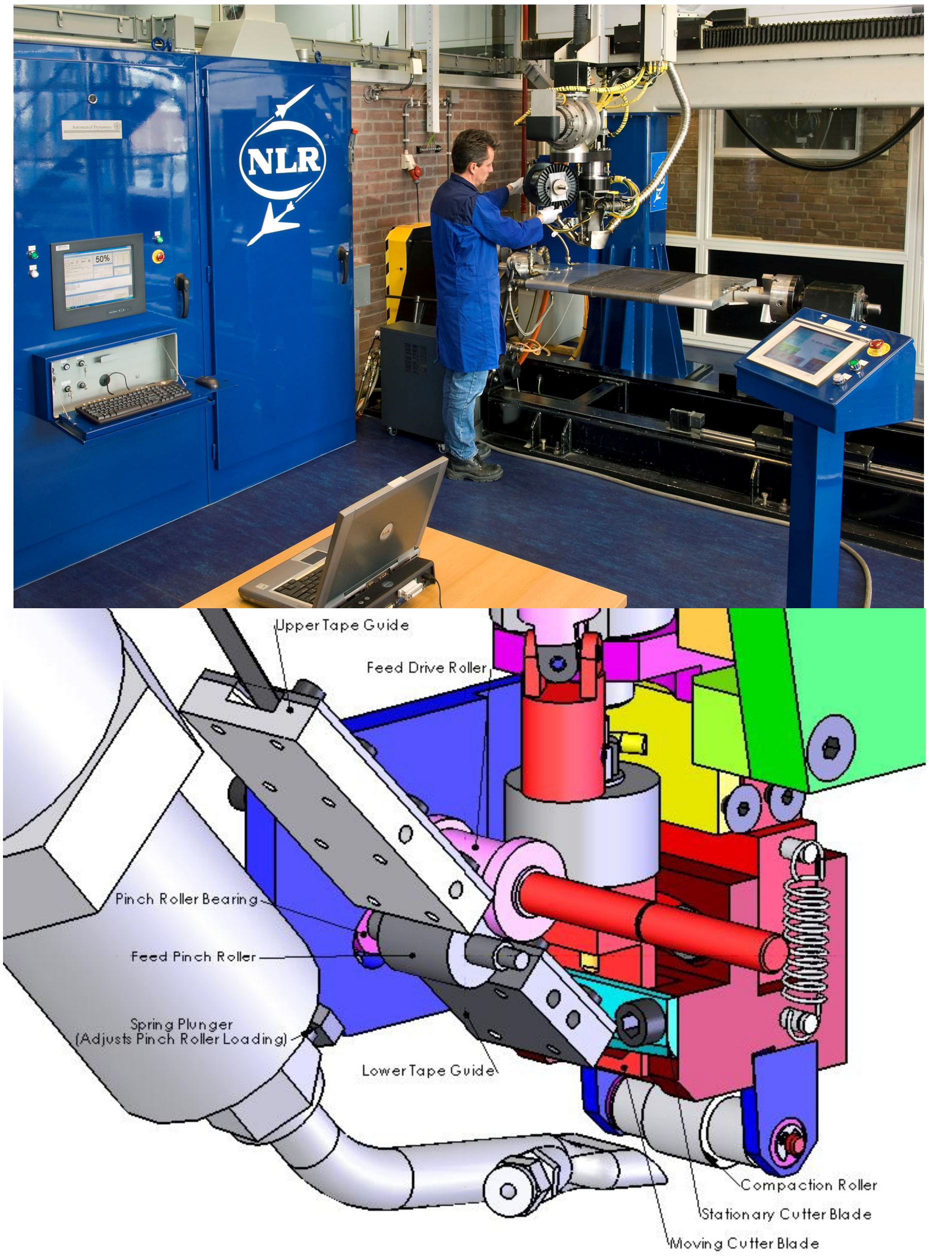

Figure 2. Advanced fibre placement machine

The main idea was to pre-fabricate stringers and position the stringers up side down in a large mould and place the skin on the stringers, i.e. without bonding. The mould would be complex, but for a series production this would save costs, since only one autoclave cycle would be necessary for the fabrication. Within this program however (in which one skin is manufactured), the cost of the mould would be too expensive.

However, to demonstrate the feasibility of this integrated skin manufacturing concept two small demonstration panels were manufactured successfully:

- Panel 1 in which a skin laminate was fibre placed directly onto two simulated stringer flanges (see figure 3)
- Panel 2 in which local reinforcements and a lightning strike foil were integrated in a skin laminate during fibre placement (see figure 4)

Figure 3. Skin demo placed directly on stringer bases

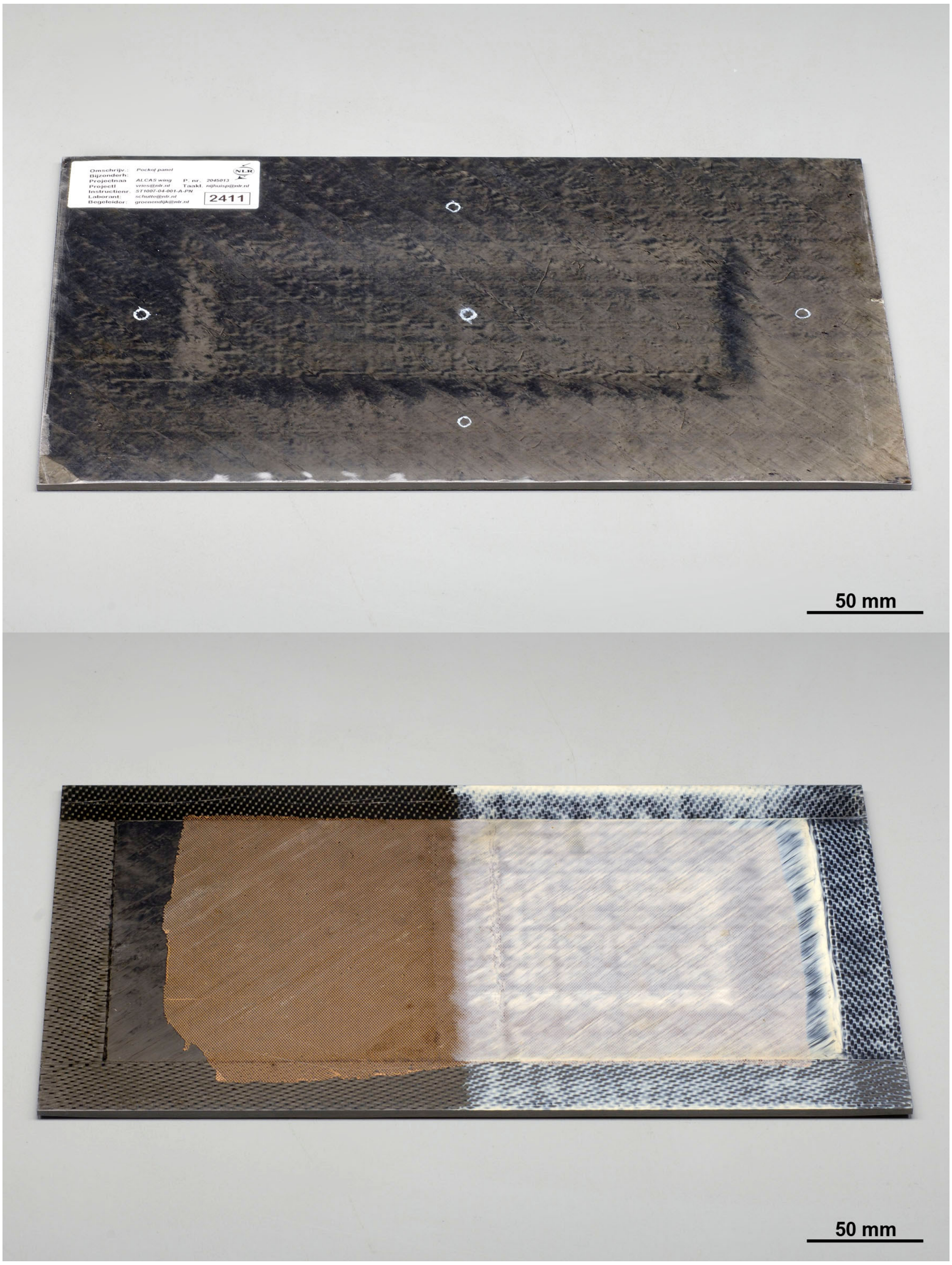

Figure 4. Skin demo with local reinforcements and integrated lightning strike foil

2.2 Stringer manufacturing

The stringers are made of unidirectional thermoplastic tape (PEKK/AS4D) which is similar to the material for the skin. For the stringers a manufacturing concept was defined which enabled a nearly fully automated stringer manufacturing, which resulted in a T-shaped stringer configuration. The stringers are build-up from four elements. A base, a filler and two L-shaped bodies (figure 5). The stringers are made in the following steps:

- Hand lay-up of the base from 300 mm width UD tape. Pre-compacted under vacuum in the oven at 200 °C and cut to the correct size by hand
- Hand lay-up of the fillers from 300 mm width UD tape. Consolidated and milled in shape
- Fibre placement of a partly tapered square tube and machined into L-shaped sub-components
- Assembly of the four sub-components on a consolidation tool and consolidation in an autoclave at 360 °C
- C-scan inspection
- Milled to final dimensions

Figure 5. Stringer build up

The L-shaped sub-components were placed four at a time on a square tool (figure 6). The stringers are not straight at one end, but are bend up to created a joggle. By using the fibre placement technique in combination with active fibre steering, a stringer with a double curved zone in the area of the joggle could be made successfully by using unidirectional tape with a width of 12.7 mm, see the red line in figure 7.

Figure 6. Advanced fibre placement machine with stringer tool

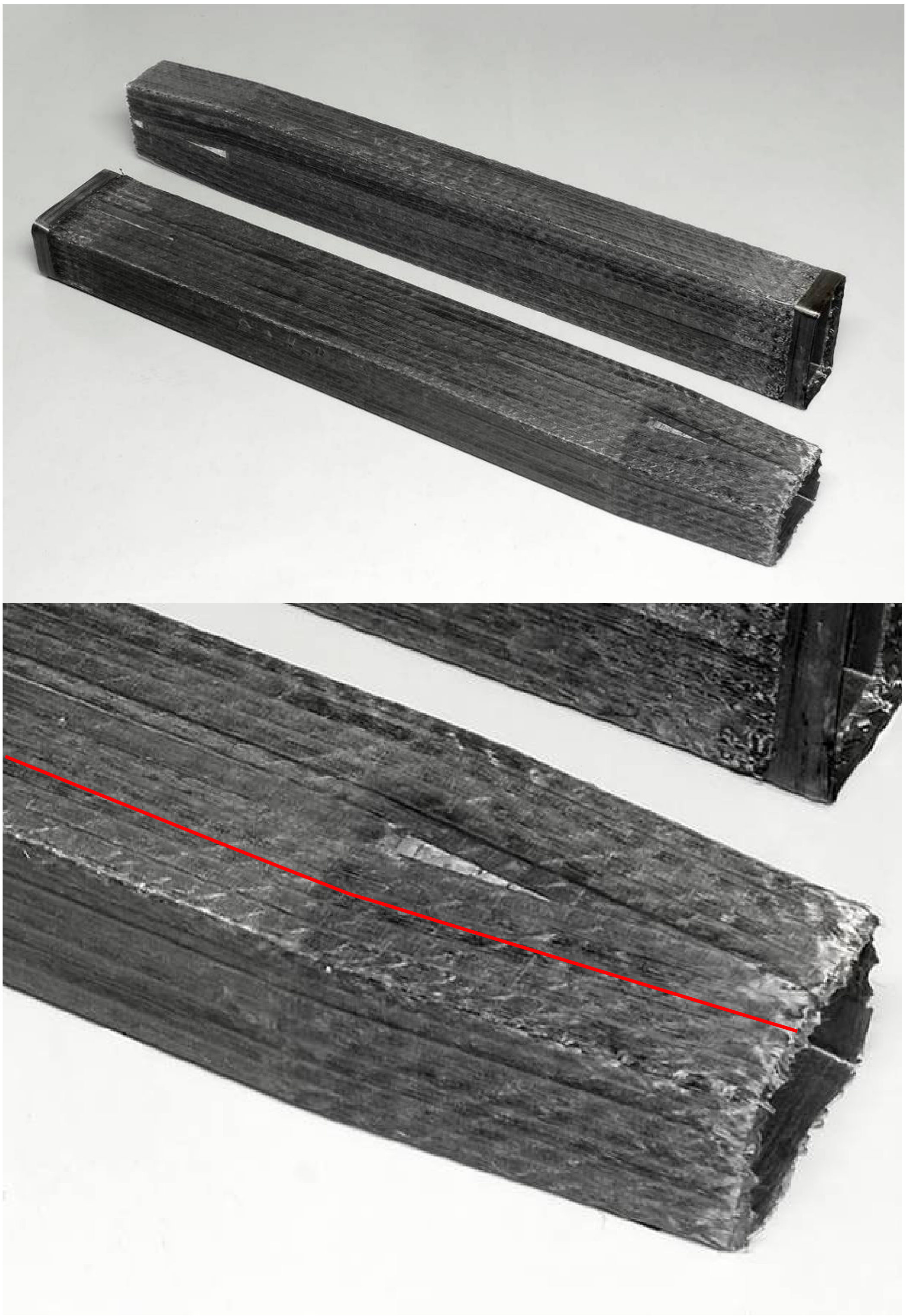

Figure 7. Square tube with fibre steering at the joggle

After fibre placement of the unidirectional tape on the mould, the square tube (preform) was removed from the mould by cooling down the mould and the tube. The tube was then cut in four L-shaped parts.

The individual elements for the stringers were placed on steel mould elements with small metal dams at the edges and a caul plate on top. The filler and the base plate were heated locally to bend in shape. The stringers were co-consolidated in the autoclave (figure 8) at 360 °C for 20 minutes.

After removing the stringers from the mould a small angle (springback) was found in the stringer flange of 1°.

Figure 8. Co-consolidation of the stringers

2.3 Skin manufacturing

The skin is also made using an advanced fibre placement machine. With the AFP machine, unidirectional thermoplastic tape (PEKK/AS4D) of 12.7 mm width was placed on a concave mould. One of the key technologies to be developed was the first ply deposition of the thermoplastic tape on a concave mould that was treated with a release agent. In order to be able to fibre place the first ply on the concave mould special start and stop elements were build in into the mould. The technical details of these start and stop elements will not be presented in the present paper.

The dimensions of the skin were slightly too large for the NLR machine. To enable skin manufacturing, the mould therefore was configured with a rotation point to increase the span of the fibre placement machine, see figure 9.

Figure 9. Advance fibre placement machine with skin mould

The skin exists of maximum 76 carbon fibre layers near the kink rib (see figure 10) and spar connections and respectively 60 or 48 layers in the middle of the outboard and inboard section of the skin. Furthermore, the inboard and outboard ends of the skin are reinforced for the load introduction during the mechanical test. By this, a skin with pockets is created, see figure 10.

After placing, the edges of the skin were trimmed and the skin was consolidated on the same mould in an autoclave, with small metal dams at the edges and a caul plate on top.

Figure 10. Skin with local reinforcements after consolidation in the autoclave

After consolidating, the skin was ultrasonic inspected using C-scan equipment, see figure 11.

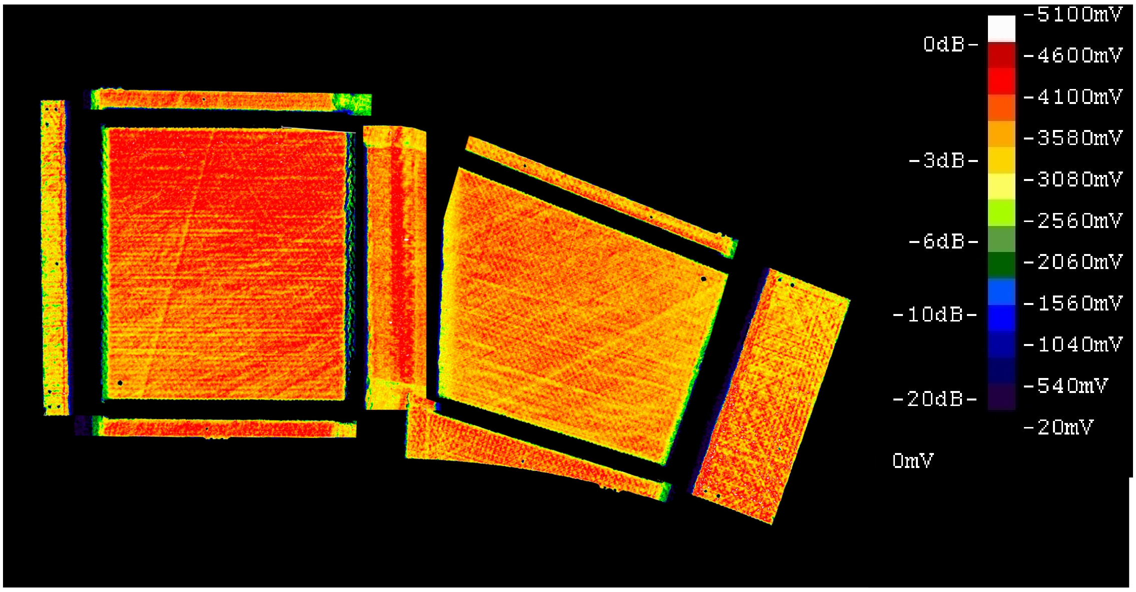

Figure 11. C-scan results of the skin

2.4 Assembly of the stringers to the skin

The stringers were bonded to the skin with FM 300K 390 gsm adhesive film. Before bonding, the stringer flanges and the skin were degreased and sanded. The stringers were positioned on the skin using markers on the mould, see figure 12.

Figure 12. The stringers were bonded in the autoclave

After bonding, the bonding of the stinger was inspected with normal C-scan equipment for the flat areas and phased array equipment for the transition areas. Examples of the results are given in figure 14 and figure 15. Two very minor defects were found. The two spots with improper bonding (< 300 mm2, < 0.5 inch2), were repaired by injecting adhesive in the cavities.

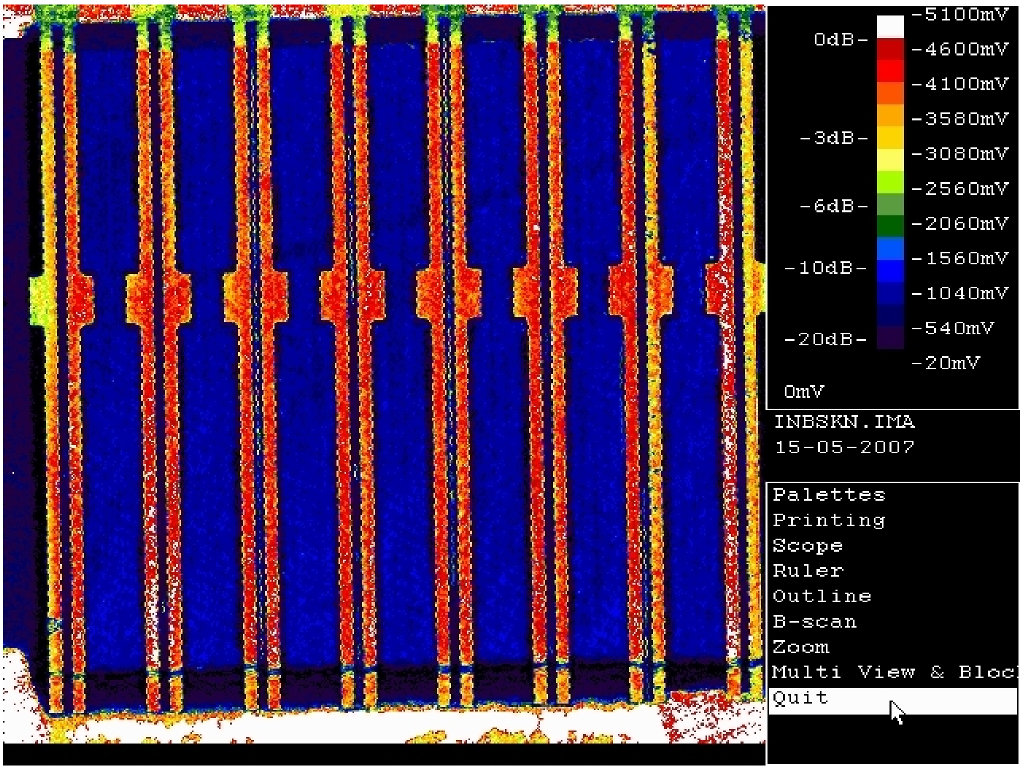

Figure 13. Example of a bond layer C-scans

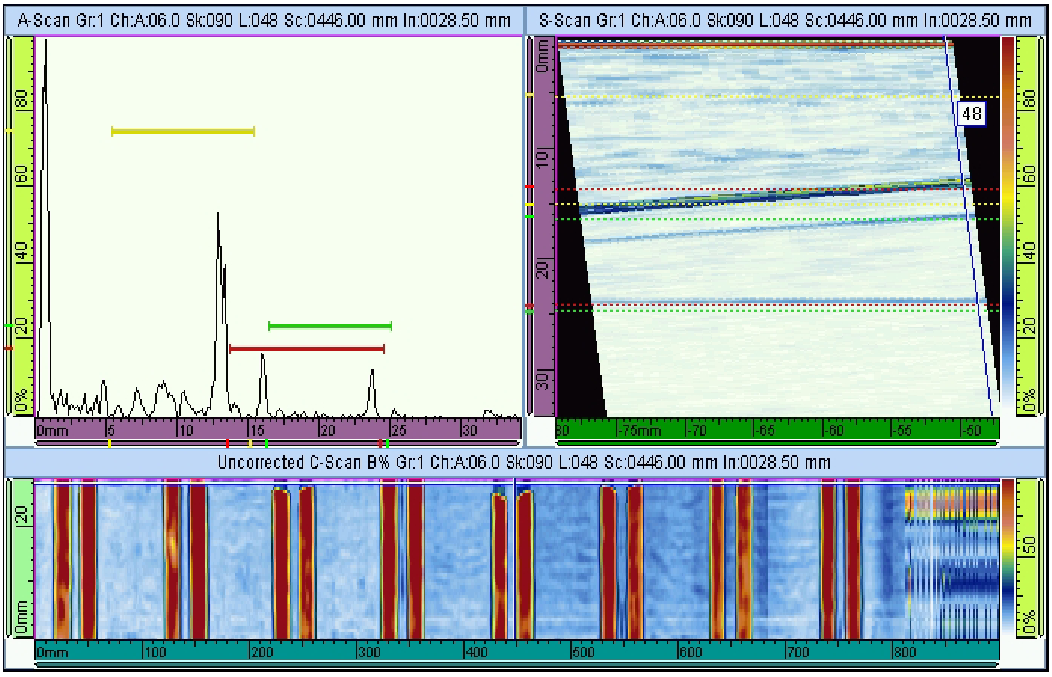

Figure 14. Example of a bond layer phased array C-scan in the transition area

After inspection, the upper skin was trimmed to the final size and send to Stork Fokker AESP for assembly on a thermoset grid, which was made by Stork Fokker AESP, see figure 15 (Ref. 2).

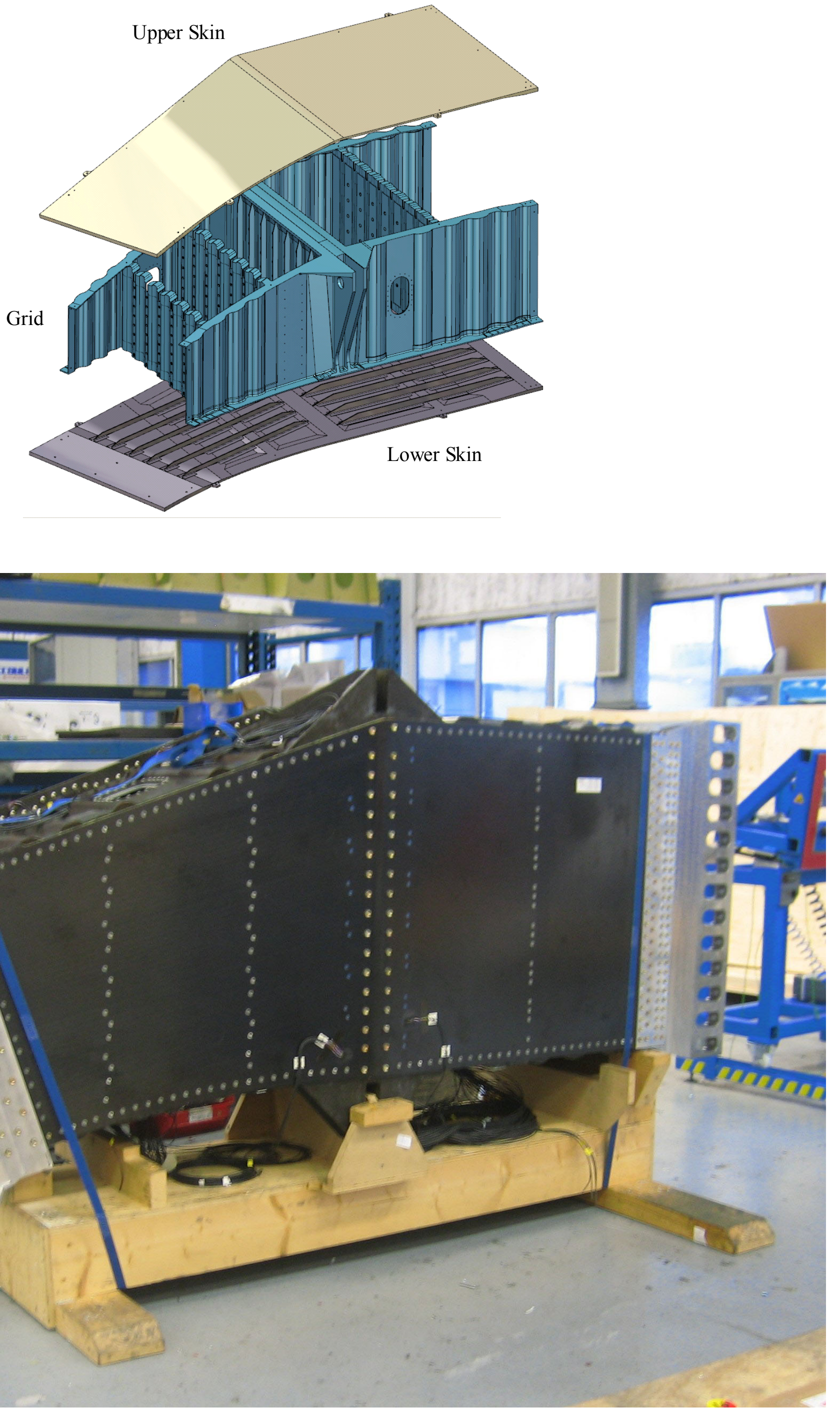

Figure 15. Skin assembled on thermoset grid

3 Results

3.1 Manufacturing results

The selected manufacturing process performed as expected. In this case the skin was consolidated in the autoclave. By this, the material lay down rate is high. In-situ consolidation is also possible but would require lower lay down rates and the process would cause more thermal stresses in the skin. As a result material properties of an in-situ placed skin would be slightly lower than a skin that was consolidated in the autoclave.

The integration of lightning strike foil is no problem with (co-)consolidation in the autoclave. Also fibre placement of a skin on stringer flange is possible. A major cost improvement can be achieved by the use of co-consolidation of stringers and skin in one autoclave cycle.

Within the ALCAS program, four wing boxes had to be made by four different international teams with different manufacturing processes, like RTM, oven curing prepregs and vacuum injection. The manufacturing costs had to be estimated for the 300th shipset, i.e. a smooth running manufacturing environment without start-up problems. Unfortunately, not all teams have finished the box, so no further results can be given here yet.

3.2 Test results

The sub scale wing box with the thermoplastic skin was tested at VZLU in Prague. See figure 16, for the test setup. Before testing, the skin and grid were impacted at various levels. The box was tested statically and in fatigue. Five actuators and internal pressure were used to simulate upwards and downwards bending load cases and loads generated by the inertia of the internal fuel tanks. The box sustained all limit load tests before and after the fatigue tests without failure (Ref. 3).

A small damage occurred in the grid at 140 % of limit load, but the structure sustained its load carrying ability. The structure successfully completed all ultimate load (1.5 x Limit Load) tests with this small damage. The structure finally failed during an upwards bending case without internal pressure at 165 % of limit load. Failure most probably started at the middle rib and caused upper skin buckling.

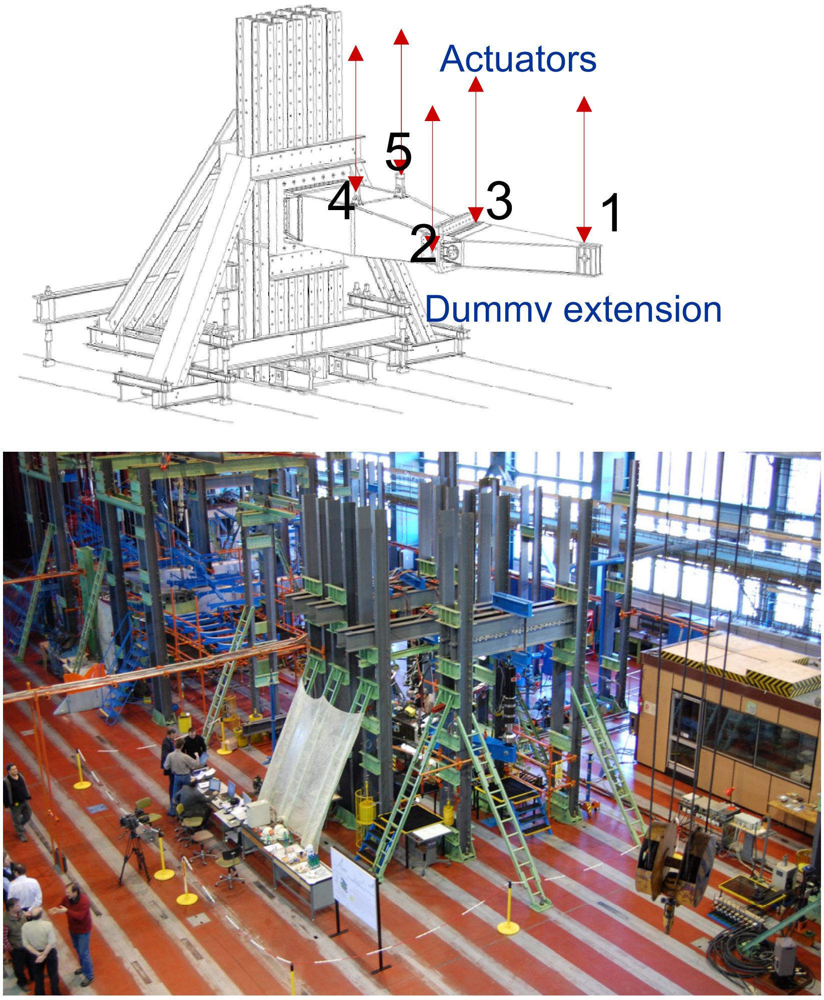

Figure 16 Test setup at VZLU in Prague

4 Conclusions

The main target was to develop a highly integrated composite wing box to reduce the assembly costs while maintaining the advantages of composites. With the use of a fibre placement machine, stiffeners with a joggle can be made in thermoplastic material at a highly automated level. The stringers and lightning strike mesh can be integrated in a skin if co-consolidation is used, so only one autoclave cycle for a complete skin would be necessary. By using consolidation in the autoclave, higher lay down rates could be possible then in case of in-situ consolidation. Both methods are possible. The most efficient method depends on the design drivers. The best mechanical properties can be achieved with autoclave consolidation (low weight). The lowest manufacturing costs for both methods depend on the product and production rates.

Acknowledgement
Special thanks to all ALCAS partners involved in Platform 3, especially to Dassault, VZLU and Team 2 partners, Stork Fokker AESP, ACG and Atkins-Nedtech.

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