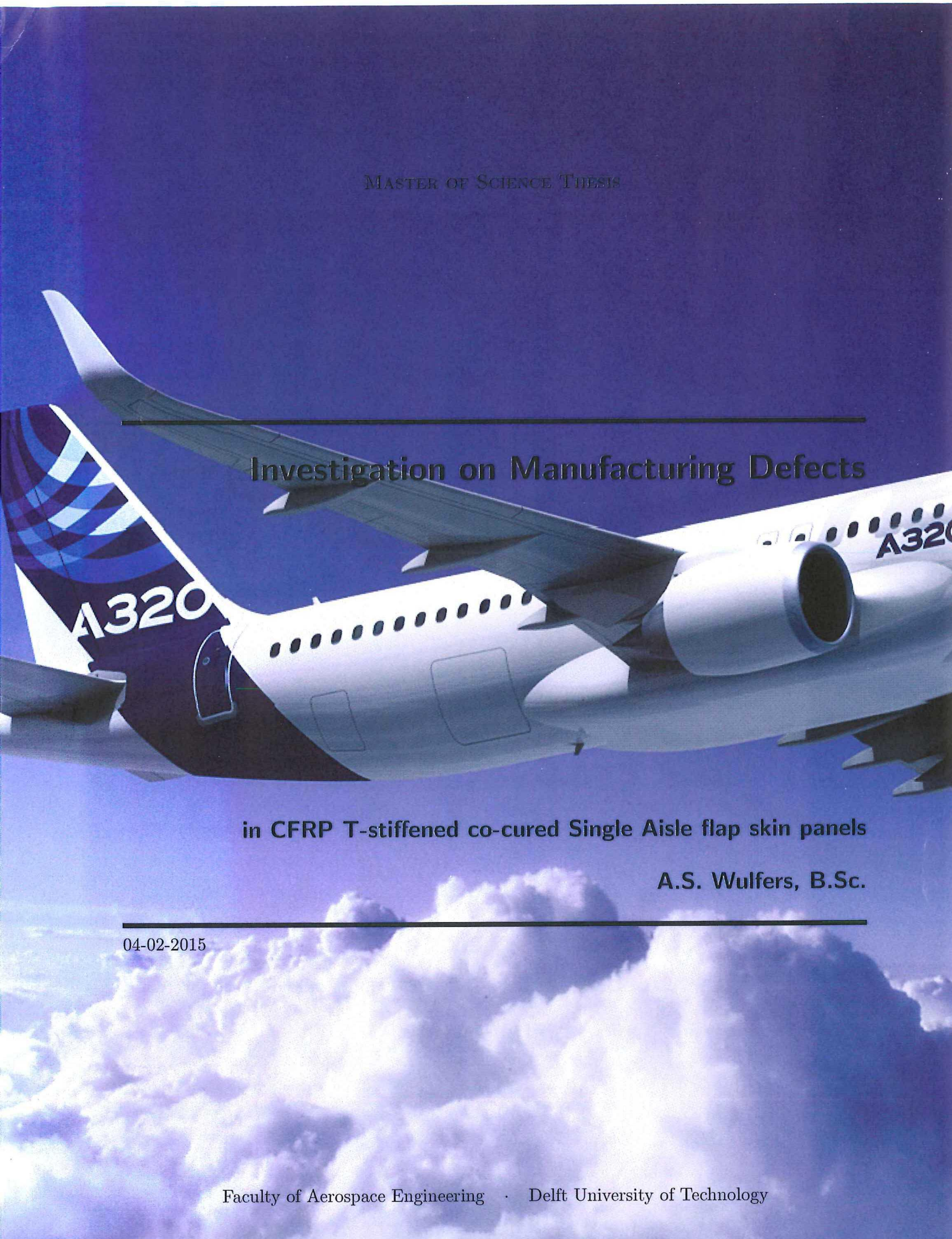

Master of Science Thesis

Investigation on Manufacturing Defects

in CFRP T-stiffened co-cured Single Aisle flap skin panels

A.S. Wulfers, B.Sc.

04-02-2015

Faculty of Aerospace Engineering · Delft University of Technology

TU Delft Delft University of Technology

Challenge the future

Investigation on Manufacturing Defects
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MASTER OF SCIENCE THESIS

For obtaining the degree of Master of Science in Aerospace Engineering
at Delft University of Technology

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04-02-2015

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DELFT UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF
AEROSPACE STRUCTURES AND MATERIALS

The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Investigation on Manufacturing Defects"** by **A.S. Wulfers, B.Sc.** in partial fulfillment of the requirements for the degree of **Master of Science**. The contents of the thesis may only be made accessible to the supervisors and the members of the examination office. The use of the thesis particularly as part of lectures is not allowed without written consent of the Airbus Operations GmbH.

Dated: 04-02-2015

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Summary

The scope of this thesis is to improve the production of the Single Aisle (SA) aircraft family carbon fibre outboard flaps produced at Airbus Stade. Currently, the SA outboard flaps are of insufficient quality and many need to be repaired after manufacturing due to manufacturing defects. In order to save time and money, a new tooling concept needs to be developed which can produce panels of good quality. The causes of manufacturing defects were previously unknown. So as a first step, the causes have to be identified for the defects that are currently present in the SA outboard flaps. Finding the causes and setting the requirements for the tooling are the main topics of this thesis. In this master thesis, the following main research question was answered:

What are the requirements of a new tooling concept in order to eliminate the causes of the manufacturing defects that occur in the production of the CFRP T-stiffened co-cured SA flaps skin panels?

In order to answer this question, actual panels from the production were examined for defects and were described, and also a literature study was performed to examine the current production methods for T-stiffened panels as well as the current state-of-the-art solutions with respect to different toolings. These tooling and manufacturing solutions remove certain defects and serve as a basis for examining the current defects and pose several solutions for the defects.
The defects were observed in the actual panels by both a visual inspection to examine the outer quality and by evaluation of the cross sections to examine the inner quality. The defects that are present in the actual flaps are: in- and out-of-plane undulations, slipped stringer plies, wrinkles, resin rich areas, and filler material misalignment in horizontal direction. Furthermore, the possible causes of these defects were determined by inspecting the current production process, the tooling and by referring to literature. These possible causes are simulated by process alterations that were introduced to the test panels that were constructed in order to reproduce the defects.

The next step to answer was to simulate the possible causes in the manufacturing of test panels. The goal was to try and recreate the defects in test panels by changing process parameters. For this, test panels were manufactured that represent a section of the out board flap. By changing the process parameters, the causes of the defects were simulated successfully by means of altering the process. The process alterations that were done were to make panels where the preform core width was smaller than autoclave core width as well as bigger, introduce hanging cores with equal size preform and autoclave cores, higher and lower stringers than the stringer cavity, incorporate core movement during the autoclave cycle in longitudinal direction with ramps present as well as and lateral movement and rotation of the cores and finally to produce a panel where the filler shape and size was changed.

Additionally to the defects that are present in the actual flaps, also dry spots and vertical filler movement defects were simulated. However, these defects were not expected as a cause from the process alterations and were caused during the production of the test panels. Nevertheless, their causes were determined and also described below. As a main conclusion to what the main causes can be for the defects in the actual flaps is the mismatch and removal and insertion back of preform cores and the autoclave caul plate cores. Additionally, the tooling is not placed correctly, causing shifting and rotation of the tooling in the autoclave. To a small extend, the length of the stringer laminates with respect to the height of the stringer cavity influences the quality of the stringers. The shifting of the cores in longitudinal direction is of a lesser influence, but the expansion of the laminate under the autoclave pressure and the ramps does have influence on the panel quality.

These causes describe also the defects map that was constructed. The map can be used to identify defects in the actual process and the matching causes easily. This defect map served as a basis for setting the requirements for the new tooling concept.

In addition finding the causes of the defects, an economical analysis is done in order to determine the budget that would be available for a new tooling concept. There is a big potential of cost saving when the number of defects can be reduced.

As an answer to the main research question, the requirements are set-up which need to be followed, in order to produce perfect panels. It could be that not all the requirements can be achieved simultaneously. As a result, a trade-off needs to be made on which requirements to fulfil depending on the requirements and constraints that are set by Airbus.

Acknowledgements

Looking back at my thesis, I can say that I am satisfied, with the work done and the experience I gained. The interaction between the office work with setting up the trials, analyzing the defects and processing the results combined with working in the shopfloor to manufacture my parts was a good combination to turn the thesis work into an enjoyable experience. Before my thesis I already did my internship in the same department of Manufacturing Engineering at Airbus Stade. This allowed me to find this interesting and suitable topic for my master thesis with the help of my colleagues at Airbus as well as my supervisor from the university.

In this chapter I would like to take the time to thank the people that helped and assisted me during my thesis. First and foremost I would like to thank my supervisor from the Delft University of technology Jos Sinke and Wolfgang Nemetz from Airbus GmbH Stade. I am thankful for the support that I got from Jos Sinke first of all for setting up the contacts with Airbus to get my internship position in Stade and with the input on how to formulate my thesis, guiding me through the process in coming to a well structured master thesis. Also thank you for coming to Stade for the midterm review and taking personal interest in the topic of my master thesis.
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I would like to thank my other colleagues from Airbus, namely Jelle Bloemhof for supporting me do my internship and thesis in his department of manufacturing engineering. Many thanks as well to Alpaslan Dikfidan to support me as my manager and helping me find my thesis topic.
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Lastly I want to say thanks to my direct colleagues Rubén Buelga, Ciro Farinelli and Guillaume Grieve for giving their inputs in the defect analyses and helping me in the shopfloor.

During this master thesis I experienced that team work is an important factor in achieving goals and without the persons mentioned above, my thesis would not have been successful in the way it is now. Thank you all for an unforgettable and pleasant time at Airbus.

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α	Thermal expansion coefficient	$[K^{-1}]$
θ	Ramp angle	$[deg]$
A	Area	$[mm^2]$
h	Height difference between stringer and stringer cavity	$[mm]$
L	Tooling width	$[mm]$
l	Length of the ramp	$[mm]$
R	Tooling radius	$[mm]$
t	Laminate thickness	$[mm]$
T	Temperature	$[degC]$
$t\%$	Laminate thickness increase	$[-]$
w	width difference between preform and autoclave core	$[mm]$

Abbreviations

AIPI	Airbus Process Instruction
AIPS	Airbus Process Specification
AITM	Airbus Test Method
CAD	Computer Aided Design
CEO	Current Engine Option
CFRP	Carbon Fibre Reinforced Plastics
CNQ	Costs of Non-Quality
CTE	Coefficient of Thermal Expansion
DT	Destructive Testing
FPQ	First Part Qualification
IBF	InBoard Flaps
IML	Inner Mould Line
IPS	Individual Product Specification
NDI	Non-Destructive Inspection
NDT	Non-Destructive Testing
NEO	New Engine Option
OBF	OutBoard Flaps
OML	Outer Mould Line
QTR	Quality Test Report
ROI	Return Of Investments
SA	Single Aisle
TPV	Teilprozess Variantenbescheibung (part process description)
VTP	Vertical Tail Plane

Chapter 1

Introduction

In the aerospace industry, it is often a challenge to save as much weight as possible in the final design of an aircraft. The weight that is saved on an aircraft, directly results in fuel savings and/or more load carrying capability [21]. Nowadays, more and more aircraft panels are made from composites, with an annual increase of 10 % [21]. In particular carbon fibre reinforced plastics (CFRP) are used, because of their high strength to weight ratio compared to for instance aluminium [10]. The Boeing Dreamliner and Airbus A350 both consist of about 50 % of the weight of CRFP [21].
Aircraft manufacturers, like Airbus, are continuously trying to save more weight by implementing more composite panels. For these composite panels, there are still a lot of possibilities to decrease the production costs by optimising the manufacturing process. In this decrease of the production costs, is also the amount of rework included that is necessary after manufacture to deliver final panels of satisfactory quality.

The scope of the work is the Single Aisle (SA) aircraft family's carbon fibre outboard flaps produced at Airbus Stade in Shopfloor 15 New. The production and tooling concept for the flaps is more than 25 years old and the production rate is rising continuously. At the same time, the failure rate of panels that need rework is increasing, because the current tooling concept is causing manufacturing defects. For an increasing production rate and the aim of improving the panel quality, the goal is to develop a new tooling design and process flow. As a first step, the causes have to be identified for the individual defects that are currently present in the SA outboard flaps. Finding the causes and setting up the requirements for the tooling are the main topics of this thesis.

The challenge here is to find what the current available tooling options are that have been investigated by other companies, institutions and universities for similar panels and production methods in order to eliminate production defects. Currently, the panels show defects mainly in the form of in- and out-of-plane undulations and wrinkles in the skin, slipped stringer plies in the stiffener itself and resin rich areas in the corner sections. Finding the causes of the defects that occur in the production of the SA flaps during the thesis will be a unique research where the causes of a combination of different manufacturing defects have to be found that are present in one specific part.

The main research question that will need to be answered during the master thesis project is the following:

What are the requirements of a new tooling concept in order to eliminate the causes of the manufacturing defects that occur in the production of the CFRP T-stiffened co-cured SA flaps skin panels?

In order to answer this question, the question is divided into several different sub questions. The answers to these sub questions combined will give a well-argued answer to the main research question. Also, they serve as the objectives that need to be achieved during the thesis. The three sub research questions are:

1. Which defects are currently present in the panels and what could be the possible causes?
2. How can the possible causes be related to the anticipated defects that are currently present in the part?
3. What are the requirements for a tooling concept in order to produce a perfect part?

For sub-question one, actual panels from the production need to be examined for defects. The defects can be observed by either visual inspection, or by evaluation of cross sections or both. By checking the quality, the defects can be determined and categorized. Furthermore, the possible causes of these defects can be determined by inspecting the current production process, the tooling and by referring to literature.
The next step to answer question two is to simulate the possible causes in the manufacturing of test panels. The goal is to try and recreate the defects in test panels by changing process parameters. For this, test panels are manufactured that represent a section of the out board flaps. By changing the process parameters, the cause of the defects can be found. Therefore, the approach that will be used is going to be of experimental nature since test panels are made to simulate the defect causes. The initial assumptions on what the causes are can be verified by manufacturing these test panels. The manufacturing of the test panels needs to be as identical as possible to the actual flap manufacturing process. As a limitation, only the preform and autoclave build up process steps including the handling and placement of the tooling are considered in order to limit the project to the set workload. In addition, the current carbon fibre prepreg and autoclave need to be used for producing the test panels. Also, Airbus has a production process that is being operated continuously for the production of the A320 flaps, so the work should be done in parallel with the production itself without halting the process.
The first step is to create a panel which is of good quality to use as a benchmark to make changes to the process. As a result, a defect map can be constructed, that shows images of the defects per category and its respective cause. The map can be used to identify defects easily in the actual process and the matching causes.
This defect map will also serve as a basis for setting the requirements for the new tooling concept in order to answer sub-question three. The new tooling needs to fulfill these requirements in order to produce the perfect panel without any defects. It could be that not all the requirements can be achieved simultaneously. As a result, a trade-off needs to be made on which requirements to fulfill depending on the requirements and constraints that are set by Airbus.

As a start of the thesis, the literature study that was done as a preparation for the thesis is summarized in chapter 2, followed by the description of the current production process of the SA outboard flaps and the tooling that is used, also for other similar T-stiffened carbon fibre panel production processes in terms of tooling used within Airbus in chapter 3. In chapter 4,the analysis is done of the current defects and the possible causes of them by analyzing the production process. Chapter 5 explains how the test panels are manufactured and how the production and the tooling deviates from the actual flap production. The recreation of the defects from the possible causes is done by making alterations to the tooling and the production process in the test panel production and is explained in chapter 6. The test panels are divided in four different groups, that represent different kinds of alterations to the production process, tooling and the laminate. The first step is to create a panel which is of a good quality to use as a benchmark. Next, the test panels are made where changes to the tooling were introduced. These panels are followed by the panels where movement of the cores is simulated that occurs in the autoclave. Finally, the panels are explained where the laminate and the panel itself are changed with respect to the stringer height and the filler material.
As a conclusion, the causes of the defects will be determined in the same chapter. An economical analysis is done to determine the budget that can be spend on the tooling and is described in chapter 7. The budget and the causes of the defects are the basis for the requirements for a new tooling concept which are given in chapter 8. Finally, conclusions are given in chapter 9 followed by recommendations in chapter 10.

Chapter 2

Literature Study

This literature study is a summary of the actual literature study that was done in preparation for the master thesis. In this study, several available tooling options and materials and their effect on the panel quality will be presented that have been investigated by other companies, institutions and universities for similar panels and production methods. The objective is to understand what tooling types are currently used in the production of T-stiffened panels. New tooling concepts are often introduced to prevent formation of defects that are present in the part. By introducing a new tooling concept, these defects are removed and are therefore an indication for the cause of the defects.

This research is considered to be unique, since is it concerns an industrial specific application of a tooling for a unique panel and production process and its corresponding defects.
The research can be subdivided into three main areas of interest, namely the manufacturing techniques for stiffened composite panels and the tooling itself and are discussed individually in section 2.1. How the work of the master thesis will expand on this literature that is reviewed, is explained in section 2.2. To summarize, the conclusions are given in section 2.3.

2.1 State of the art / Literature review

In this part of the study, a detailed review is given to investigate the research that has already been carried out by academics and other researchers. The research that has been performed in industry is also reviewed, and then particularly the research at Airbus. The goal of the literature review is to establish the current state of the art knowledge and what the thesis work should contribute to the current body of knowledge.
The research can be subdivided into two main areas of interest, namely the manufacturing techniques for stiffened composite panels, and the tooling itself.

2.1.1 Manufacturing techniques of stiffened composite panels

Currently, the stringers of the A320 flaps are first preformed with a hot forming production process. There are different types and shapes of open-section stiffeners of which the T-stiffeners is the simplest form. This form of stiffener is also the one used in the flaps here at Airbus. Most of the time the stringer consists of two halves, left and right side, that are joined together during curing [11, 27, 28, 29]. By combining different shapes of the halves (e.g. U-profiles, T-profile, etc), most stiffener shapes can be manufactured (e.g. T-stiffeners, I-stiffeners, S-stiffeners). To obtain the shape of the stiffener halves, tools with the negative shape and final panel dimensions are used.

In the hot forming process, the prepreg is heated and curved around an aluminium tool by applying pressure with the silicon membrane that is located above the prepreg and mould. A common problem that can arise in the hot forming process steps are voids and wrinkles in the preform [22, 26]. The defects occur because of the interlaminar friction between plies during forming. If the plies cannot slide properly with respect to each other, the wrinkles and voids occur. These defects can exist because of a too high rate of applying the pressure or that the forming temperature is too low. Adjusting the rate of applying pressure and the forming temperature could have a favourable effect on the panel quality.

For attaching the stiffeners to the skin, there are three main techniques in doing so [12, 29]:

- Co-curing, where the stiffener and skin are cured simultaneously
- Co-bonding, were the stacked prepregs are cured with other panels
- Secondary bonding, where cured panels are joined together by using an adhesive

It is considered that the co-curing technique offers many advantages above the co-bonding and secondary bonding techniques [11, 14, 18, 29]:
Most of the advantages either involve a cost reduction, because of the usage of less material and a simpler production method, the fact that the panel is one panel so only one panel quality check is required without the need for an extra bondline quality check, or the possibility for an increased panel quality due to less handling. However, co-curing also has the main disadvantage that it is very difficult to repair certain defects in the assembly [18]. So a precise and accurate tooling concept needs to be designed that is capable of producing panels of a good and reproducible quality.

Literature states that with an equal pressure distribution over the panel during curing, also the fibre compaction is more uniform [27, 28, 29]. A higher fibre compaction leads in its turn a better quality with fewer possibilities for porosities and wrinkles to occur. Factors that have an effect on the pressure distribution in the corner section are the size, material and shape of the filler material in the junction of the web and flange [12, 14, 18, 27]. Without fillers there are resin rich areas on the outside of the stiffener and fibre waviness of the skin on the junction of the skin and stiffener halves. With an insufficient size of fillers it is shown that one halve of the stiffener is pushed upwards and that the other halve is pulled down. This is due to the fact that the filler has shifted to one of the sides instead if it is situated in the middle. It could also happen if the filler has a wrong shape. This could be a cause for the slipped stringer plies, which is one of the defects that occurs in the flaps produced at Airbus. At Airbus they also use fillers for the stiffeners, but the question still remains if the right size is used.

2.1.2 Tooling

Tooling determines to a large extend the final quality of the part, so attention should be paid to the design and the materials of the tool. Researchers generally agree that a high quality of the

final panel closely relates to an even pressure distribution in the corners. This can be achieved by applying fillers in the junction of skin and stiffener as explained earlier, but also by the right design of the tooling [12, 14, 19, 23, 28, 29]. The right pressure distribution ensures that there is equal compaction of the fibres and a uniform distribution of the resin. Additionally, no pressure gradients will be present which may result in entrapped air causing voids.
There are two major types of tooling, namely hard and soft tooling. The definition for hard tooling is that it is assumed that the thermal expansion of the tool corresponds to the thermal expansion of the panel or at least that it is negligible to take into consideration. For hard tooling, aluminium is a preferred choice of tooling material since it has a low density for easy handling, is easy to machine and robust in use at the same time [11, 18]. Also the accuracies of the mould line are very high and exhibit an excellent surface quality [12].
Steel can also be used as tooling material [12]. It is more robust and damage tolerant than aluminium, but has as its disadvantages that it is more difficult to machine and has a high density making the tools more difficult to handle. Generally, hard metal tools are only used for simple composite shapes without curvature [12] and are therefore less suited when the ply drop ramps are present.

Currently, only hard tooling is used for both the production steps, namely aluminium and carbon fibre. The reason that carbon fibre is being used for the final curing is because of the identical Coefficient of Thermal Expansion(CTE) with the part. The identical CTE is because of the same material that is used for the tooling and orientation of the plies as for the panel. In the panel itself there are several ply drops in the lengthwise direction that are also incorporated in the design of the tool. If the ply drop location in the panel and in the tool is not the same, defects could occur. Therefore, great care should be taken in the design of the tool that these locations match up for the final cure.

The thermal expansion of carbon fibre composites depends on the percentages of $\pm$ 45, 0 and 90 degree layers. In composites, the greatest contribution to thermal expansion is the resin itself. That means that a ply will have less expansion in the direction of the fibres than in the other direction. The relation of the percentages of fibre directions, together with common tooling materials can be seen in Figure 2.1 [20]. The data in the graph is valid for a fibre volume content of 60%, which is the same as in the production of the outboard flaps.

To easily remove the tool after curing and to avoid cracks in the corner sections of the part, it is advantageous to have a CTE of the tool which is smaller than the CTE of the laminate for a convex tool. For a concave tool is advantageous to have a CTE of the tool which is larger than the CTE of the laminate. If a panel needs to be constructed with ramp-ups, the CTE should be similar for the panel and tool.

Several studies have been conducted by researchers whereby hard tools are used in the production of stiffened composite skins [12, 18, 29]. A problem that could occur with the tooling is that they start shifting from their original position either due to the thermal expansion [18] or mispositioning and misalignment of the tools by the workers. This can happen when the workers are building up the mould before the autoclave cycle.
The thermal expansion of the individual tools is accommodated for by pressing against the adjacent tools. Constraints can be placed around the panel to further constrain the outer edges of the individual tool elements, to fully secure them and constrain any movement in any direction. The constraining of movements will however lead to the build up of stresses in the individual tool elements and the over pressurization of the stiffeners. Another possibility to avoid these problems would be to constrain the tools on one side with for example bolting the tools onto the base plate [18], to line them up perfectly, and to let them expand in the other direction.

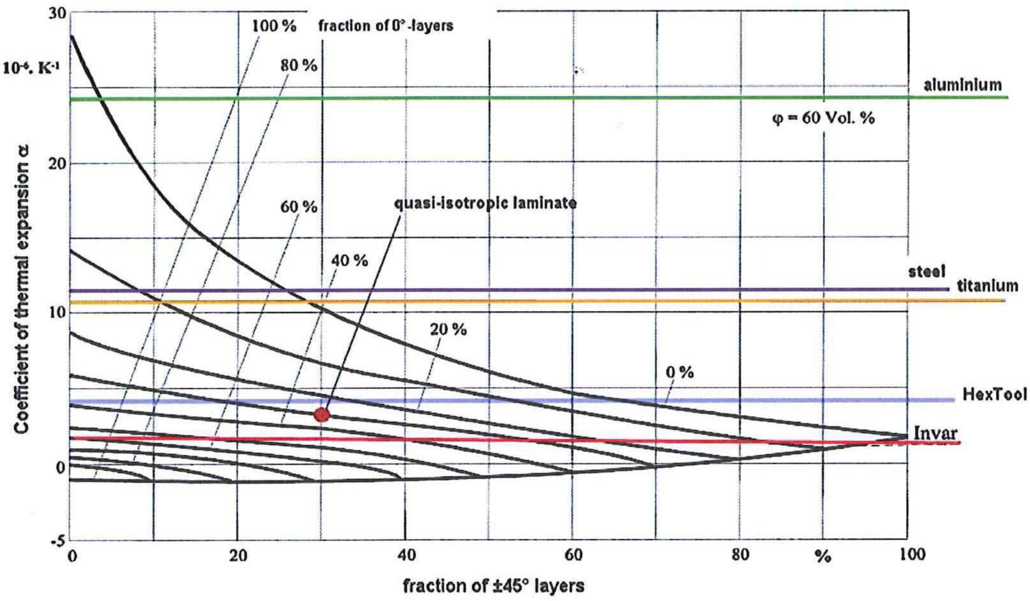


Figure 2.1: CTE of a laminate with a fibre volume content of 60 percent as a function of the fibre orientations

Research has been carried out on removing fibre waviness that arises in the stiffener corners during manufacturing [29]. Applying a position limit around the tools, to prevent tool movement, eliminates the fibre waviness and a uniform thickness is also obtained.

One of the other problems that arises with the hard tooling is that a void could be present in the corner of the stiffener as shown in Figure 2.2 [27].

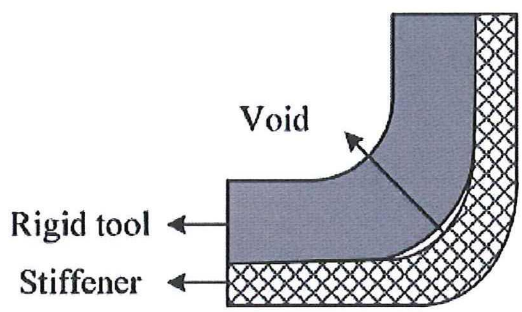


Figure 2.2: Void in the corner of the stiffener

This void will either fill up with resin or plies start to shift due to the empty space. Therefore it is of key importance that the tool matches with the final panel in terms of the outer radius of the tool and the inner corner radius of the part [14, 28].

With soft urethane tooling, the difference in the thermal expansion coefficient of the carbon fibre of the panel and the tooling itself ensures compaction of the fibres [12, 19, 23]. The soft tooling tends to expand more with increasing temperatures than the carbon fibre. So when the tooling and panel are heated up in for example an autoclave or oven, the tool compresses the fibres of the panel due to its own incompressibility. When fully utilising the potential of soft

tooling, no additional pressure is needed, which eliminates the use of an autoclave for providing the pressure for the fibre compaction [12, 23]. The hydrostatic pressure that is applied by the tooling is enough for the full compaction of the composite.
However, if a combination of hard and soft tooling is used, an autoclave should still be used for applying the needed pressure on the panels where the hard tooling is present [28].
As stated before, the curing pressure needed to compact the fibres is generated by the expansion of the mould during the curing process when using elastomeric tooling [28]. An advantage is that a uniform pressure distribution can be achieved and that voids between the tool and panel are avoided. This results in better fibre compaction when comparing it to hard tooling. Also, at room temperature, the mould can be easily removed since they are smaller than the cavity it needs to fill. Only during heating they will expand, making the demoulding less complicated.

Reinforced elastomeric tooling uses a directed application of controlled pressure to all areas of the laminate [19]. It makes advantage of the combination of the stiff properties of hard tooling and the pressure distributing properties of soft tooling. The tooling should help with the problem of bridging where voids are present between the tooling and the laminate and is able to provide enough support to maintain the stiffener shape when the autoclave pressure is applied. The combining of hard and soft tooling is also done in the manufacture of isogrid panels [16, 17, 24].

Reinforced elastomeric tooling uses the same principle of elastomeric tooling where the difference in CTE between the tool and metal/composite materials is used for better compaction. The reinforced tooling is most often made from polyacrylic rubber, where the main manufacturer is Airtech International that produced the material known as Airpad [1].
The Airpad is a rubber elastomeric sheet that is placed between the mould tool and the panel itself in the case of the production of T-stiffened panels. The rubber is reinforced locally to prevent shrinkage of the rubber and to provide a stiff pressure intensifier where necessary. These local reinforcements can be made from a variety of materials like, perforated metal sheets, wire mesh, dry glass, carbon fabrics and glass and carbon prepregs. The basic concept of reinforced elastomeric tooling is shown in Figure 2.3.

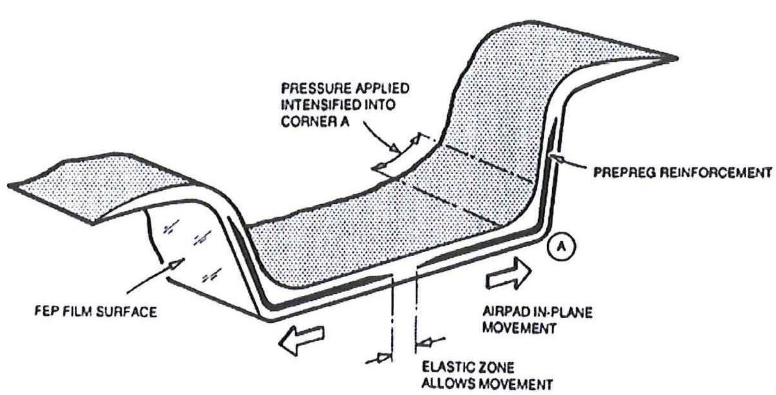


Figure 2.3: Concept of reinforced elastomeric tooling

In addition to the Airpad tooling that is described above, several other examples of reinforced elastomeric tooling are proven in successfully producing stiffened skin panels [13]. Wang carried out a research where the tooling consisted from a flexible section of only rubber in the corner of the stiffener and a combination of silicon rubber and glass cloth to transfer pressure selectively. He used the stacking sequence of one layer of silicon rubber, four layers of glass cloth followed by a layer of silicon rubber. In the contrary to the polyacrylic Airpad example given above, which uses thermal expanding rubber, Wang uses silicon pressure-transferring rubber which has a thermal expansibility that is much lower than that of the thermal expanding rubber. With the pressure-transferring tooling, only the pressure applied in the autoclave is causing the required pressure in the corners. It was examined that these flexible corners are beneficial in compacting fibres in the corner sections by transferring pressure to these sections effectively.

The manufacture of isogrid panels is commonly done utilising the advantageous material properties of combining both hard and soft tooling. Isogrid panels are panels which have stiffeners placed in a grid-like structure. This is an efficient way of distributing loads. The basic design of the panel is different than that of T-stiffened panels, but a lot of research has been done on the manufacturing of isogrid panels, using co-curing techniques [16, 17, 24]. These techniques and the corresponding tooling could provide a basis for a new tooling concept for T-stiffened panels. Most often, elastomeric tooling is used with the shape of the stiffeners embedded as grooves in it, a steel caul plate is placed on top of it and barriers are located on the sides to constrain the rubber from expanding sideways. As a result, the rubber will compress the stiffeners to provide the curing pressure. Next to rubber tooling, also research has been done with regards to the usage of hybrid tooling [24]. In hybrid tooling, the base tool is made from a different material as the expansion tool. The base tool provides the stiffeners with the basic shape and the expansion tool compacts the ribs. This way, the advantages of both different materials are used.
Another method is the expansion block method where expansion blocks are bolted on a stiff base plate. These blocks should be made from a material that has a low compressibility and a high CTE. Like in the hybrid tooling, the expansion blocks will compact the stiffeners with an increasing temperature.
These concepts can be useful in providing the final shape of stiffeners in addition to using only flexible tooling where the stiffeners can collapse without proper support.

2.2 Results and Analysis

It can be said that the manufacturing techniques and tooling that is presented in literature was tested and examined as alternatives to diminish certain manufacturing defects. The current state of the art is the reinforced elastomeric tooling which uses an application of directed controlled pressure to all areas of the laminate. It makes advantage of the combination of the stiff properties of hard tooling and the pressure distributing properties of soft tooling. However, all the research only focuses on one defect at the time while here at Airbus there is the combination of defects in the form of undulations as well as the slippage of the stringer plies. Also, most articles and solutions focus on only simple stiffened panels, while the SA flaps are more complex due to their size in the lengthwise direction and the ply drops that are present. Therefore, it is key that the causes of the individual defects are found in this thesis by changing the preform and autoclave tooling as well as the production process itself. By isolating the causes of the individual defects, a new tooling could be designed that produces panels of good quality without any defects.
Finding the causes of the defects that occur in the production of the SA flaps during the thesis will be unique in that sense that it is the solution in finding the causes of a combination of different defects present in one specific part.

2.3 Discussions and Conclusions

In this literature study the different possibilities that are currently available to produce the A320 outboard flaps of the same or better quality are explained. Several available tooling and manufacturing process options possibilities have been presented as well as how they remove defects present in the respective panels. These are investigations by other companies, institutions and universities for similar panels and production methods in order to answer the following main research question:

What are the requirements of a new tooling concept in order to eliminate all the causes of the manufacturing defects that occur in the production of the CFRP T-stiffened co-cured SA flaps skin panels

Adjusting the parameters of the hot forming process could result in a better panel quality of the preforms. For alternative production techniques, the conclusion from literature is that the co-curing technique offers the most advantages compared to others like co-bonding and secondary bonding. For the manufacturing techniques, it is important to achieve a uniform pressure distribution in the corners. One way to regulate the pressure distributions is to insert the right amount of filler of the right shape in the intersection of skin and stiffener. The quality of the final panel is also determined to a large extend by the type and design of the tooling. The design of a tool is therefore important in achieving an improved panel quality. Both hard and soft tooling offer their advantages. Hard tooling can achieve high accuracies of the mould line and exhibit an excellent surface quality. However, the pressure in the corners could not be distributed evenly, resulting in the possibility of voids to be present in the corners. Therefore are the tool and the tool radius design critical in achieving a good panel quality.
Soft tooling, like elastomeric tooling, does have the capability to distribute pressure more evenly, but lacks sometimes the rigidity to provide enough structural support during curing. Combining soft and hard tooling or reinforcing the soft tooling offer the advantages of both tooling concepts and is also used often in the manufacture of isogrid stiffened panels.
The analysis of these tooling alternatives and manufacturing alternatives will serve as a basis for identifying the causes of the defects present in the SA outboard flaps. During this thesis, the tooling and production process are changed in order to simulate defects and find their respective causes.

Chapter 3

Production process and tooling used

In this chapter, a description of the actual production process is given of the A320 outboard flaps. Also, the currently used tooling is explained, not only for the A320 outboard flaps, but also for the A320 inboard flaps and the A380 flaps. The production process of the A320 outboard flaps is used as a reference to which the test panels that will be manufactured. In addition to the process description and the tooling used, a brief overview is given about the types of documents that are used within Airbus.

3.1 Airbus Documents

At Airbus, they have several different types of internal documents that will describe the different processes, materials, panels, requirements in a detailed manner. These documents must be followed when producing similar aircraft panels or when identical process steps and/or materials are used at other production sites within Airbus. Most of the process documents are however site specific, because the production process is different at the different sites.

- 80-T-X-XXX: Process specification that contains general manufacturing instructions for local production processes. These instructions fall within the requirements that are set by the AIPS.
- AIMS: AIrbus Material Specification that contains general material requirements
- AIPI: AIrbus Process Instruction that contains detailed manufacturing instructions, specifically for A350 panels. These instructions fall within the requirements that are set by the AIPS.
- AIPS: AIrbus Process Specification with the general manufacturing instructions. These instructions are considered as the master set of requirements where all other requirements fall within these constraints.
- AITM: AIrbus Test Method that contains general requirements for test methods
- IPS: Individual Product Specification with the individual requirements that a material needs to possess.

- QTR: Quality Test Report is the description on how tests need to be performed and which variables should be tested during the qualification of a process
- TPV: Teilprozess Variantenbescheibung (panel process description) explanation of the production process of a single part, for instance of the A320 outboard flaps.

3.1.1 Tooling Used

In this section, the research that was done within Airbus on the different tooling concepts is explained.
For the A320 outboard flaps, aluminium tools are used for the preforming of the stringers. The tools are used in the hot foming station (solarium) where the stiffeners are curved into their shape, in the press station where the two halves of the stiffener are pressed together for all the stiffeners so that they are combined in one pack, see figure 3.1 [8], and during the rotation and the assembly of the stiffeners to the skin.

Figure 3.1: Compaction of the stiffener halves

The CFRP tools are inserted for the autoclave (ACL) build-up step and are present to maintain the shape of the stiffeners and applied pressure on the laminate as evenly as possible. The base plate of the build-up is made from invar (nickel-iron alloy notable for its low CTE). The carbon fibre tools have a U-shaped profile and are shown placed on the laminate in figure 3.2 when the vacuum bag still needs to be placed over the panel and mould.

The schematical drawing (figure 3.3) of the cross section shows what the final build-up, including the grey carbon fibre tool, should look like [8].

As can be seen from Figure 3.3, the two halves of the cores makes contact at the top of the stiffener web. This could also be a reason on why the plies of the stiffener show signs of slippage. If the two tools do no match up properly, resin and fibres can slip through an opening between the two tools.

In the tooling of the inboard flaps, a different concept is used and only one set of tooling is used for both the preforming of the fibres as well as the build up for the autoclave. The base plate for the autoclave build-up is made from steel for the inboard flaps. The tools are made from

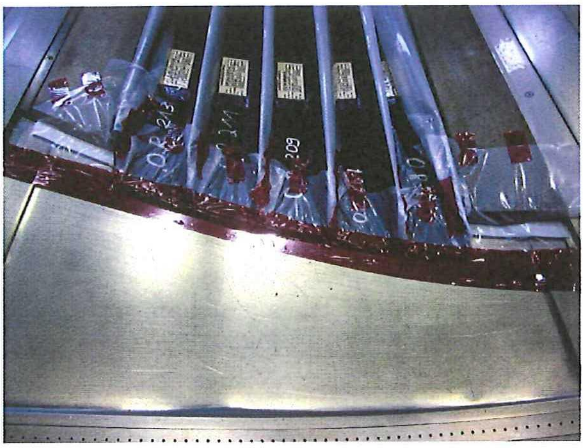


Figure 3.2: Carbon fibre tooling setup

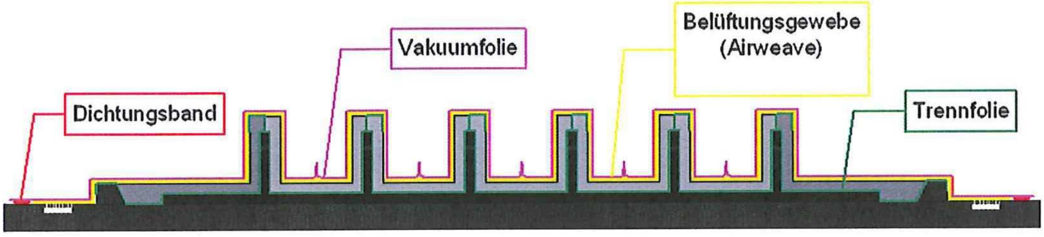


Figure 3.3: Autoclave build-up

aluminium. With the inboard flaps less defects occur and especially almost no fibre waviness and slipped stiffener plies. This could be an indication that the aluminium tooling for the autoclave build-up provides enough support and a uniform pressure distribution. It also corresponds to the literature [12] that metal tooling provides very high accuracies of the mould line and exhibit an excellent surface quality.
It could also be that the usage of only one tooling concept for both preform and autoclave build up is beneficial for an increased panel quality. As explained before, the usage of only one set of tooling reduces the possibility of a mismatch between the two different tools, plus the handling is also reduced. Less handling will result in fewer possibilities for defects to occur, like for instance the slipping of individual plies and positioning problems of the individual components.
It could also be that the matching of the tooling is better designed for the inboard flaps. For the inboard flaps, the aluminium tools are overlapping so that they cannot have a void between the tools to let the resin and fibres flow through. The inboard tooling concept can be seen in figure 3.4.

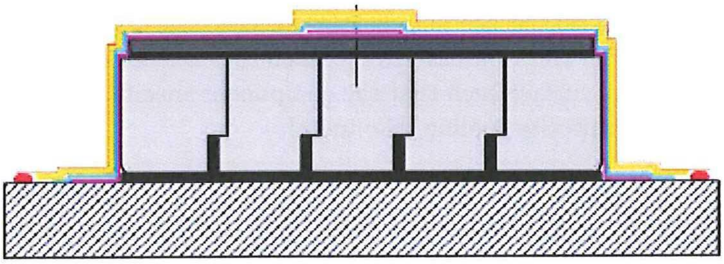


Figure 3.4: Inboard flaps tooling setup

The reason that one set of aluminium tooling can be used for the inboard flaps and not for the

outboard flaps is that the inboard flaps have a high ramp up section in the middle of the skin (ramp up and ramp down) and two ramp-ups on the side, as seen in figure 3.5. The aluminium core needs to be smaller than the CFRP preform core to have the identical shape as the CFRP preform in the autoclave due to the larger expansion of the aluminium in order to prevent over pressurization of the two ramp ups on the side. The tool is positioned on the middle ramp up area and the aluminium expands to both the left and right side, providing pressure to the two ramp-ups on the side.
For the outboard flaps, there are two ramp up sections in the middle (instead of one) and two ramp-ups on the side, as seen in figure 3.6. The aluminium core could then not be placed over one of the ramp sections, since the tool will then not fit over the other ramp-up section at room temperature because it is smaller than the CFRP preform. From figure 3.6 the mismatch of geometries of the aluminium tooling that will expand in the autoclave and the CFRP preform is clearly shown. If the tooling would be placed on like this, the tooling would fit over one ramp, but at the other ramp the corner of the tooling would press in the flat panel of the ramp of the CFRP preform. Therefore, the tools for the autoclave are made from carbon fibre to have a similar CTE, so that the tools both fit at room temperature and during curing.

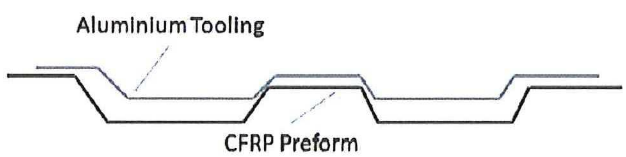


Figure 3.5: Inboard flaps tooling geometry in lengthwise direction

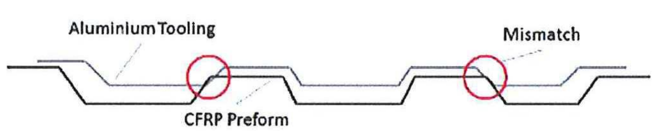


Figure 3.6: Outboard flaps tooling geometry in lengthwise direction

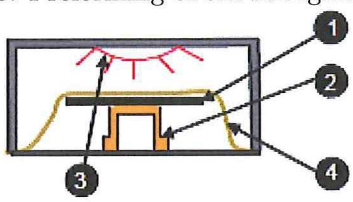
For the A380 flaps, also only one set of tooling is used. Only this time, the tools and the base plate are made of invar, which is known for its very low CTE [9, 15]. The low CTE is very close to the CTE of the carbon fibre laminate and won't have the problem like the mismatched CTE between aluminium and carbon fibre.

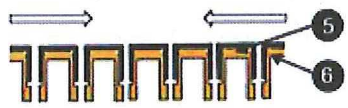
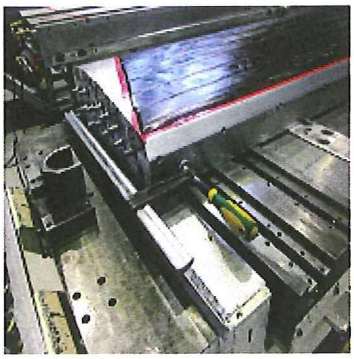
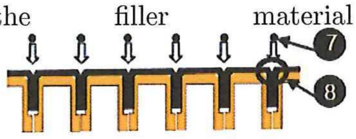
From the 80-T and AIPI documents from Airbus [2, 3, 4, 5, 6, 7], the requirements for new tools and jigs prescribe that during the manufacture of new tools, the different heat expansion coefficients between the panel and tool have to be taken into account. Also, it is stated that the new tooling shall have a tool surface such that the component specific requirements are satisfied. This can be done best with precise tooling, like metal.

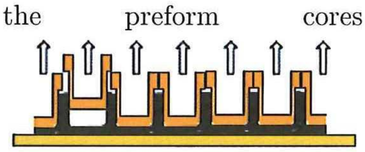
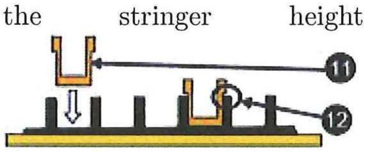
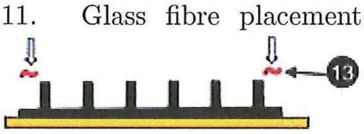
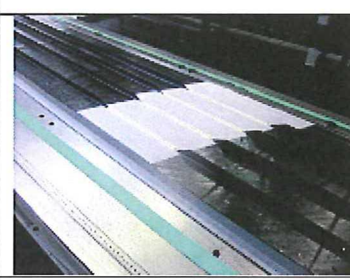
3.2 Production process

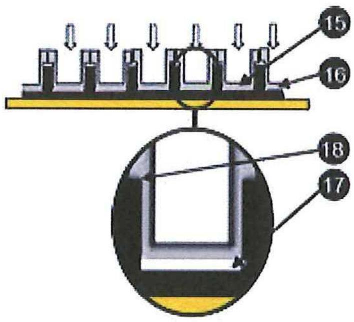
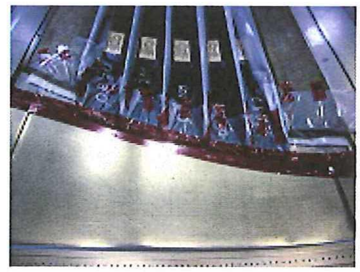
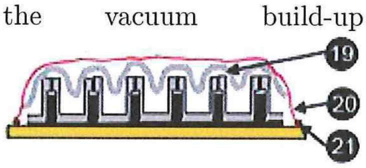
The manufacturing of the test panels needs to be done as accurately as possible. The production process of the test panels deviates slightly from the actual production process as will be explained in chapter 6. For any deviations to the actual production, an explanation is given on which effect it has on the final panel quality, so that the causes of the defects can be isolated in a precise manner.

The main process steps of the production of the A320 outboard flaps that need to be followed strictly according to the corresponding TPV and are as follows:

Process step	Description	Shopfloor image (from TPV)
1. Layup and cutting	The layup is done by the Automatic Tape Layer for both the stringers and skin sections. The correct layup is done automatically, followed by the layup of a release film to protect the laminate. Afterwards, the laminate is cut into the shape of the individual panels.	
2. Build-up of the individual laminate sections	While the laminates of the stringers are automatically laid up and cut in the tape layer, the skin panel is built up by hand from the skin sections. The skin panel consists of several individual sections, which include the ramps and local reinforcements. The sections are delivered from the cutting table and placed on a vacuum table. Subsequently, the resulting laminate is placed under vacuum in order to minimize air entrapment between individual laminate layers.	
3. Preforming of the stringers 	The stringer laminate (1) is formed with the help of diaphragm forming. The laminate is positioned by hand on the preform core (2). The preform core is made from aluminium, because of the durability of aluminium, the attachment of sliding rails underneath the cores and the fact that the cores can be secured easily for the rotation of the pack in step 6. Also, the pack can be compressed with more force, than if for instance the carbon fibre caul plate cores would be used. Infrared heaters (3) heat to the laminate. Under the influence of vacuum, a flexible membrane (4) shapes the laminate around the preform core. The laminate, which lies between the membrane and preform core, attains to the exact shape of the preform core.	

4. Compression of the pack 	The release film on the outside of the stringers is removed first. All of the reshaped stringer laminates are pressed are pressed together by force, while they are still attached to the preform cores. The laminate is sticky because of the resin. This will glue the stringer halves of the flange of the U-profile of two stringers together. Between two preform cores, a stringer is formed. 5 U-sections (5) and 2 L-profiles (6) make up the total stringer pack of one flap.	
5. Placement of the filler material 	A prepreg strip of a width of 20 mm is twisted into a filler with a 3mm diameter (7). The filler is placed into the cavity at the intersection of the two stringer halves (8). The cavity is caused by the presence of the radius of the preform core.	
6. Rotation 	The pack is rotated as a whole in the turning station	
7. Joining of the skin laminate and the stringer pack 	The assembled skin panel (9) is positioned on production tool (FEMI) (10). The FEMI is then placed under the already rotated stringer pack. The skin panel and stringer pack are pressed together by means of gravity and the stickiness of the laminates	

8. Removal of the preform cores 	The preform cores are removed from the stringer pack	
9. Checking of the stringer height 	Using a measuring tool (11), the stringer height is checked. The measurement template has ideal dimensions of the later used CFRP caul plate. The height of the stringer is larger than the final stringer height. It is reworked by hand using a craft knife to cut it to the precise height. Inaccurate stringer heights lead to an air gap and could lead to quality problems(12).	
10. Removal of the release film	The release film that is covering the inside of the stringer laminate, or the inner mould line (IML), is removed	
11. Glass fibre placement 	Glass fibre strips (13) are applied by hand to the edges of the flap and in the track area. The glass layers form an insulating layer between flap and aircraft structure.	

12. Placement of the CFRP caul plate cores and steel edge bars 	CFRP caul plate cores (15) and steel edge bars (16) are placed by hand in the stringer cavities in the location where the preform cores used to be. Why CFRP caul plates are used instead of the aluminium cores was explained previously. If the preform cores do not have the same dimensions as the CFRP cores, defects can occur in the final panel when the core is pressing on top of the stringers (18) and that a gap is present between the stringer web and core(17).	
13. Finishing of the vacuum build-up 	The vacuum build-up is completed in the last step before the autoclave. This includes the application of airweave (19), which helps in establishing a uniform vacuum and protects the vacuum bag against damaging by covering sharp edges of the build-up. Finally, the vacuum bag (20) is placed over and is secured by airtight sealing tape (21) on the FEMI.	
14. Vacuuming the build-up	The build-up is placed under vacuum that pulls through small holes on the edges of the FEMI. This is done to ensure that the vacuum bag and the airweave are shaped over the cores and panel correctly before it goes into the autoclave.	
15. Autoclave cycle	The component is cured in the autoclave. The predetermined conditions for the resin to cure are 2 hours at 175 C at a heating rate of 2-5 C per minute. The autoclave pressure is 7 bars.	

16. Demoulding 	The panel is removed from the autoclave and all the ancillary materials and CFRP caul plate cores are removed	
17. Cleaning panel and moulds	Access resin is removed from the panel and the CFRP caul plate cores.	
18. Machining and trimming	The panel is machined and trimmed around the edges, to give the final shape of the part.	
19. Non-destructive testing (NDT)	The panel undergoes non-destructive quality testing by means of ultrasounds. Both the inner and outer quality is checked with this test for voids and porosities.	
20. Finishing	The outer surface of the panel is cleaned.	
21. Visual inspection	The panels outer quality is inspected by means of a visual inspection.	
22. Shipping	The finished flap is shipped to Bremen when no defects are found or it is reworked and repaired and then shipped.	

Chapter 4

Current Defects

In the outboard flaps there exists a combination of four different defects. However, only two of these defects need rework when they occur during manufacturing. The defect that does not need to be reworked is the misalignment of the filler with the centre of the stringer. The first defect that does require rework is the slippage of either the outer plies of the stringer or that the whole stringer web is pushed down as a whole, causing wrinkles in the carbon fibre layers. The second defect is the undulations or waviness which can occur in both the in- and out-of-plane direction and the third are the dry spots. The four defects are described also briefly in the literature review in chapter 2 including different methods that exist to remove those defects.

The misalignment of the filler material is not a critical defect, but it can be the cause of the other defects as can also be concluded from literature [25]. In the SA flaps there is the unique situation that the combination exists of three defects (slipped stringer plies, undulations and dry spots), so the final solution should be able to remove at least the two critical defects simultaneously. An example of a well-made panel without any of these three defects can be seen in the cross sectional image of a stringer in figure 4.1. The goal in the end of the thesis is to produce panels which have a consistent quality as can be seen in the figure across the entire part.

As a start, the defects in the current panels are examined. An overview of the amount of rework that had to be done per aircraft due to different defects can be seen in figure 4.2

During the last year there were several projects at Airbus to remove the defects of the thickness deviations across the stringers and skin as well as to remove the bulges. These were proven to be successful in reducing the rework of these defects, but the slipped stringer plies and fibre undulations are still the main drivers for rework on the outboard flaps. The rework due to the fibre undulations has even increased, which results in only a small decrease in total rework. The reason for the shift of amount of rework from the thickness deviations to the fibre undulations are for now unclear. For that reason the focus of this thesis lies in avoiding the occurrence of the two critical defects of slipped stringer plies and fibre undulations.

The defects are either observed by visual inspection or by close up images taken by a microscope of the cross sections. The elaborate explanation of the quality control on how to detect these defects and their tolerances is given in section 4.1. An elaborate explanation of the different defects themselves is explained in section 4.2. Here the misalignment of the filler, the slipped

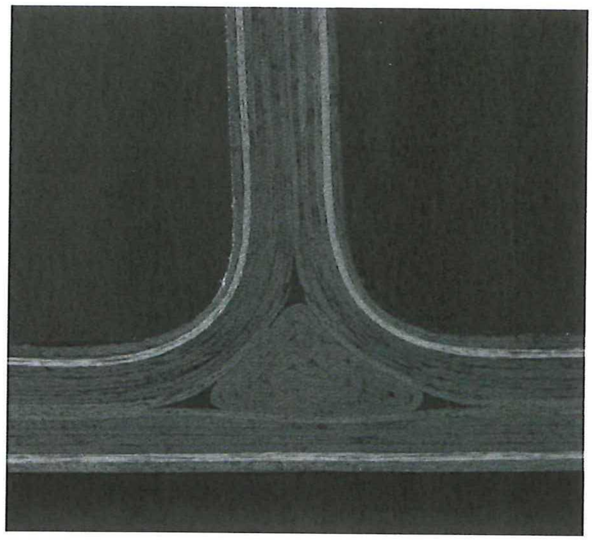


Figure 4.1: Cross section of a stringer and skin without any defects

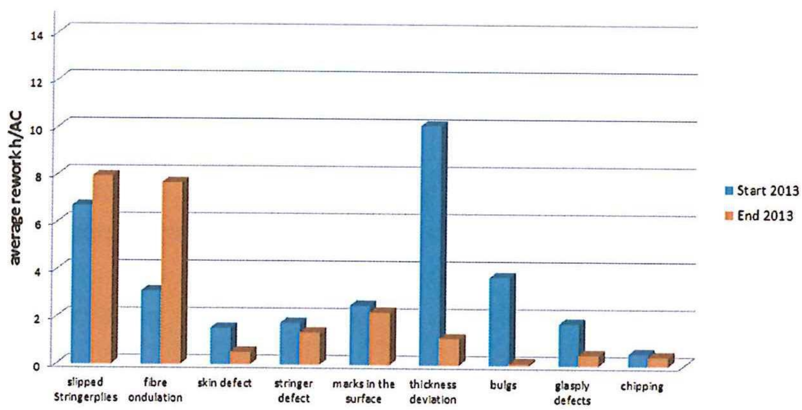


Figure 4.2: Amount of rework done per aircraft due to different defects

stringer plies, undulations and dry spots are further discussed. The conclusion of the defects is given in section 4.3. After the examination of the current defects, it is the goal to recreate these defects on trial panels by using the trial mould. This is further explained in chapter 6.

4.1 Quality control

For every change in production process method, parameters, materials, machines, tools, etc., it needs to be verified by the quality assurance department within Airbus that the quality of the final panel remains the same. This department is also in charge of the destructive and non-destructive testing of the panels during regular production. For every change, a new First Panel Qualification (FPQ) is done on a test part. The panel undergoes both destructive and non-destructive testing and will not be used as a flying part. The setup of this report is described in section 4.1.1. This is followed by an explanation of the destructive and non-destructive test methods at Airbus, where the non-destructive testing and inspection are used for both the FPQ and in regular production quality control, described in section 4.1.2.

4.1.1 First Panel Qualification

As stated before, a FPQ may be performed for every change that is made of the manufacturing process (materials, processes, tooling, lay-up, etc.) The main objectives of First Panel Qualification (FPQ) are:

- To determine the inner quality of a structural part/ component taking into account materials, key parameters of the manufacturing process, design features and tooling.
- To prove the correlation between Inner Quality and Non Destructive Inspection (NDI) test results.
- To prove, that the Inner Quality of a structural part/ component meets the requirements of Engineering.

A requirement is that the panel is manufactured without any primer or paint, in order to have a clear view on the quality of the panel itself.
The FPQ panel does represent the serial panel production. That means that the complete manufacturing process applied for manufacturing of the FPQ-panel must be fixed. During the literature study, also an FPQ report was done in order to get a better understanding of the possible defects and the panel itself.

4.1.2 Testing and Inspection Methods

Outer and Inner quality of the FPQ-panel are to be inspected by both destructive tests (DT) and non-destructive tests (NDT) [6, 7]. During these tests, different defects are checked for the laminate that are caused in manufacturing or due to handling of the part.
The locations where the inner quality and the thickness measurements are checked from both the inner and outer quality, can be found in appendix A. With the FPQ samples that were examined in the appendix, the porosity, degree of cure(check if the resin is fully cured) and/or fibre volume content were determined depending on the specimen locations on the part. In addition, two different thickness measurements were performed at these locations. The locations will be referenced in the further analysis of the defects.

Determination of the Visual Inspection of the part

The outer quality is checked by visual inspection. If any defects are found, they are documented in the FPQ. The visual inspection is done for the whole part. During the visual inspection, the focus is on finding and identifying the typical defects like:

- Dry spots
- Edge delaminations
- Surface porosity
- Fibre waviness
- Dents
- Wrinkles

- Inclusions
- Resin-free areas
- Resin-rich areas
- Tacky surfaces
- Cracks in the resin
- Fibre break outs
- Discolouration

Next to the visual inspection, also a dimensional check of the entire panel is carried out. Here, both the thickness and outer dimensions are checked. For the thickness measurement, a calliper is used for the accessible areas and ultrasonic inspection for the difficult to access areas like the centre areas. For every thickness, specific tolerances from the design value are set. The measured thicknesses may not be outside these tolerances.
A thermal analysis is also carried out. Thermocouples are placed across the panel and measure the temperature in the panel during curing. As with the thickness measurement, specific tolerances on deviations from the design value are set. The measured temperature may not be outside these tolerances.
Finally, the weight of the panel is measured and documented.

Determination of the Evaluation of the cross sections

The inner quality shall be checked by NDI/ultrasonic inspection and by the inspection of cross sections taken from the critical areas. These areas are determined beforehand, and the actual panel is cut at this location for inner quality determination. Most of these critical areas include a stringer, edge of the panel or ply drops, because most defects occur at locations with a change in geometry. Defects that are looked for when determining the inner quality of the panel are:

- Porosity
- Micro-cracks
- Delaminations
- Foreign bodies
- Fibre/ply deviations from the specifications
- Fibre undulations
- Resin rich areas

For every critical area, the thickness is measured as explained in the section on the determination of the outer quality, and the porosity is determined according to the corresponding AITM [3, 5]. The porosity needs to be less than 2,5 % of the panel volume. For selected critical areas the degree of cure and the fibre volume content are determined. The degree of cure of the panel needs to be higher or equal to 95 % and the fibre volume content needs to be 60 % with a tolerance of ±4 %. Any deviations from these targets are not allowed by the quality department.

4.2 Defect Types

In this section, the different defects will be explained which are currently present in the finished panels of the flaps. To analyse the defects, the cross sectional images (schliffbilder in German) are examined and the outer surface is checked. An overview of all the defects that can be seen by visual inspection on the outer surface of the panel can be seen in figure 4.3

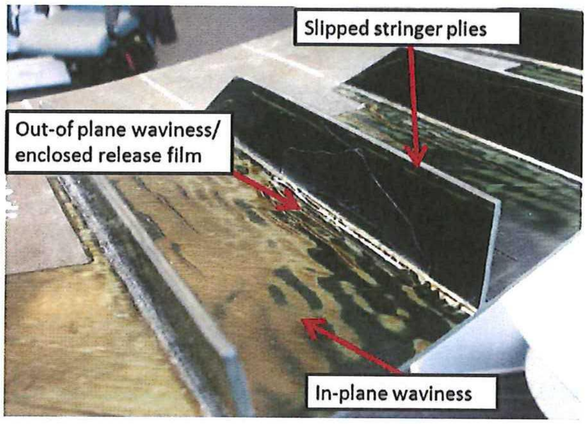


Figure 4.3: Overview of defects visible with visual inspection

In this overview of a scrapped flap part, the in- and out-of-plane undulations can be clearly seen as well as the wrinkles and slipped stringer plies. This panel also has the filler misalignment, which cannot be seen in the figure of the outer quality. The fact that all of these defects are present in one panel indicates that the defects could originate from the tooling or other external influences and that multiple defects may have a common cause. The only defect that cannot be seen, that does appear in other flaps are the dry spots.

In section 4.2.1, the misalignment of the filler material is discussed that can only be observed by determination of the inner quality. The undulations are explained in detail section 4.2.2, the wrinkles, slipped stringer plies and resin rich areas in section 4.2.3. Finally, the dry spots are discussed in section 4.2.4. The analysis of the defects will serve as a basis to recreate these defects in the next part of the thesis.

4.2.1 Filler misalignment

One of the defects that is clearly noticeable from the cross sectional images is the misalignment of the filler material. An example of this can be seen in figure 4.4. When comparing this image to that of figure 4.1, it can be clearly seen that the filler material is not in the centre of the intersection of the two stringer halves and the skin itself.

As explained in chapter 3, the filler material is placed between the two halves of the U-Profiles that form the stringer. This is done after the preforming when the stringers are compacted and still upside down before the rotation phase. It is noticed, by monitoring the actual production process, that the filler is always placed perfectly in the centre of the gap. Even with placement by hand, the accuracy is very high and it is assumed that the misalignment of the filler material in the cured panel is not due to the placement by hand. If the filler material is in the right place of the final cured panel it is located in the centre with an equal amount of filler material

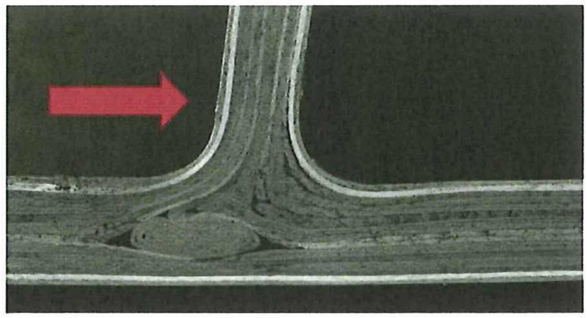


Figure 4.4: Filler misallignment

on both sides of the intersection of the stringer half. This can be clearly seen in figure 4.1.

When examining figure 4.4, it can be seen that there appears to be a sideward movement acting in the translational direction of the stringer that is indicated by the red arrow. The resulting force seems to shift the complete stringer away from its original location or constrains the movement of the stringer in relation to the movement of the filler and skin. The conclusion is therefore that either there is a force pushing the stringer sideways or that the skin and filler material have moved sideways. In addition, the left of the stringer corner appears to be stretched out since the thickness is smaller of the stringer above the filler material. Also the fold above the filler material of the right stringer halve gives the impression the stringer is pushed over the filler material and that some layers of the right stringer halve are stuck between the left halve and the filler material. The movement between of the stringer and the skin would then be around 1,9 mm if the centre of the stringer would coincide with the centre line of the filler.

A possibility for the misalignment could be that the stringer shifts when it is turned and placed on the skin itself. During the turning, there is a lot of movement and this gives rise to the possibility of the filler material and the stringer profiles to move and slip out of place. Additionally, the removal of the aluminium cores can shift the stringer itself in a certain direction. The best solution would of course be to use the same tooling for the preforming step as for the autoclave step. However, for now it was the easiest for Airbus to use aluminium cores for the preforming the durability of aluminium, the attachment of sliding rails underneath the cores and the fact that the cores can be secured easily for the rotation of the pack. Also, the pack can be compressed with more force, than if for instance the carbon fibre caul plate cores would be used due to the rigidity. The carbon fibre cores need to be used in order to have the same thermal expansion coefficient as the CFRP panel itself as explained in chapter 3.
An easier solution to this problem would be to use more constraints to perfectly align the skin and stringers by giving them less freedom to move individually. Next to constraining the tools, it would also be a solution to realign the tools with respect to each other if they do not line up properly. The possible cause of the misalignment of the filler material could also be because of the movement and misalignment of the tools in the autoclave and autoclave build-up step. If the tools are not constrained enough when the panel is in the autoclave, the applied pressure and the fact that the resin becomes liquid, it could happen that the cores start moving over the filler material. Additionally, the cores can also slide during the handling and transportation of the assembly. A solution for this problem would be to automate the process more to avoid manual handling or to setup new regulations for manual handling.

Another possible cause for the misalignment of the filler materials is that either the wrong size or shape is used or that the filler material itself is unsuitable. When looking at an example from literature, shown in figure 4.5, the misalignment of the filler material from figure 4.4 shows similarity with that of photo 4.5b where not enough filler material is used in the intersection.

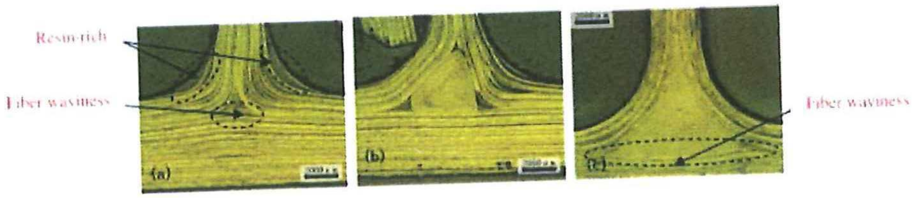


Figure 4.5: Filler misalignment comparison

The filler material in photo 4.5b has shifted more to the left side of the stringer and allows the layers on the right side of the filler to increase in volume because there is more room for resin on that side. This is also the case for the misalignment of the filler in the stringer flaps. A solution to this would obviously be to increase the amount of filler material.

Another solution would be to change the shape or rigidity of the filler material to make it fit better in the triangular region. That way, no resin rich areas will be present at the three corners around the filler. Also, by having an exact match in shape of the filler material, the filler material will be kept in place better. Currently, the filler material is bundled together by twisting UD-preprep fibres stands with the length of the whole panel with a screwdriver. This creates a round shape which becomes oval as soon as pressure is applied. When an external force is applied to the stringer, it will be less likely to shift due to the counteracting force exerted by the newly shaped filler. This is because of the larger contact surface between the filler and stringer compared to the oval shaped filler. The larger surface can be created by having a filler of the right shape or made of a material that is able to be pressed easily into the intersection, obtaining the shape of the junction. Having the right shape or a less ridged material, the filler will also remove the fibre waviness in the skin plies underneath the filler. This is caused by a too large filler that applies a too high local pressure to the layers of the skin underneath when the autoclave pressure is applied. This effect can be seen in figure 4.6.

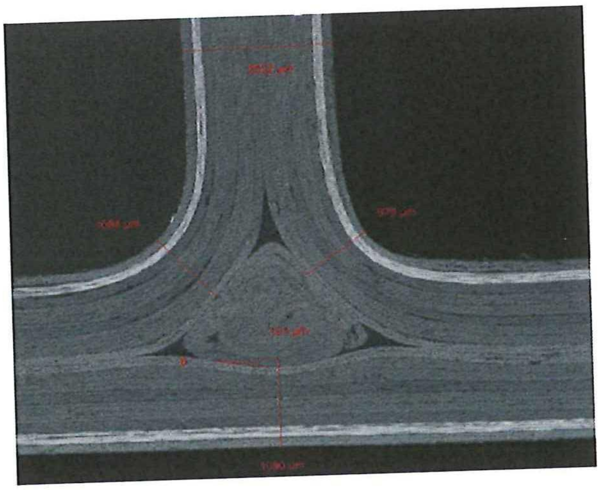


Figure 4.6: Effect of a too large filler

The misalignment of the filler material is not a reason for rework, because it is not one of the

4.2.2 Undulations, wrinkles and resin rich areas

Undulations (or waviness) and wrinkles are defects in cured carbon fibre panels whereby the individual fibres show waviness in either the in-plane or out-of-plane transverse directions of the fibre. These defects are the most common defects found in the flaps and so far, there is no working solution to avoid their occurrence. They are however assumed to form when an external force is applied in longitudinal or transverse direction to the fibres and plies or if movement of fibres is constrained due to for instance flowing resin or constraining the movement of shifting of the skin. The differences between the undulations and wrinkles and their assumed causes will be explained in the next sections. Also the resin rich areas in the corner sections show similarities with the causes of the wrinkles and undulations and are discussed in this section as well.

In-plane undulations

In-plane undulations are a form of fibre waviness that occurs in the longitudinal direction of the fibres in the plane of the ply. In other words the orientation of the fibres within the carbon fibre layer changes. Fibres change orientation along the length from for instance a -45 degree orientation to a 0 degree orientation. The in-plane waviness is most clearly seen on the outside of the part, because it concerns the waviness of individual fibres in the plane of the laminate. If a cross sectional view would be taken, it is very difficult to discover the in-plane waviness. This is because the position of the layers does not change in the cross sectional plane. The only way that the orientational change of in-plane waviness can be determined in detail in a cross sectional image is that the individual orientation of the fibres needs to be examined by checking if the cross sectional shape of the individual fibres appears circular, oval or that it is cut lengthwise. Another method to determine the presence of in-plane waviness is to look at the grey scale colour of the fibres. The grey scale changes when the orientation changes within a ply. However, the exact orientation of the fibres can not be determined by looking at the grey scale.
A perfect laminate cross section is shown in figure 4.11.

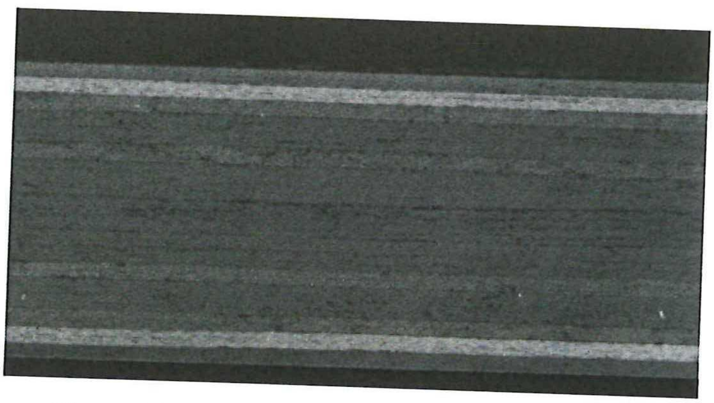


Figure 4.7: Laminate cross section without any defects

The 90 degree layers in depth direction as the second layer from the top and the second layer from the bottom can be clearly identified, because they be seen that the second layer (90 degree layer) changes from a light grey color on the left to a darker grey color in the centre. Here, the color matches the first layer from the top in terms of grey scale.

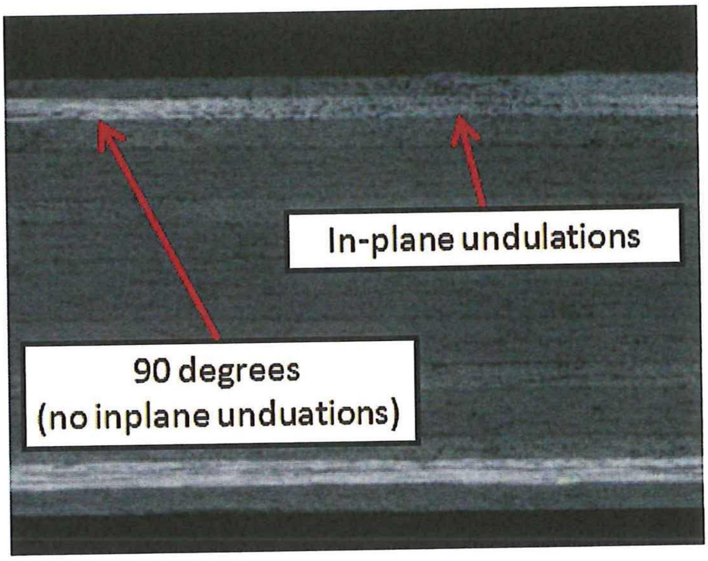


Figure 4.8: Laminate cross section with in-plane undulations in the top and second layer

A more severe in-plane undulations, including out-of plane undulations, and change in grey scale is seen in figure 4.9.

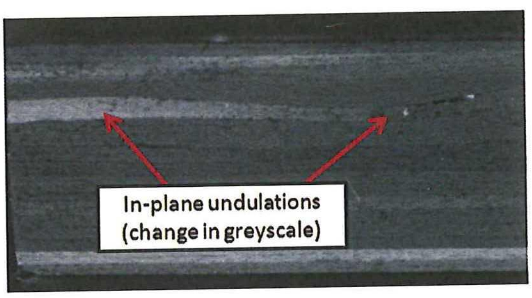


Figure 4.9: Laminate cross section with more severe undulations

The autoclave tooling has a smooth surface, which causes the surface of the finished panel to be shiny. For that reason, the fibre orientations can be clearly seen on the outer layer, because of a difference of the reflection of light. To enhance the optical inspection method further, a layer of water on the panels surface may create even a smoother surface for the reflection of light.

A skin between two flap stringers with clear in-plane fibre waviness can be seen in figure 4.10 and schematically in figure 4.11.

In figure 4.10 it can be seen that the individual fibres change orientation from their original 45 degrees to almost 90 degrees in some areas. The waviness seems to originate from the corner section of the stringer and skin at the bottom of the picture and propagates towards the top side. In the top section, the waviness is vanished and the fibres have their original orientation of 45 degrees again. From a structural point of view, a change of orientation could influence the load carrying capabilities of the part. If the fibre changes orientation, the laminate can carry less load in the specified direction. This could lead to premature failure of the panel below the

Figure 4.10: In-plane fibre waviness (undulations) on the surface

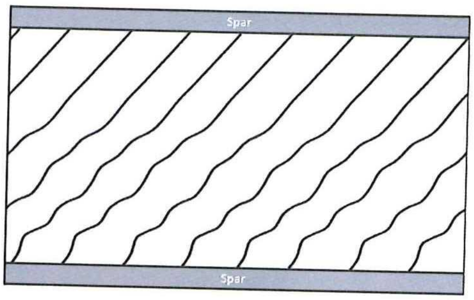


Figure 4.11: In-plane fibre waviness (undulations), schematically

designed ultimate load.

The in-plane waviness can occur in every location of the flap in both the skin and stringers. Usually, the waviness is not completely random and has a specific origin of for instance the corner section between the skin and stringer. The waviness can also be present over the entire length of for instance the skin between two stringers. This indicates that it can be a local phenomenon or that it is caused by for instance the entire autoclave core. A zoomed out example of in-plane waviness over a larger section of the flap can be seen in figure 4.12.

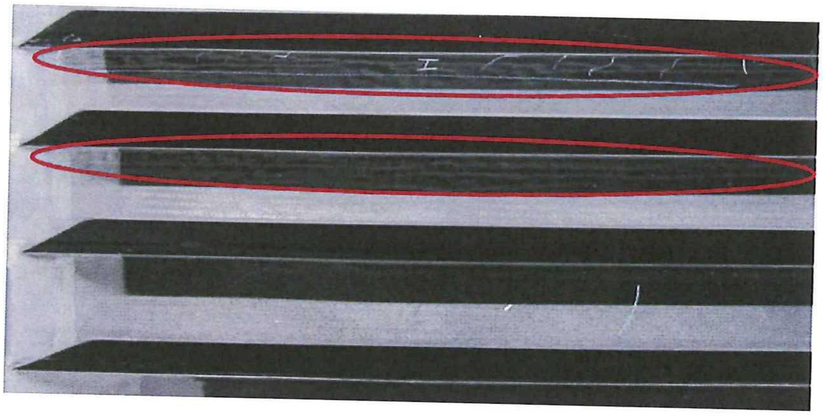


Figure 4.12: In-plane waviness over a larger section

The fact that the waviness is not random and seems to originate from the corner sections suggests that the cause of it would be in the manufacturing of the panel and that it for instance is not a standard defect in the prepreg material. The waviness depends also on the fibre orientation. In figure 4.13, which indicates the ramp section, it can be seen that the presence of the waviness is not in every layer and direction. It thus also depends on the location of the layer in the layup and maybe also on the orientation itself. However, the in-plane undulations in other layers than the top layer cannot be observed from the outside. Only an assumption can be done if there are in-plane undulations present in the outer layer that they could also be present in other layers. If there are not in-plane waves present in the outer layer, the chance is low, although still present, that they are present in the other layers.

The exact cause would be either in the application of an external force to the fibres, or the constraining of movement of the fibres or laminate, which in its turn also results in a force. As stated earlier, the external forces can originate from the following [25]:

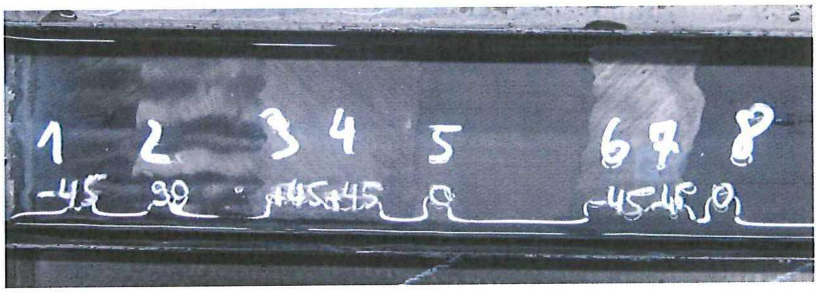


Figure 4.13: In-plane waviness depending on the fibre orientation

- Autoclave pressure that forces the cores in a certain direction
- The corresponding resin flow due to pressure differences that drags the fibres in a certain direction
- Manual handling of the uncured prepreg or the tooling
- Uneven pressure distribution caused by the tool geometry

The constraining of movement can take place during the preforming already when the layers are not able to move freely alongside of each other. The layers need to be able to slide, because of the difference in radius in the corner sections. When curving the stringer laminates into their U-shape, the outer radius will be larger than the inner. As a result, the flange of the inner ply will be slightly larger than the outer one after proper preforming. If the movement of the slipping of the plies in the flanges of the stringer is constrained, then the extra material from the inner ply needs to go somewhere. If the ply cannot move in-plane, the fibres themselves will start to show waviness, either in or out-of-plane.
The possible reasons that the plies cannot slip alongside each other during preforming are that the preforming happens at a too high speed or at a too low temperature [25]. The resin will not be in a completely liquid state at the preforming stage. If the speed of preforming is too high the layers don't have enough time to slip due to the interlaminair friction slippage. The same is true for if the temperature is not high enough. At a too low temperature, the resin will not yet have reached its state of optimal preform liquidity.

The constraining of movement can also happen during the autoclave cycle. When the laminate is subjected to pressure, the fibres are to be pushed out of the mould on the top of the flanges of the stringer. However, the autoclave pressure will also push the laminate downwards at the top of the flanges between two cores. The movement is constrained which could result in the formation of waves. The constraining of the movement is different from the application of external forces in the sense that the laminate itself wants to move. However, for both cases, a force is acting on the laminate.

Out-of-plane undulations

Out-of-plane undulations are a defect where the carbon fibre layers themselves show waviness. Out-of-plane waviness is, unlike in-plane waviness, independent on the fibre orientation. Several layers through the thickness can show waviness simultaneously. That means that the whole laminate experienced an external force or constraining of movement. This is therefore also assumed to be the cause of this defect. Also, the out-of-plane waviness is only present in the

skin of the flaps, meaning that the force or constraint is applied in the in-plane direction of the skin or that plies are being pushed downwards from the stringer.
An example of the out-of-plane undulations can be seen in figure 4.14.

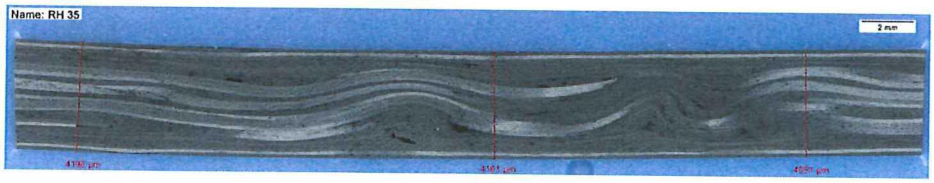


Figure 4.14: Out-of-plane waviness (undulations) through the thickness

In the figure, a cross sectional picture was taken from the skin of a scrapped part. The waviness is present in multiple layers across the thickness. The top and bottom layers in the panel show no sign of waviness at all, which means that it can be invisible from the outside. That is why it is important to examine the inner quality when determining the quality of the total part. It is also possible that the out-of plane undulations are present in the outer layer. In that case, they can be clearly seen by visual inspection. An example of the out-of-plane undulations that are also present in the top layer can be seen in figure 4.15.

Figure 4.15: Out-of-plane waviness (undulations) on the outer surface

In figure 4.15, it can be seen that the undulations are parallel to the stringers. The conclusion can therefore be drawn that the external force or movement constraint is perpendicular to the stringers. Possible causes are:

- The stringers are pushed closer towards each other, either when compressing the stringer pack together, when the stringer pack is placed on the skin, during the autoclave build-up or cure cycle itself.
- During preforming the slippage of the layers is not taking place properly.
- Layers of the stringers are being pushed down by either the cores, the autoclave pressure or handling of the part.

From a structural point of view, the out-of-plane undulations are causing the layers and fibres to have a different orientation through the thickness than that they were designed for. That means that the structural strength is lower in terms of load carrying capabilities, because the fibres cannot be loaded in axial direction in an optimal way. So, the failure strength will be

lower for a panel with out-of-plane undulations.
Also, the waviness results in stress concentrations, because, there are more layers in one area than the other. Therefore, the stress distribution is not to be considered uniform. With stress concentrations, the flap is more susceptible to fatigue and crack initiation.

4.2.3 Wrinkles, slipped stringer plies and resin rich areas

In the corner section of the stringer and skin it sometimes occurs that the release film is enclosed by the laminate. This can be seen on the bottom right side of the skin in figure 4.15. This kind of undulation is a special kind of waviness where the carbon fibre layer folds over itself, and could thereby entrap the foil in the surface layers. From now on this defect shall be referred to as wrinkles. When looking at the cross sectional image of such a wrinkle, the fold can be clearly seen in the top layer only (figure 4.16).

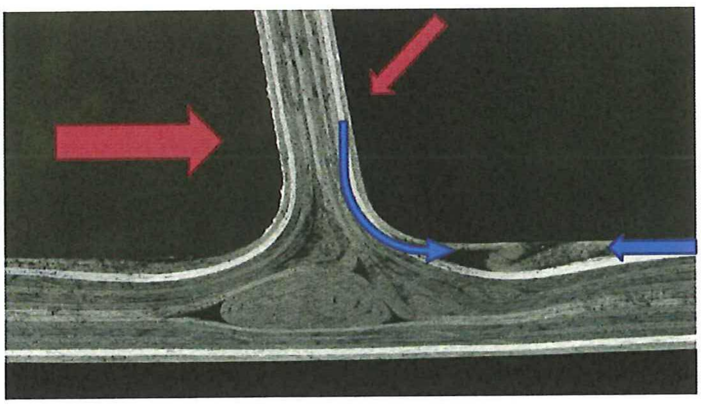


Figure 4.16: Wrinkle in the corner section

The blue arrows indicate the internal force that is causing the formation of the wrinkle. When examining figure 4.16, it can be seen that the stringer seems to have been pushed over the filler material. This could have a similar cause as described in section 4.2.1. Next to the filler misalignment it is noticeable that only the top layer has been folded over. That would suggest that there was an external acting force or a constraint pointing downward along the stringer. This is also shown in the figure 4.16.
The tooling is in contact with the outer ply of the laminate, so the most likely cause is that the tooling is pressing the outer layer downwards. Another cause could be that due to the applied pressure, the liquid resin drags the outer ply with it when the laminate is compacted. In other words, the fibres start to move freely when the resin becomes liquid. Alternatively, the pressure in the corner sections is not enough to fully compact the laminate, leaving space for the fibres to move around freely [25]. This problem is referred to as bridging, which results from a non-matching tool in terms of geometry with the laminate. The cause could also lay in the preforming step, where the temperature is not high enough or the preforming is too fast.

Slipped stringer plies

The carbon fibre material to form the wrinkles described earlier needs to come from somewhere, since it is not flexible enough to elongate by this amount. Because only the outer fibre has moved down, it also means that the slipped layer is shorter on the top of this stringer. This can be seen in figure 4.17.

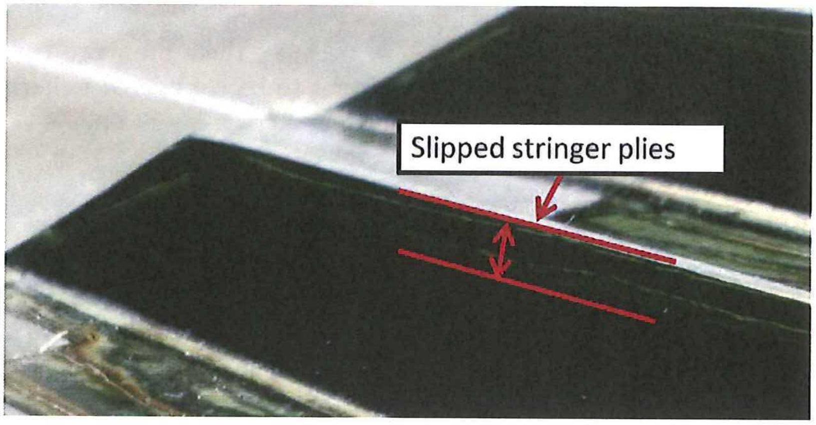


Figure 4.17: Slipped stringer plies

Since it concerns only one or several layers, this defect is referred to as a slipped stringer ply. A slipped stringer ply does however not always have to fold over to form a wrinkle. When looking at figure 4.18, the total slippage of the outer layer can be determined by subtracting the normal layer length in the corner section (depicted in green in the figure 4.18 below) and the length of the layer with the wrinkle present (depicted in red).

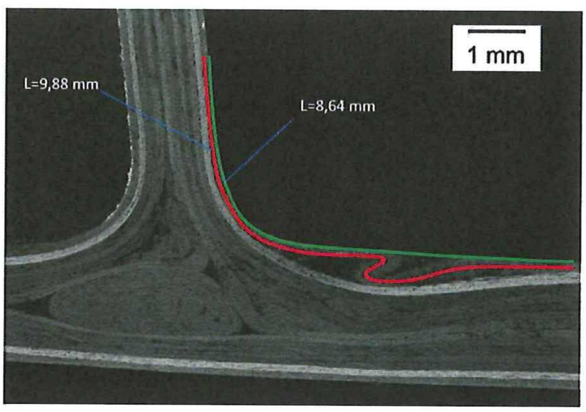


Figure 4.18: Wrinkle in the corner section

The slippage of the outer ply according to figure 4.18 is 9,88-8,64=1,24 mm.

The structural impact on the flap with the defect of slipped stringer plies and wrinkles is considered to be the same as for the out-of-plane undulations.

Resin rich areas

In cross sections of other stringers, the defect of resin rich areas can be observed. Resin rich areas occur in the corner section between the laminate and the stringer. The outer layer is over saturated with resin, which causes the carbon fibre layer to expand in thickness. This defect is almost the same as the wrinkles, with the difference that the whole stringer seems to be pushed down without the outer layer moving separately from the other layers. In this case, no fold of only the outer layer of the laminate will occur. In figure 4.19, the resin rich areas can be seen on both sides of the stringer and schematically in figure 4.20.

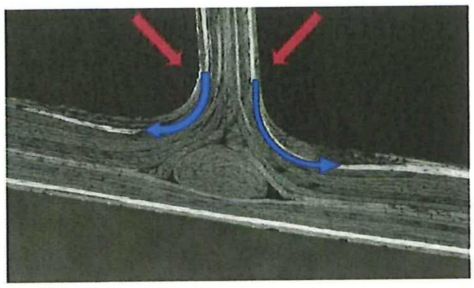


Figure 4.19: Resin rich area in the corner section

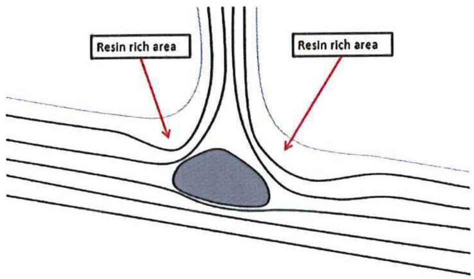


Figure 4.20: Resin rich area in the corner section, schematically

In the figure 4.19, the blue arrows indicate the internal forces and the red arrows the external forces. The outer layers of the laminate in the corners are oversaturated with resin, because the whole layer pack is pushed down leaving a cavity in the corner section. This cavity starts to fill up with resin and causes the outer layer to 'soak up' the excess resin. For these resin rich areas the same causes are assumed as for the wrinkles.
The impact on the structural strength of the resin rich areas is less than that of the undulations. However, the load carrying fibres are shifted inwards. For loads in longitudinal direction of the stringer, the resin rich areas might be harmless. For the stability of the stringer there might be a small impact.

4.2.4 Dry spots

Dry spots are defects that occur when there is not enough resin in a section of the laminate to completely cover the carbon fibres. They can be detected by visual inspection on the surface of the part. On the inside, they can be detected with ultrasounds. Also, the individual fibres can be seen, because the resin does not enclose the fibres anymore. The shiny smooth surface is therefore interrupted with these dry spots making them easy to identify. An example of the dry spots in one of the flaps can be seen in figure 4.21.

In the figure it can be seen that the dry spots occur between the fibres itself in the form of cavities on the surface. Dry spots will also help in identifying in-plane waviness because it highlights the contours of the fibres as can be seen in the figure.
A cause of the dry spots could be that air is enclosed between the mould and the laminate. If the evacuation of that air is not done properly when the autoclave pressure is applied, the air remains entrapped in the laminate causing these dry spots. Improper evacuation of air can be caused by sealing the panel too much on the sides and top with air impermeable foils or tape, a too low autoclave pressure or temperature or an improperly designed tool or mould that does

Figure 4.21: Dry spots on the surface

not allow the air to escape from the mould.
Dry spots don't occur that often in the flaps, and are relatively easy to repair compared to the other defects discussed earlier. That is why the dry spots do not have the main focus in designing a new tooling concept, but need to be considered.

4.3 Conclusion

In this chapter, the defects present in the flaps and their detection methods were explained. The defects are either observed by visual inspection or by close up images taken by a microscope of the cross sections. With these inspection methods, both the inner and outer quality of the flap is checked against tolerances that are provided by the quality department.

The defects that are currently present in the panels are the filler misalignment, the in- and out-of-plane undulations as well as the wrinkles, slipped stringer plies and dry spots. The misalignment of the filler material is not a critical defect, but it can be the cause of the other defects as can also be concluded from literature.
Undulations (or waviness) and wrinkles are defects in cured carbon fibre panels whereby the fibres show waviness in either the in-plane or out-of-plane direction of the fibre. These defects are the most common defects found in the flaps and so far, there is no working solution in order to avoid their occurrence. They are however assumed to originate when an external force is applied to the fibres or if movement is constrained. Wrinkles are a special type of undulation, whereby a carbon fibre layer is folded over itself. Most often, a wrinkle occurs simultaneously with the slippage of the stringer ply because the layer is being pushed or pulled down. Also the resin rich areas in the corner sections show similarities with the causes of the wrinkles and undulations.
In the SA flaps there is the unique situation that the combination exists of these defects, so the final solution for a new tooling concept should be able to remove at least the critical defects simultaneously.

Chapt

Manufacturing set-up of the test pa

The defects that are currently present in the flaps were discussed in chapter 4. Th
is to try and recreate the defects in test panels by changing process parameters. F
panels are manufactured that represent a section of the out board flaps.
The reason that test panels are made, instead of making change in the actual flap
line, is that it is less costly. Reworking the panels and halting them for transport, lea
for Airbus and high costs due to the rework. Also, it is not possible to check the i
by making cross sectional images, because the panels need to be destroyed beyond rep

By changing the process parameters, the cause of the defects can be found. Also
assumptions on what the causes are can be verified by manufacturing these test pa
alteration can lead to a defect in the test panel that does not occur in the actual pa
may lead to the absence of defects compared to the actual panels. That would make
of the individual causes of the defects very difficult.
It is therefore of key importance that the test panels are representative for the
in terms of boundary conditions, production process, usage of ancillary materials,
etc. The mould and tooling that is used for the production of the test panels
in section 5.2. The production process of the test panels and any deviation from
production process as well as its effect on the final panel quality of the produced tes
be explained in section 5.2. Finally, the conclusion is given in section 5.3.

5.1 Mould and tooling

For the manufacturing of the test part, a mould and cores are necessary which are
possible to the actual flaps. Also the tolerances between the real and test panel
to be similar. Airbus has a small mould available to manufacture test panels of
panel. This mould is used for the manufacturing of the test panels in finding the
global layout and dimensions of this mould and its cores can be seen in figure 5.1.

The main difference with the actual panel is that for the test panels only four c
instead of the normal five. This results in the test part, having one stringer less th
flaps. For the test panels, it is important that the interaction between the core
simulated. That is why more than one core in combination with the edge bars
present. However, it is assumed that one core less than the actual production will

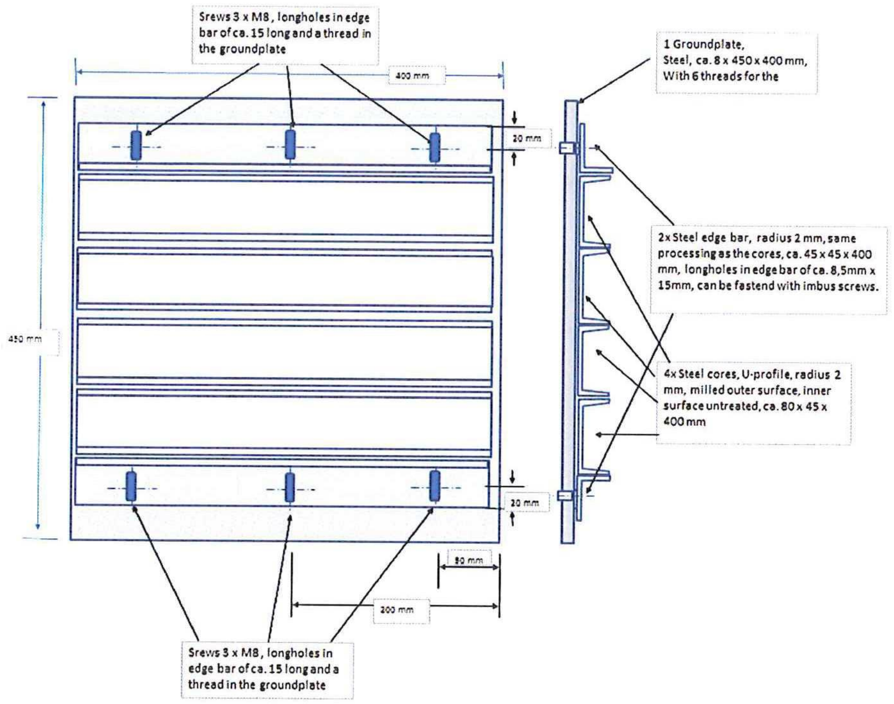


Figure 5.1: Layout and dimensions of the test panel mould and its cores

is representative for the flaps. There could be small differences in a panel with 4 red to 5, but to find the global cause of defects, this is assumed to be negligible. difference is that the test panel has a flat skin. This can however lead to noticeable the panel quality. For the actual part, cores are used that also have a curved outer atch the curvature of the mould for the skin. A curved skin has the effect that at the stiffeners are not symmetrical on both sides and will have different radii. An ffect of the curvature of the panel is that gravitational forces play an effect, since so be a horizontally acting force component present because of the slope of the s could for instance result in a horizontal force acting on the stringer, causing the downwards in the autoclave when the resin because liquid.
erence is that the dimensions of the test panel tooling are different than that of the The cores for the actual flaps are about 60 mm wide, compared to the 80 mm of the oling tooling. This difference will probably result in some deviations in the severity ith for instance the undulations, because any elongation or pressure is divided over . However, to find the causes of the defects it is less important to what extent the r as long as they do occur. The same goes for the length of the tooling. In the s, the tooling is almost 7 m long. For the test panel it is only 0,4 m. The defects in ur in the corner sections and in the transverse directions of the cores. In both the roduction and the test panel production, there are no constraints in the lengthwise the panel and the laminate is allowed to extent freely in that direction. For that assumed that the panel quality is negligibly influenced by the size reduction in the ion in order to simulate the defects.
ference of the test panel tooling compared to the tooling used in the actual process is only one set of tooling available for creating the test panels. As described in ifferent tooling sets are used for the preforming as for the autoclave build-up. At surements were done on the sizes of the preform and autoclave cores and in some re not equal and show slight differences. This could have a major impact on the if the preformed panel is not manufactured in the autoclave with identical tooling

for both steps. Having different tooling for both steps, means that the tolerances need to be increased for the panels, because there might be twice the amount of error in dimensions present in these steps as when only one set of tooling is used. It could lead to significant differences in the final panel dimension as well as the occurrence of defects in the part. That is also the reason why some of the test panels are manufactured with a different width for the preforming than the width of the autoclave cores to understand the influence of these differences between the core sizes.
Finally, the material for the tooling that is used is also different for the test panels compared to the preform and autoclave tooling for the actual flaps. The actual preform cores are made from aluminium and the actual autoclave cores are made out of carbon fibre. The test panel cores are made from stainless steel. The stainless steel cores are used since these were made available by Airbus for the trials. The reason that two different materials are used for the preforming and autoclave cycle is because the cores need to possess different coefficients of thermal expansion to match the geometry of the part. For now it was the easiest for Airbus to use aluminium cores for the preforming because of the durability of aluminium, the attachment of sliding rails underneath the cores and the fact that the cores can be secured easily for the rotation of the pack. Also, the pack can be compressed with more force, than if for instance the carbon fibre caul plate cores would be used due to the rigidity. The carbon fibre cores need to be used in order to have the same thermal expansion coefficient as the CFRP panel itself. This is also explained in chapter 3. The use of two different cores and the removal and inserting of the the cores are already assumed to be causes for the defects. Therefore, some of the test panel process alterations are based on the difference having two core sets of different materials.

Ideally, aluminium cores would be used for the preform and CFRP cores for the autoclave cycle for the test panels as well. When the test panel goes in the autoclave, the steel cores (with a linear thermal expansion coefficient at 20 C of $12 \cdot 10^{-6}K^{-1}$) will expand more compared to the carbon fibre core that are used for the actual panels (linear thermal expansion coefficient of $4,5 \cdot 10^{-6}K^{-1}$ in width direction). This will compact the fibres in the laminate more when the heat is increased, because the sides have clamped boundary conditions. As can be seen from the literature [25], the compaction is of great importance to the quality of the final part. Therefore, in the testing, this difference in thermal expansion coefficient will have to be taken into account to obtain a similar panel quality.

5.2 Manufacturing process

Comparable to the tooling, the manufacturing process for the test panels also needs to correspond to the actual flap as closely as possible in order to obtain panels of a representative quality with the flaps. The production process of the flaps will therefore have to include as many identical steps and usage of ancillary materials. In this sub section, the manufacturing process of the test panels is explained for further reference and reproducibility of the obtained results. Most importantly, the differences with the actual production of the flaps are stated and the influence that they have on the final panel quality and the defects.

To start off, the same prepreg carbon fibre material is used for the manufacture of the test panels. This material is HexPly 6376C-HTS(12K)-5-35% and its properties can be found in appendix C). The material is obtained from the end of the carbon fibre rolls and has a width of 300 mm. In order to have an estimate on how much material is needed for one test part, the layup needs to be determined first. In the flaps, there are several different layups present for different locations. A layup for the test panel is chosen that is representative enough for the panel and that is also present at most locations of the stringers. The laminate needs to be symmetrical and balanced in order for the panel not to warp or deflect after curing. Taking these considerations in mind, the following layup was used for the test panels for the combination of the total cured panel that included both the U-profile and the skin laminate as shown in table 5.1.

Table 5.1: Lay-up of the test panels

U-profile laminate	
Layer number from the top	Fibre orientation of the ply
1	45
2	90
3	-45
4	0
5	0
6	-45
7	0
8	0
9	45
Skin laminate	
10	45
11	0
12	0
13	-45
14	0
15	0
16	-45
17	90
18	45

The orientation is such that 0 degrees is in the direction parallel to the stringers and the 90 degrees is perpendicular to them. As can be seen, a total laminate thickness of 18 plies is made which corresponds, with a ply thickness of 0,125 mm, to a nominal laminate thickness of 2,25 mm. The quality tolerances at Airbus for a laminate of this thickness are + 0,500 mm and -0,150 mm. This means that the thickness of the panel is not allowed to have values outside of these tolerances in order for it to be of acceptable quality.
In the test panels, the thickness is also measured at various locations in the skin and stringers at the different cross section locations. A deviation in the thickness of the individual plies is also present. Therefore it is difficult to compare thicknesses of different sections of a test panel. However, in the same locations in the laminate that consists of the same continuous fibres (for example in the laminate around one core), the thickness of the cured laminate will not deviate significantly. For the evaluation of the thickness measurements, a minimum relevant thickness difference is set in order to make relevant conclusions with respect to interaction and rotation of individual cores. The relevant thickness difference is set to be 5%. When the thickness difference is below 5%, the thickness differences are seen as an indication only and no solid conclusion is drawn from it.

For one part, there needs to be one skin and four stringers present. The finished U-profile stringer has a height of 45 mm and a width of 80 mm. To make the U-profile consisting of 9 layers(half of the total layers of skin and web of the U-profile combined) from a flat laminate it needs to have a width of 45x2+80=170 mm. The overview of dimensions for the skin and the flat stringer laminates before preforming are as shown in table 5.2.

The skin dimensions are 320x400mm because it only needs to cover the bottom of the cores and not the whole ground plate. To simplify the manual cutting and layup of the plies of the

Table 5.2: Dimensions for the skin and flat stringer

	Dimension(mm)
Skin width	320
Skin length	400
Stringer width flat	170
Stringer length	400

different orientations, plates are made with a dimension of 850x380mm. From this, two skins or four stringer plates can be cut. The extra material is cut away to ensure that all the layers are perfectly stacked. This is due to the fact that with manual layup, small deviations in the dimensions of the plies lead to inaccuracies at the edges of the laminate that not all layers are overlapping properly. By making one laminate, less plies have to be cut and the layup only has to be done once for two skins. For the ± 45 degree plies, hand cut templates were made that fit the 850x380 mm laminate. With these templates, sections were cut from the 300 mm wide roll and laid up parallel to each other to form the ±45 layers within the part.
A rough calculation for the total amount of prepreg for one panel (one skin, four stringers) was done for the 0 and 90 degree plies with an estimation for the ±45 degree plies. In total, a length around 14 meters of 300 mm wide prepreg roll is needed for one complete test part.

As stated before, the plies are laid up by hand in the correct orientation as soon as the prepreg material is gathered from the ATL machine. The laminates for the skin and stringers are cut to size and are covered on both sides with release film. The same release film is used for the actual production. Since the layup is done by hand, the laminate is compacted with a vacuum every 4 or 5 layers in order to compact the layers and remove all the air bubbles between the layers. At the ATL, the layers are laid up perfectly on top of each other, so no in between compaction is necessary there.
First, a liquid release agent is applied on the cores, so that demoulding is much simpler. A layer of Tooltec tape (properties given in appendix C)is taped on both sides of the flanges of the core U-profile. The cores with Tooltec tape can be seen in figure 5.2.

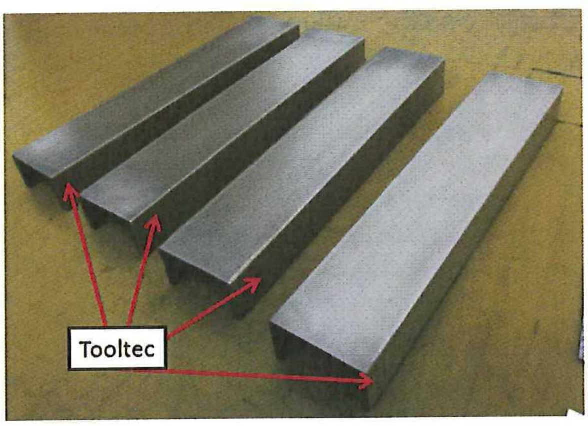


Figure 5.2: The cores with Tooltec tape

Similarly as for the flaps, the Tooltec is applied to make the prepreg stick to the core during preforming to prevent springback. To make the laminate flanges stick to the tooltec on the steel cores, the laminates of the stringers are placed on the web of the core, secured with tape and a strip of 10 mm of release film is removed from the top of the inside of the U-profile laminate flange. The carbon fibre of the laminate is exposed where the strip is removed and will stick to the Tooltec during the preforming. The U-profiles are preformed in the same machine and with the same program as for the actual flaps in order to keep the parameters constant. Even though that the test panel cores have a different material and different dimensions, it is assumed that the preforming is done properly, because in the end a nicely shaped preform is obtained that looks similar to the actual stringers. As stated in the literature, the temperature, pressure and preform time influence the quality of preforming [25].

When the prepreg is preformed, it is cut to size on the flanges to match the contour of the core. The release film is removed from the outside of the stringers prepreg and the whole pack of stringers is compressed together with manual clamps, (see figure 5.3).

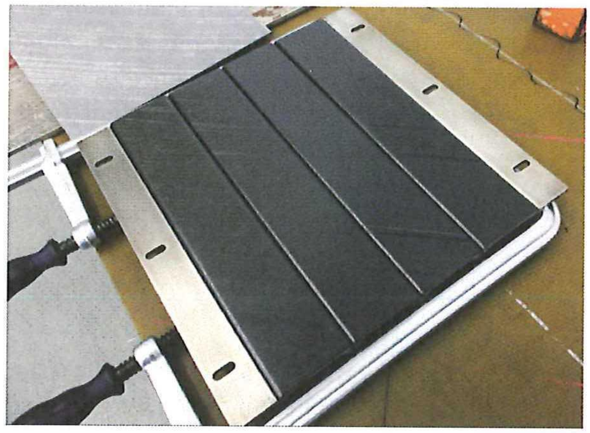


Figure 5.3: Compressing of the stringer pack

As long as it is made sure that the profiles are compressed with a more or less equal pressure on the both sides it is assumed that this production step is similar to that of the actual production. After the compaction, the filler material is applied, which is taken directly from the actual production process. That way it is assured that the filler material and its production are identical to that of the flaps. However, the radius of the corner sections of the tooling are 2 mm instead of the 1,6 mm of the actual carbon fibre tools. A larger tooling radius means that the cavity which the filler material has to fill up is also larger. Taken into account the thickness of the laminate, the filler material was calculated to cover the cavity of the test panel with radius 2 mm of 4,19 mm^2 compared the actual panel with radius 1,6 mm of 3,19 mm^2. That means that the filler material should have a 1,31 times larger cross sectional area than that of the actual flap. The calculations and further explanation on the filler cross sections is explained in section 6.4.4. As can be seen from literature, [25] the size of the filler material is of great importance to the quality of the corner section of the stiffened panel. Therefore, having not the same amount of filler material in the test panels will have an influence on the panel quality. The degree of influence that the filler material size has on the individual test panels will be explained in the corresponding sections. The size difference is still relatively small, so the quality differences are minimal, but still present.

With the filler material applied in the corner sections of the stringers, the release film of the skin is removed and the skin is placed on top of the stringers. This is different than in the actual flaps where the stringer pack is turned onto the skin. Since the cores are relatively heavy and no machine is available for turning the pack it was chosen to place the skin on top of the stringer pack in order to obtain a high accuracy of correct placement. Placing the skin on the stringer and then turning the whole pack is assumed not to have any effect on the quality that is different from the actual production. However, the rotation in both the actual production as in the test panel production can have an influence on the panel quality due to the shifting of the laminate and cores.

Next, the pack is unclamped and the edge bars are removed from the compressed pack. There is a slight expansion of the pack after unclamping. During this step the cores and laminate could shift. Another release film is placed over the complete pack on the outside to ensure that the resin doesn‘t flow sideways underneath the edge bars. After the placement of the release film, the pack is compressed again. This can be seen in figure 5.4.

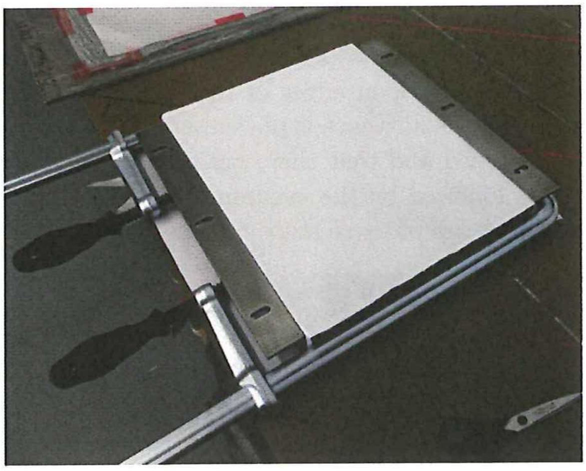


Figure 5.4: Release film placement over the complete stringer pack followed by further compaction

Similar to the placement of the skin, the release film is placed on top of the pack and skin instead of placed in the mould first, followed by the skin and pack. Since the release film is the same as in the actual production, it is assumed that it has no effect on the quality.

As described in the tooling section for the test part, a ground plate is used to secure the edge bars and to provide a smooth surface for the skin. This ground plate is however not big enough for a vacuum bag and vacuum channel to be placed around it. That is why an additional ground plate is used for under the ground plate of the tooling. In the actual production, the mould has an edge with small holes so that the vacuum can be applied evenly over the whole part. In the test mould it is not the case, so an air channel of folded aluminium mesh is placed around the mould and secured with tape and the vacuum inlets are secured on top of it. One is for the vacuum application at the shopfloor and one is for the autoclave. A release film is placed on top of that ground plate and the ground plate of the tooling is placed on top of that. The pack of stringers, skin, edge bars and release film is manually turned on the tooling ground plate. This can be seen in figure 5.5.

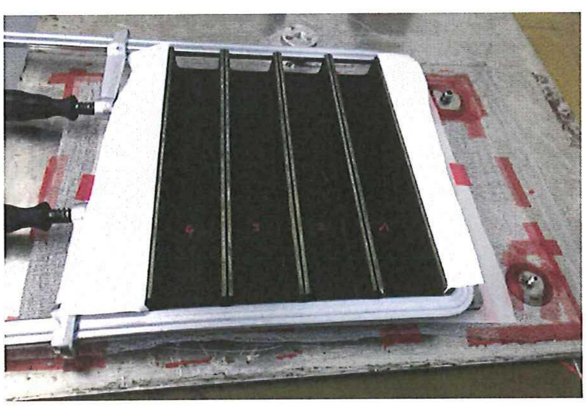


Figure 5.5: Turned stringer pack

The differences mentioned above have no influence on the panel quality, since it only concerns ancillary materials and process modifications that will lead to the same end part. The cores are taken out of the panel and are then modified and/or the release film on the inside of the stringers is removed depending on the test part. This could lead to defects, but these are not different from the actual production. The edge bars are secured and the cores are placed back.

For the vacuum build-up, first a release film is placed over the whole pack, so that the resin cannot flow out of the top of the profile, which would otherwise flow between and over all the cores. A peel ply is placed over the open edges of the part, to allow for easy removal of the vacuum bag and airweave. Then the airweave is placed, which makes sure that the vacuum flow is evenly distributed over the panel and that there are no sharp corners that can puncture the vacuum bag. The airweave is followed by the vacuum bag which is secured with tacky tape to the bottom ground plate. The setup of these steps can be seen in figure 5.6 - 5.9.

Figure 5.6: Application of release film over the cores

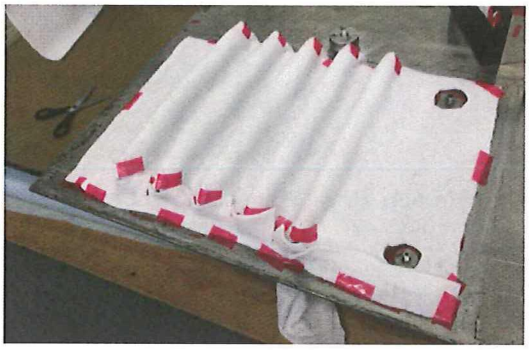


Figure 5.7: Application of peel ply

Figure 5.8: Application of airweave breather

Figure 5.9: Application of the vacuum bag

When the vacuum build up is finished, the panel is placed in the same autoclave with the actual outboard flaps. That way it is ensured that the test panel undergoes the same autoclave cycle, with the same temperatures and pressure as the actual flaps. As soon as the panel is taken out from the autoclave, all the ancillary materials are removed and the cores are removed from the part. In the descriptions of the test panels and their defects, the finished panels front and back view are shown. In the description the cores and stringers will be referenced by number. The

same numbering is used for all the panels and is shown in figure 5.10.
To maintain consistency in the production, all panels are self-made including the layup and vacuum build up. In actual production, different workers will do these tasks for the actual flaps and differences in quality can arise.

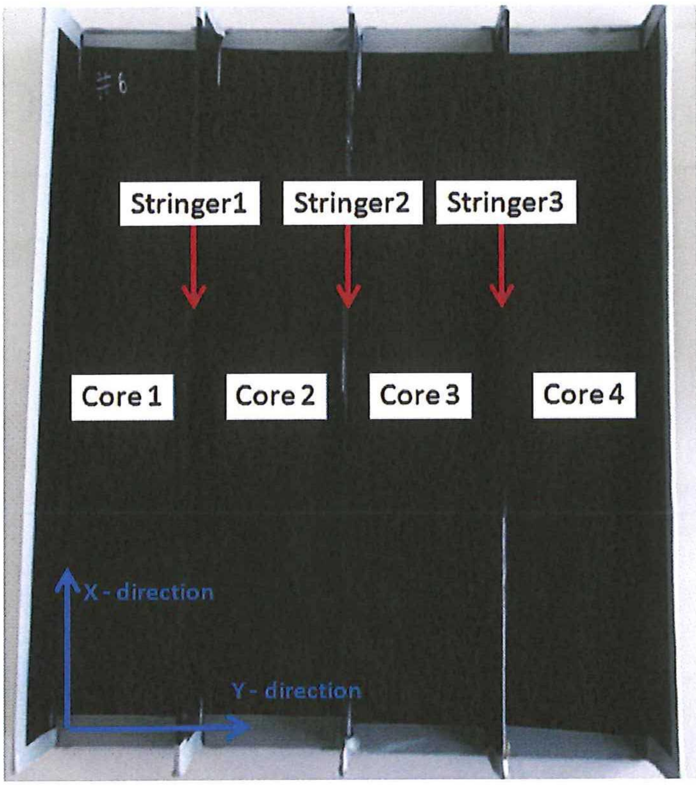


Figure 5.10: Numbering of the core locations and stringer numbers of a cured test part

5.3 Conclusions

Key in producing test panels that represent the actual flaps from serial production is to use tooling, materials and a manufacturing process that is as similar as possible to the actual panels. With the test panels, the causes of the defects need to be found. Therefore, some slight deviations in the production process will have a negligible effect on the results that are derived from the test panels. Examples are the dimensions of the tooling, the number of cores used, manual ply layup, placing the skin on the stringer pack followed by turning and the vacuum channel and vacuum build-up.
Some alterations in the production have more effect on the panel quality and can influence the cause of defects to some extent. These differences are the tooling material, one set of tooling that is used for preforming and autoclave, flat skin, filler size. The influence is described in this section and will be elaborated on more for the individual test panels in the next sections.

Chapter 6

Test panels

In this chapter, the individual test panels are elaborated on the production process alterations, and the resulting quality of the panels. For every part, the deviations in the production method, panel geometry and material usage compared to chapter 5 are stated. These deviations are mostly intentional to simulate a specific cause of a defect, but also deviations in terms of accidental production errors are stated and which effect they have on the final panel quality.

The different test panels that were made are explained in sections 6.1.1 - 6.4.4. The test panels are divided in four different groups, that represent different kinds of alterations to the production process, tooling and the laminate. The first step is to create a panel which is of a good quality to use as a benchmark (panels 1-3). However, even though there is no intended difference with good production, these panels also showed defects that are explained in the respective sections. Next, the test panels 4-8 are explained where changes to the tooling dimensions were introduced. These panels are followed by the panels 9-11 where movement of the cores is simulated that occurs in the autoclave. Finally, the panels 12-14 explain the panels where the laminate and the panel dimensions are changed with respect to the stringer height and the filler material. The overview of the test panels with the process variations in order to recreate the defects and the corresponding sections is shown in table 6.1.

For every of these test panels, the manufacturing is described, which includes the process alterations with respect to standard manufacturing process used to produce panels of good quality. Additionally, the inner and outer quality is checked for defects by visual inspection and microscopic inspection of the cross section. All the cross sectional images can be found in appendix D and a selection is made to be used in the test panel sections. Explanations are done to indicate clearly which defects can be seen on the outside and which can only be observed by destructive testing and also the correlation between the two. When it has been identified which defects can be observed by which kind of inspection method, it can be useful to avoid for instance destructive testing of a panel if the presence of defects can be ruled out by a visual inspection. Also, a thickness measurement analysis is done to examine the thickness deviations in the skin and stringer of the respective cross sections. Finally, the conclusions of a specific test panel are given as well as a summary of which defects are found.
In section 6.5, the conclusions and comparison are stated with respect to the results that were obtained from the test panels. As an overall result, a defect map was constructed, that shows images of the defects per category and its respective cause. The map can be used to identify defects in the actual process and the matching causes. This defect map will also serve as a basis for setting the requirements for the new tooling concept.

Table 6.1: Test panel overview

Panel number	Intended process alteration	Section number	Remarks
Good quality panels (section 6.1)			
1	Panel of good quality	6.1.1	Preforming error
2	Panel of good quality	6.1.2	Preforming error
3	Good part, plus stringer height and larger preform to incorporate thermal expansion difference	6.1.3	
Panels with tooling alterations (section 6.2)			
4	Preform core width smaller than autoclave core width	6.2.1	
5	Preform core width smaller than autoclave core width, width difference larger than panel 4	6.2.2	
6	Hanging cores, with equal size preform and autoclave cores	6.2.3	
7	Hanging cores, with equal size preform and autoclave cores	6.2.4	
8	Preform core width larger than autoclave core width	6.2.5	
Panels core movement (section 6.3)			
9	Core movement in x-direction with ramps	6.3.1	
10	Core rotation around the z-axis	6.3.2	
11	Core movement in y-direction	6.3.3	
Panels with laminate alterations (section 6.4)			
12	Higher stringer than the stringer cavity	6.4.1	
13.1	Shorter stringers than the stringer cavity	6.4.2	Compressing of the stinger pack error
13.2	Shorter stringers than the stringer cavity	6.4.3	
14	Filler material size and shape	6.4.4	

6.1 Good quality panels

The first step is to create panels which are of a good quality to use as a benchmark. However, even though there is no intended difference with good production, these panels also showed defects that are explained in the respective sections. The intention of panels 1 and 2 was to be of a good quality without any production alterations. Instead, the preforming was not done properly leading to unexpected defects. These two panels are described in section 6.1.1 and section 6.1.3. In panel 3 a good panel was constructed, plus the stringer height was changed and the preform core was made wider than the autoclave core to incorporate thermal expansion difference. Panel 3 is described in section 6.1.3.

6.1.1 Test panel 1: panel of good quality plus wrong preforming

The first test panel was supposed to be a reference panel of good quality and proof that the production process is understood. However, some alterations are present which were corrected for the panels produced after panel 2. This panel was chosen as a test part, because some interesting results were obtained when cross sections were cut from the part. The main cause for defects in the panel is that the preforming and compaction was not done properly.

Manufacturing

One of the deviations from the standard production process as stated in chapter 5, is that one side of the tooling is not clamped: The tooling and ground plate dimensions did not allow for one of the edge bars to be secured with the bolts, because the pack was too wide. This could have a great effect on the panel quality, since one boundary condition is different. This leads to a different stress distribution and could result in different defects than if the edge bar would have been clamped. From test panel 3 onwards, this deviation was eliminated.
Another deviation is that the edge of the skin was placed underneath the edge bar. This means that the skin is not constrained in horizontal movement while expanding. As a result, no in-plane compression will occur in the skin of the part. Also no release film was surrounding the panel, only the bottom of the skin. The result is that the resin could move freely in all directions. This has less effect on the panel quality, but it does make demoulding more complicated due to the excess resin under the edge bars. There is however also release film used on the inside of the cores. A production error was made that the layup for the skin was inverted, so instead of [45/0/0/−45/0/0/−45/90/45] the layup is [45/90/−45/0/0/−45/0/0/45]. For defects in the individual plies, this only has a small effect. The orientation of the plies is only of a small importance, because the focus is on out-of-plane deviations and in-plane differences in orientations.

In addition, the stiffener laminates are cut 5 mm shorter than the steel core flanges, in order to ensure that the preforming is done properly that would otherwise cause the flanges to be too long. This was changed after test panel 2. An exact height better represents the actual flap production, since the top of the stringer is constrained in the flap production.
Next, the preforming was not done properly due to the stringers of the laminate that did not want to stick to the flanges of the steel core after and during preforming. No sticking occurred because the flanges were not pressed by hand after the preforming onto the Tooltec. This was also the case for test panel 2. As a result, during the compression of the stringer pack, the laminate separated from the web of the core. In addition, the pack was first compressed without the skin and then further compressed with the skin. The corresponding defects to this manufacturing error are described in the section of the evaluation of the cross sections.
The overviews of the front and back of the panel after curing are shown in figure 6.1 - 6.2.

In these images, the cross sections are also indicated on the front side, which is the same for all the other test panels. The back image has the orientation of when the front panel is rotated over the axis parallel to the stringers, meaning that the top and bottom edges are the same for the two views and that the location of the cores is reversed in the back image. This will be the same for all test panels.

Visual Inspection of the part

By visual inspection, the following defects are observed:

- In-plane waviness (to a small degree)

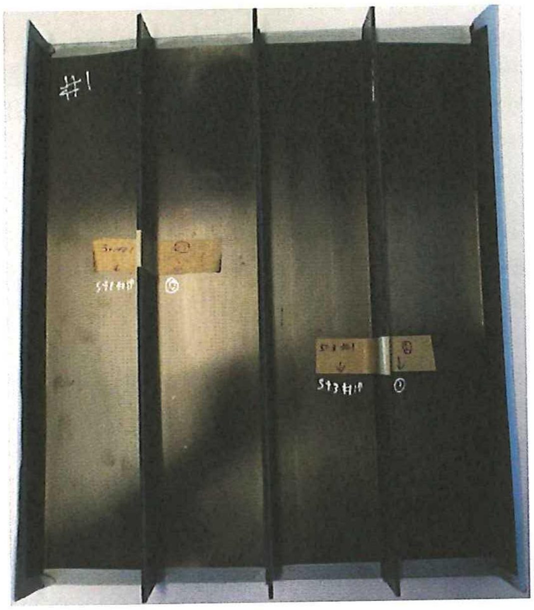


Figure 6.1: Panel 1: finished panel front view

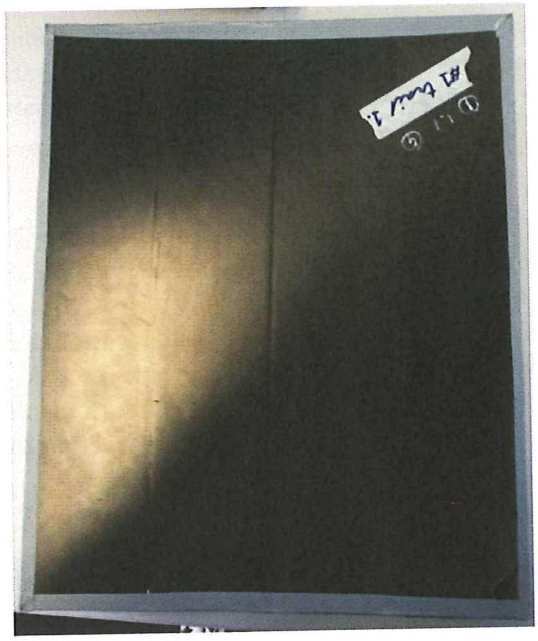


Figure 6.2: Panel 1: finished panel back view

- Out-of-plane waviness (to a small degree at the filler location in the skin)
- Enclosed release film in the resin
- Filler indentations on the back
- Dry spots
- Curved plate

The small in-plane waviness can be seen in every panel that is manufactured and also occur in the actual flaps. The small in-plane waves that are present in the test panel can be seen in figure 6.3.

Figure 6.3: In-plane waviness that is present in the prepreg material

Especially on the back of the panel it is observed that these undulations are at completely random locations and only concern complete bands of fibres. Research has been done at Airbus and from the supervisor at Airbus it is stated that this in-plane waviness is already present in the prepreg before the panels are being made. For that reason, these in-plane waves are not considered to be formed in the panel production and can also not be eliminated with new tooling or an improved process. These small in-plane waves will, for that reason, not be considered as a defect that needs to be removed.

The enclosed release film by the skin is explained by the bad preforming such that the stringer laminate released from the core. A graphical representation of that situation is explained using the evaluation of the cross sections paragraph which also explains the filler indentations at the back. These indentations are along the length of the stringers at the location where the filler material should be located. This can be seen in figure 6.4 where local in- and out-of-plane waves can also be observed next to the filler indentations. The origins of these waves are explained in the evaluation of the cross sections section and can be seen below as a close up in figure 6.5.

Figure 6.4: Filler indentations on the back of the skin of the panel along the filler location

Figure 6.5: Local in- and out-of-plane waviness, originating from the filler indentation

The dry spots result from improper evacuation of entrapped air and are located in several corner sections. Non-porous release film was placed over the cores and the cores themselves were also taped on the sides. This leaves not enough open space for all the air to be squeezed out completely. Also, what can be seen from the thickness measurements is that the skin is not pressurized sufficiently so that the air is not properly evacuated. The dry spots are shown in figure 6.6.

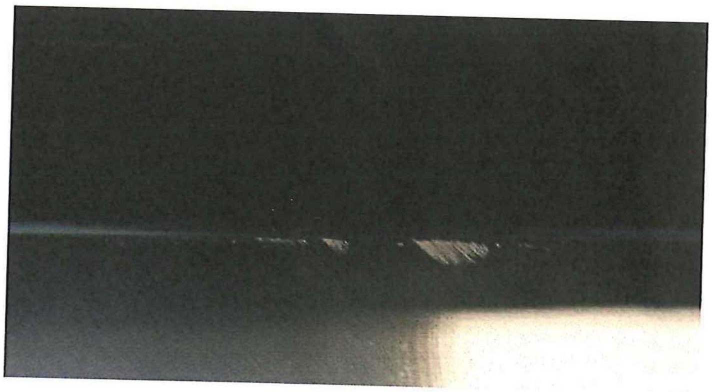


Figure 6.6: Dry spots in the corner sections

The curved plate is due to the lay-up error, which was explained in the manufacturing section, which makes the lay-up asymmetrical. This results in residual stresses due to a difference in the fibre orientation, and thus an asymmetrical CTE distribution through the thickness. This is a clear defect that results from the lay-up error and is therefore not representative as a defect that is found from other steps of the manufacturing.
The unclamped side did not create any defects neither that the skin was placed under the edge bars. On the other hand it might have prevented defects to occur since the laminate was free to expand in all directions.

Evaluation of the cross sections

The locations to evaluate the inner quality by cross sections are indicated in figure 6.12. The views are also indicated in that picture. The complete images can be seen in appendix D which include all the thickness measurements of the cross sections. Two defects can be noticed with ease in the cross sections. One is the wrong layup, which is not relevant for the defects, and two, which is a more important defect, is the vertical filler movement. The wrong lay-up can be seen clearly that the bottom white layer (the 90 degree layer) should be the second layer of from the bottom instead of being located in the middle of the laminate. These defects can be seen up close in figure 6.7, which is cross section 1 at stringer 3.

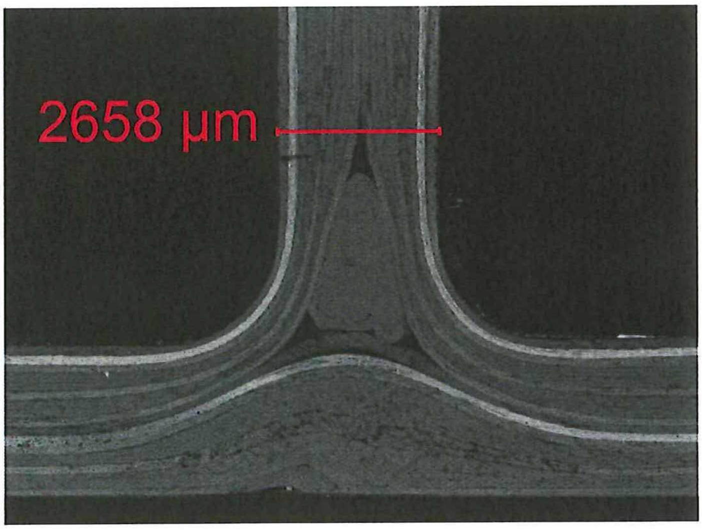


Figure 6.7: Vertical filler movement

The movement of the filler material is also observed in cross section 0 at stringer 1. This movement can be explained by the error that occurred in the preforming stage of the manufacturing with the help of the following figure 6.8.

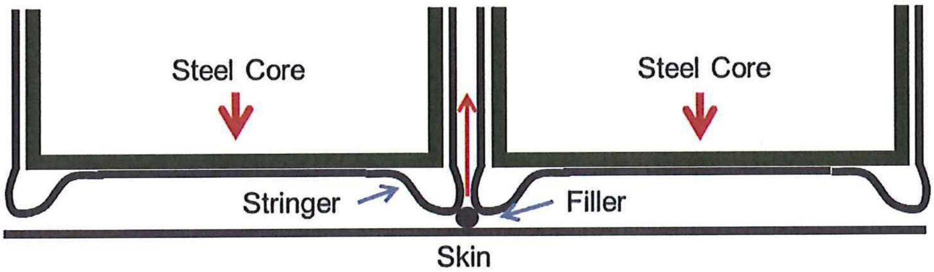


Figure 6.8: Vertical filler movement due to wrong preforming

The preforming is not done properly where the laminate is located above the core after compressing, followed by the placement of the filler as can be seen above. In the preforming, the laminate does not follow the contour of the outer surface of the steel cores. Then, as soon as the skin is placed on the web of the U-profile laminates or if the pack is placed on the skin, there is extra material in the corner sections known as bulging. The filler material sticks to the skin and the stringer. As soon as the autoclave pressure is applied and the temperature is increased, the stringer plies together with the filler and skin start to move upwards due to the decreased viscosity of the resin. The end result is that the filler is not located at the original cross section anymore. Also, the skin underneath the filler shows a large out-of-plane wave that follows the contour of the stringers and filler on one side and the flat ground plate on the other side. This is also visible on the visual inspection as the filler indentation on the skin, the waviness next to the indentations and the enclosed release film. This in-plane waviness is also visible next to the indentation in the cross section with the slight colour change in grey scale. This indication is based on experience in examining the cross sections. In the cross sectional image it can also be seen that the enclosed release film is only in the resin and not in between the fibres. The enclosing of the film could be due to the fact that the pack was also compressed after the skin was placed on, creating wrinkles in the release film. When the resin turns liquid, it flows between the release film, enclosing it with resin.
There is a gap between the stringer and the top of the core which in the end is filled with the carbon fibre material. The 0 degree plies in the depth direction of the cross section(darker layers) shift up more than the 90 degree plies (lighter almost outer layers), which is logical since individual fibres in the 0 degree plies are more easy to move away from one another due to the liquid resin. For the 90 degree plies to fill the cavity, the fibres themselves would need to elongate. This elongation is almost zero because of the high stiffness of the fibres. From the outside, the top of the stringers seems to show slipped stringer plies, while in fact the inner layers moved up instead of the outer layers moving down. The top of stringer 3 with the elongated layers is shown in figure 6.9.

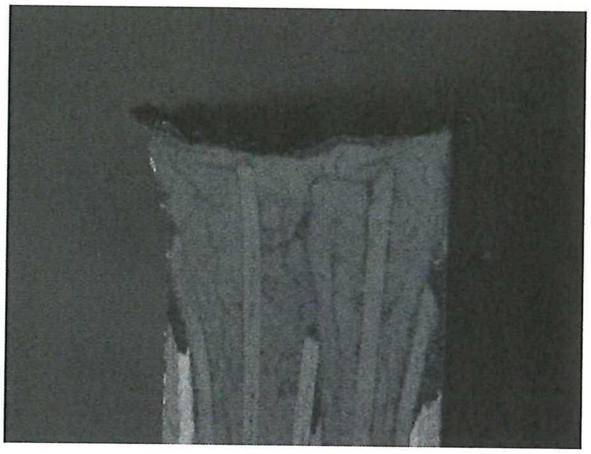


Figure 6.9: Cross section of the top of the stringer with the moved up layers

Thickness measurement

In addition to the defects in the cross sectional images, it can also be noticed that there is a significant thickness deviation in the stringer thickness. The thicknesses of the skin and stringers are displayed below in figure 6.10 and figure 6.11. Here, the actual measured thickness is portrayed as a percentage of the nominal thickness that the laminate should have. This is namely the cured thickness of a single layer multiplied by the number of layers in the laminate. The total number of layers is 18 and the thickness of one ply is 0,125 mm, resulting in a total thickness of 2,250 mm. This was also explained in chapter 5. A smaller actual measured thickness means that the laminate is over pressurized and will have a higher fibre volume content. This is because, the resin is squeezed out more out of this measured region while the fibres remain in place. When the laminate has a larger actual measured thickness it means that either more resin is present in this section or that there are more fibres present, e.g. by forming wrinkles or waves. If there are no wrinkles or waves present, it means that the laminate is under pressurized. Since not all measurement points are taken at the same locations for the different test panels and since that the cross sections do not have precisely the same length, the thickness percentages are displayed as a rough fraction of the total cross section length. The graphs give an overview of the general shape of the cross section by using the measured data points and show the comparison between the different cross sections in the panels. In figure 6.57, the fraction of the stringer height at value 0 is the skin and at value 1 is the top of the stringer.

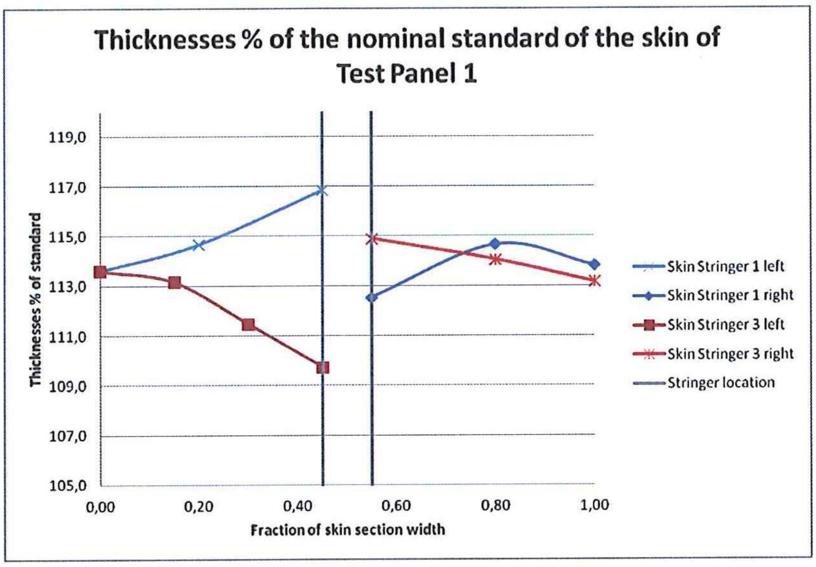


Figure 6.10: Panel 1: Thickness percentage of the nominal of the skin

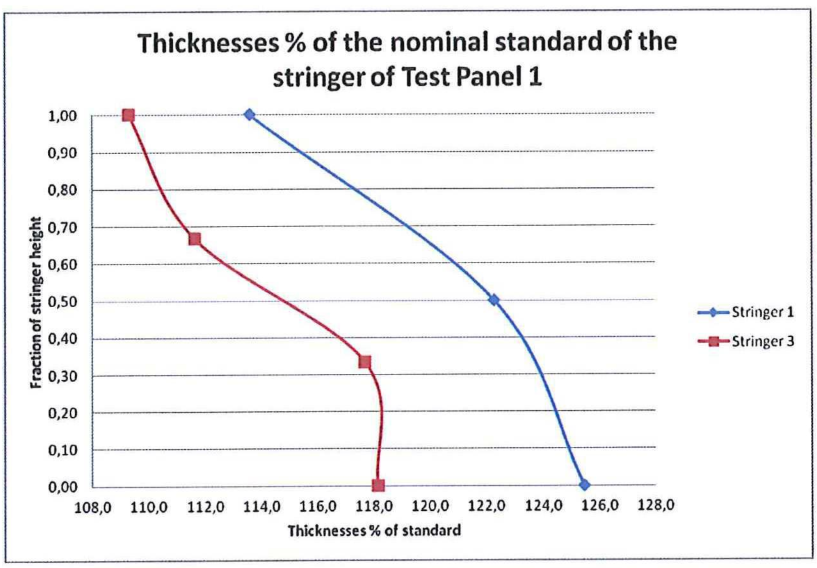


Figure 6.11: Panel 1: Thickness percentage of the nominal of the stringers

The thicknesses in the skin are relatively high compared to the nominal value. Since there is no out-of-plane waviness present, it means that the skin was slightly under pressurized. In the skin,

the thickness on the left of stringer 1 is larger, closer to the stringer. The thickness is smaller on the right side of the stringer and becomes larger, further away from the stringer. This could indicate the interaction of the two cores 1 and 2 on both sides of the stringer when they are rotated slightly in counter clockwise direction by the autoclave pressure. The same is true for the skin at stringer 3, but then with a rotation in clockwise direction. A small shift of the cores could also lead to the thickness difference.
From an absolute point of view, these thicknesses have a difference between the middle of the skin and the corner section of the skin of only several hundreds of a mm. However, thicknesses at the left and right side in the corner section of stringer 3 differ about 5% and do have a similar thickness in the middle of the skin. The same goes for the thickness on the left of stringer 1 and 3 where the difference between the two is about 7% So the thicknesses do give an indication the a rotation of the cores is present.

For stringer 1, the thickness is 2,823 mm and at the top 2,256 mm which is a difference of 0,567 mm or a value of 25,5%. The thickness measurements can be seen in appendix D and the deviations from the tolerances in appendix E. From a quality point of view, the thickness at the bottom of the stringer is outside the tolerances as described in chapter 5. The target thickness of the laminate should be 2,250 mm with tolerances of +0,500 mm and -0,150 mm. That means that the thickness at the bottom of the stringer is 0,073 mm too large in order for the panel to be approved. At stringer 3 there is also a thickness difference for the top and bottom of the stringer where it is 2,658 mm at the bottom and 2,459 mm at the top. These values are however both within the tolerances. Both stringers are significantly wider at the bottom than in the top. The reasons for the large thickness differences are that the filler material has shifted upward, resulting in more carbon fibre just above the filler and the fact that the cores were allowed to move sideways so that the laminate could have room to expand. Also, the reason that the stringers at the top are thinner than below is that the laminates were cut 5 mm shorter than the core, but obtained the same height as them after curing when filling the cavity. That means that the carbon fibre in the top is distributed over a larger height, resulting in a lower thickness with an almost constant volume. The core flanges could also show signs of bending as is also explained in test panel 4.

Summary and conclusions

As a summary, the defects that were found with the outer quality visual inspection were in-plane waviness (to a small degree), out-of-plane waviness (to a small degree), enclosed release film in the resin, filler indentations on the back, dry spots and a curved plate. The in-plane waviness is assumed to be already present in the prepreg, the dry spots due to improper evacuation of entrapped air and the curved plate due to an error in the lay-up of the laminate. These are however acceptable defects or are unexpected (like the curved plate) and that have a negligible influence on the unacceptable defects.
The out-of-plane waviness, enclosed release film in the skin and the filler indentations on the back are explained by looking at the cross sectional images to determine the inner quality. For these images, it can be seen that the filler material has shifted upwards, which is due to improper preforming. Therefore, it is an indication that with the defects that can be seen with visual inspection, a shifted filler is present in the part. In other words, it can be assumed that the inner quality is affected of a panel when these outer quality defects are present.

In addition to the defects mentioned above, the thickness differences of the stringer is explained by the shifting of the filler material, the unclamped edge bar and that the stringer laminate was 5 mm shorter than the core. Also the skin is slightly under pressurized.

6.1.2 Test panel 2: First panel plus wrong preforming

The second test panel was, like the first part, supposed to be a reference panel of good quality and a proof to understand the production process. Some errors in the production were removed when compared to the first part. However, some alterations are present which were corrected for the panels produced hereafter. Like the first part, the preforming was not done perfectly and one edge bar was still not clamped, but is simply supported now. A panel of good quality was produced from an outer quality point of view, but still has inner defects.

Manufacturing

As stated before, one of the deviations from the standard production process as stated in chapter 5 is that one side of the tooling is not clamped. Differently from the first part, the edge bar is now simply supported by fitting in smaller screws in the holes. However, the screws could not be tightened, since the radius of the screw is smaller than that of the edge bar hole. As a result, the edge bar cannot move sideways, but can be lifted up. From test panel 3 onwards, this deviation was completely eliminated when the edge bar was modified to fit the screws properly. Like in test panel 1, the deviation is still present and the edge of the skin was placed underneath the edge bar. Furthermore no release film was surrounding the panel, only on the bottom of the skin and on the inside of the cores. The stiffener laminates are also cut 5 mm shorter than the steel core flanges.
Next, the preforming was not done properly again due to the stringers that did not want to stick to the flanges after and during preforming.

As can be seen, the panel is manufactured in a similar way as test panel one, with the difference that the lay-up was done correctly and that the panel was first compressed properly before the skin was placed on. Like panel 1, the pack was compressed a bit more after the skin was placed. The overview of the front and back of the panel after curing one shown in figure 6.12 - 6.13.

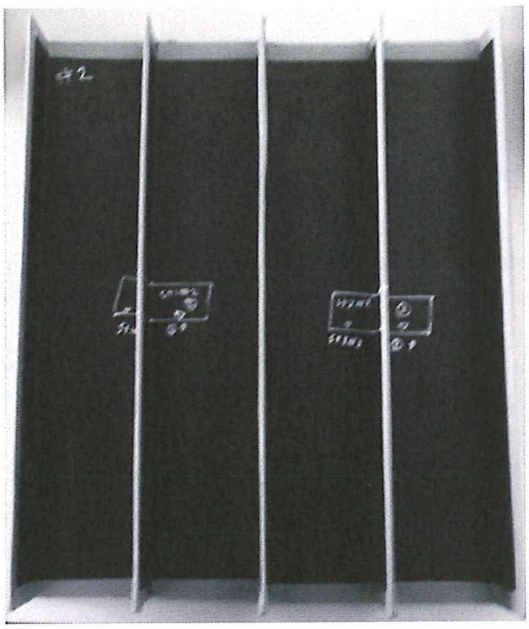


Figure 6.12: Panel 2: finished panel front view

Figure 6.13: Panel 2: finished panel back view

Visual Inspection of the part

By visual inspection, the following defect is observed:

- Filler indentations visible on the back

The small in-plane waviness is exactly the same as in test panel 1 and is assumed to be present in the prepreg material already. Differently, when compared to test panel 1, no dry spots are present, so the evacuation of air was done properly. Also, the plate was not curved, because the correct lay-up was done. However, the filler indentations are still present only to a smaller degree. An important difference is that the release film is not enclosed by the resin in this panel at the filler location. That is probably because the pack was already sufficiently compressed before the skin was placed on. No wrinkles were formed in the release film for that resin and it could not be enclosed like in panel 1. Also, no waviness is seen around the filler indentations. A close up of the filler indentation is shown in figure 6.14.

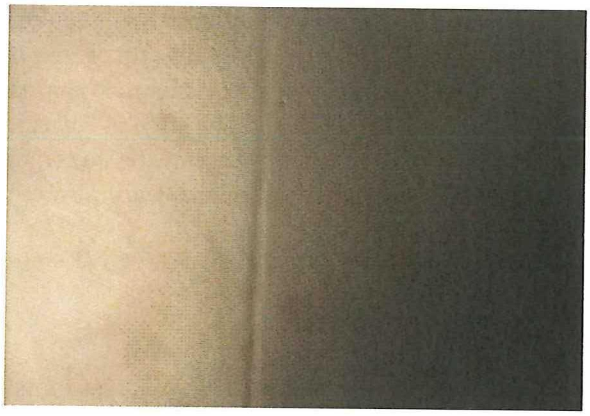


Figure 6.14: Filler indentation on the back of the skin of the part

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.20. The views are also indicated in that picture. The complete images can be seen in appendix D which include all the thickness measurements of the cross sections.
The main defect that is observed is the vertical filler movement. This defect can be seen in figure 6.15, which is cross section 3 at stringer 3.

The filler movement occurs for the same reason as for test panel 1, displayed in figure 6.8, that the preforming is not done properly. In addition to the filler movement, a void is present in the skin underneath the filler. Air was entrapped here probably due to the bad preforming. The skin needs to fill the area underneath the filler and when there is not enough resin it is filled with air that comes from other areas of the part. On the other hand, there is no void present in the other cross section that was taken from test panel 2, but the filler movement is present.
Since the filler movement is also present in test panel 2, and there is no enclosed release film present in this part, the following conclusion can be drawn that the waviness in the skin around the filler indentation of test panel 1 was formed due to the enclosing of the release film.

Thickness measurement

Similarly to test panel 1, there is a significant thickness difference in the stringers. The thicknesses of the skin and stringers are displayed below in figure 6.16 and figure 6.17. The explanation

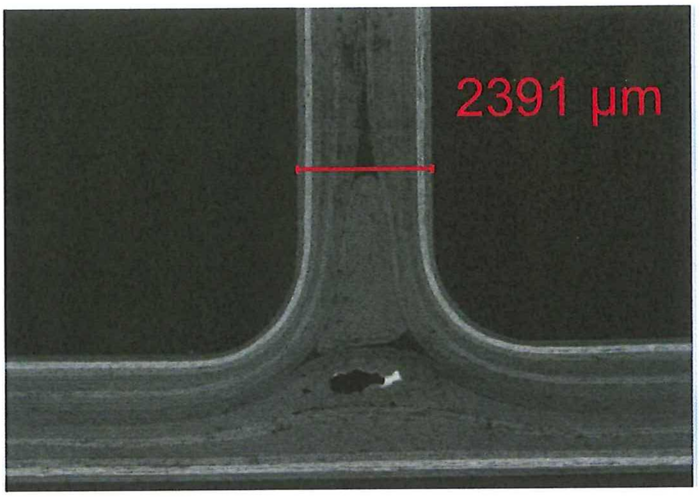


Figure 6.15: Vertical filler movement in stringer 3

on how the graphs are constructed is explained section 6.1.1.

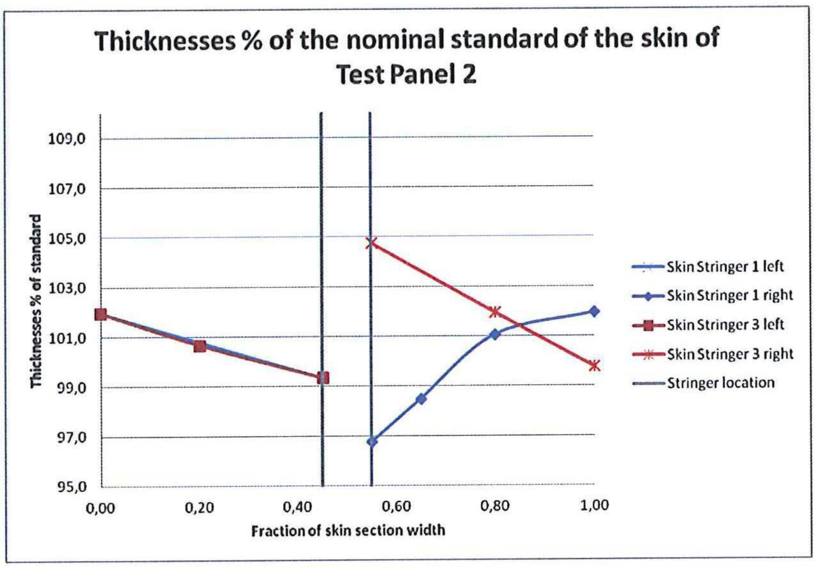


Figure 6.16: Panel 2: Thickness percentage of the nominal of the skin

The thicknesses in the skin are less high compared to the nominal value and the measured values for panel 1. In the skin, the thickness on the left of stringer 1 is smaller, closer to the stringer compared to further away. The skin thickness is larger just right of the stringer and decreasing further away from the stringer. This could indicate the interaction of the two cores on both sides of the stringer when they are rotated slightly in opposite directions with core 1 rotating clockwise and core two counter clockwise by the autoclave pressure or the cores shifted slightly. For stringer 3, core 2 and 3 both rotated clockwise or also shifted slightly by looking at the thicknesses.
From an absolute point of view, these thicknesses have a difference between the middle of the skin and the corner section of the skin of several hundreds of a mm. However, thicknesses at the right sides in the corner sections of stringers 1 and 3 differ about 5% compared to the thickness in the middle of the skin. So the thicknesses do give an indication the a rotation of the cores is present.

For stringer 1, the thickness is 2,566 mm or 114% at the bottom and at the top 2,138 mm or

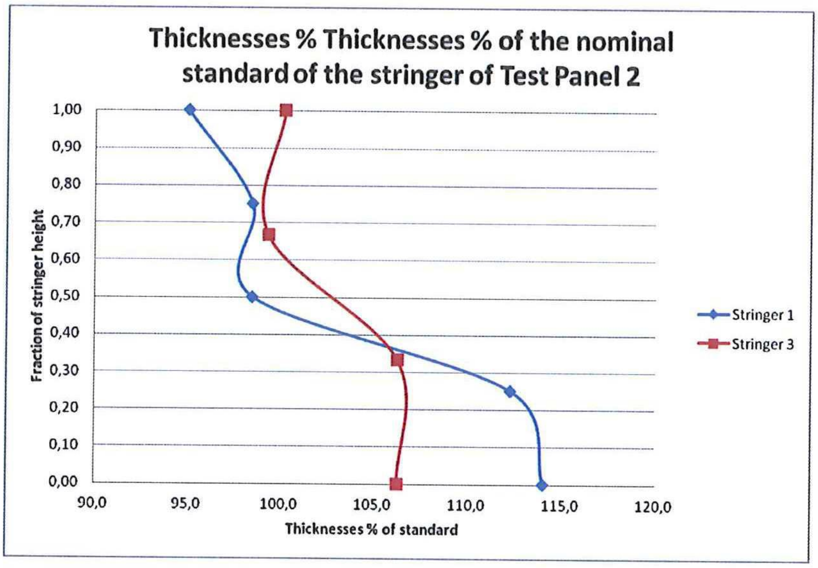


Figure 6.17: Panel 2: Thickness percentage of the nominal of the stringers

95% which is a difference of 0,428 mm. The thickness measurements can be seen in appendix D and the deviations from the tolerances in appendix E. At stringer 3 there is also a thickness difference for the top and bottom of the stringer where it is 2,391 mm or 106% at the bottom and 2,255 mm or 100% at the top and does not make the difference of 0,166 mm too significant. All the values of this panel are however within the tolerances and from a quality point of view this panel would still be acceptable.

The reasons for the large thickness differences are the same as for test panel 1 due to the shifting of the filler material, the unclamped edge bar and that the stringer laminate was 5 mm shorter than the core. Again, the 0 degree plies elongate more than the 90 degree plies for the same reasons as for panel 1. However, the thickness differences are larger than in test panel 1, a reason for this could be that the flanges of the cores bend more than in panel 1.

Summary and conclusions

As a summary, the defects that were found with the outer quality visual inspection were in-plane waviness (to a small degree) and filler indentations on the back. The in-plane waviness is assumed to be already present in the prepreg. The indentations at the filler locations on the back are explained by looking at the cross sectional images to determine the inner quality and are similar to the filler movement found in test panel 1, with the addition of a void in the skin below the filler, and occur due to the same reason of improper preforming. However, no release film was enclosed by the resin in the skin, because the stringer pack was properly compressed before the skin was placed on and not afterwards anymore.

With this panel it can be concluded that improper preforming, when the laminate is not fully attached to the core, can lead to filler material shifting upwards. By visual inspection an indication for the filler movement is given by the indentations at the filler locations in the skin.

In addition to the defects mentioned above, the thickness difference of the stringer is explained by the same reasons as for test panel 1, but with a better compression of the skin.

6.1.3 Test panel 3: stringer height and core size

For the third panel that was made, some manufacturing alterations were done compared to panel 1 and 2 (sections 6.1.1 and 6.1.2). The main difference is that the edge bar is now fully clamped and that the stringer pack plus skin is fully enclosed with release film. Next to these alterations, the stringer height is varied for two cores to have the exact height and two stringers that are 8 mm smaller. The core size is adjusted with layers of Tooltec tape to simulate the difference in thermal expansion coefficient of the actual carbon fibre cores and the steel ones that are used for to manufacture the test panels.

Manufacturing

As stated in the introduction, some alterations were done for the manufacturing of the panel compared to the first and second part. First of all, both the edge bars are now fully clamped, because one of the edge bars has been machined to fit all the screws with the laminate in between the cores. This modification ensures that the edge bar cannot move from left to right, but can also not rotate or move up and down. The clamped edge bars are used for all the other test panels that will be described hereafter.
Secondly, the whole panel is enclosed in release film in one piece on the skin and between the outer flanges of the outer stringers and the edge bars. Additionally, the sides of the panel at the end of the stringers were also taped, just like test panel 1 and 2. With the release film placed on top of the cores, the panel was almost completely sealed off. The effects on the panel quality of this alteration are described in the outer quality section. Because of the release film, the skin is also no longer placed under the edge bars.

After a low quality preforming for the first and the second test part, it was made sure that the flanges of the preform were pressed onto the Tooltec tape carefully by hand as soon as the preforming was done. Pressing the laminate immediately after the preforming will ensure that the material is still flexible, sticky and doesn't spring back when it is manually deformed. As can be seen in figure 6.18, the preformed material now fits perfectly around the core, especially around the corner sections during the compressing of the pack.

Figure 6.18: Good fit of the laminate around the corner sections of the core

To simulate the production of the flaps even better, the preform cores were made slightly bigger than the autoclave cores to simulate the less expanding carbon fibre cores compared to the steel cores. The width difference will be calculated hereafter. Steel expands more than carbon fibre so the steel cores need to be slightly smaller than the preformed laminate in order to have the same compression due to the expanding material as the carbon fibre cores. To realize this, a number of Tooltec layers are stuck on the flanges of the cores, which will be removed for the autoclave cycle. The first step in this is to calculate how many plies of Tooltec are necessary. The linear thermal expansion coefficient(α_{steel}) of the steel cores at 20 C is $12 \cdot 10^{-6} K^{-1}$ and the linear thermal expansion coefficient of the carbon fibre cores is $4,5 \cdot 10^{-6} K^{-1}$ in width direction. The thermal expansion coefficient of the carbon fibre is estimated with help of figure 2.1 from literature. The steel cores will expand more than the carbon fibre cores. The steel cores are made to have the same dimension after the temperature increase as for the carbon fibre cores by decreasing the width of the steel cores for the autoclave cycle compared to the preforming. In order to estimate the thermal expansion coefficient of the carbon fibre cores, the percentages of ply orientations need to be determined. For the test panel in width direction there are the following percentages of ply orientations present. (44% ±45 deg, 11% 0 deg, 44% 90 deg). Note that the orientation of 0 degree plies changes to 90 degree to read the graph, because the expansion in width direction, not length direction should be used. The thermal expansion coefficient can be read from the graph using these values.

The expansion of the steel core in width direction with a temperature difference T, from 23 degrees heating up to 180 degrees, of 157 degrees and a width L of 80 mm is calculated as follows:

$$\delta L_{steel} = L\alpha_{steel}\delta T = 0,151mm \tag{6.1}$$

The expansion of a carbon fibre core in width direction for the same temperature difference is:

$$\delta L_{steel} = L\alpha_{steel}\delta T = 0,057mm \tag{6.2}$$

This comes down to a width difference of δL_{steel} -δL_{carbon}=0,151-0,057=0,094 mm. One sheet of Tooltec has a thickness 0,115 mm, so to match the same end width in the autoclave, 0,82 plies, or rounded off 1 ply, of Tooltec needs to be used on one of the flanges per steel core. This way, the steel core will have the same width as the carbon fibre core with the temperature increase compared to the preform core. In other words, the steel core needs to be smaller before the autoclave than a carbon fibre core since it expands more in the autoclave in order to have the same final width.
To simplify and to make sure that the steel core pressurizes the laminate not at all due to the temperature increase, 2 plies of Tooltec are used per preform steel core on the flanges. This corresponds to one layer of Tooltec per flange that is present during the preforming, but removed during the autoclave cycle. For panel 1 and 2, the Tooltec that was used for preforming stayed on the core and also went into the autoclave, but will now be removed.

The last intentional alteration is to have two cores with stringers of the exact height of the flanges of the cores and two stringers with a stringer height which is 8 mm lower. Cores 1 and 2 have the exact height and the stringers of core 3 and 4 are 8 mm shorter. The reason that this alteration is put in is to see what the effect of a lower or higher stringer is on the rest of the part. The difference in stringer height for stringer 3, which is half the exact height and half 8 mm shorter, is shown in figure 6.19.

The overview of the front and back of the panel after curing is shown in figure 6.20 - 6.21.

Visual Inspection of the part

By visual inspection, the following defects are observed:

- In-plane waviness (to a small degree)
- Dry spots (to a large degree in the stringers)

Figure 6.19: 8 mm shorter stringer laminate for core 3

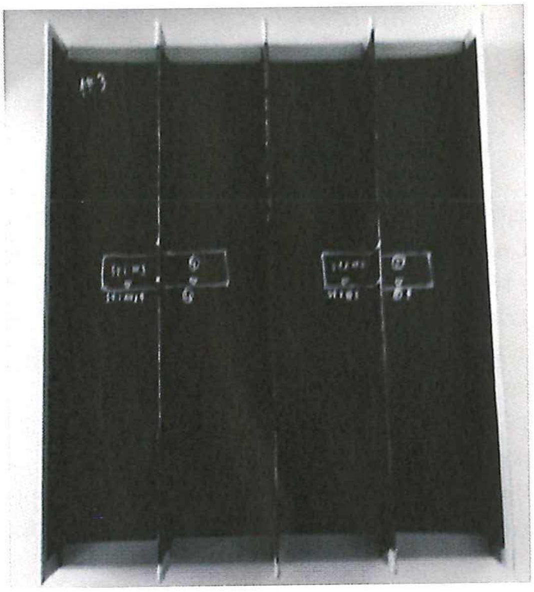


Figure 6.20: Panel 3: finished panel front view

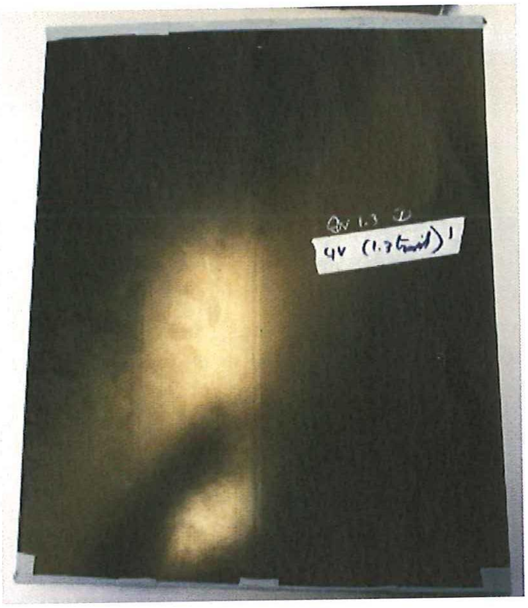


Figure 6.21: Panel 3: finished panel back view

Again the small in-plane waviness is present in the whole part. There is however also in-plane waviness present in the web of the stringers near the corner sections. This is shown in figure 6.22.

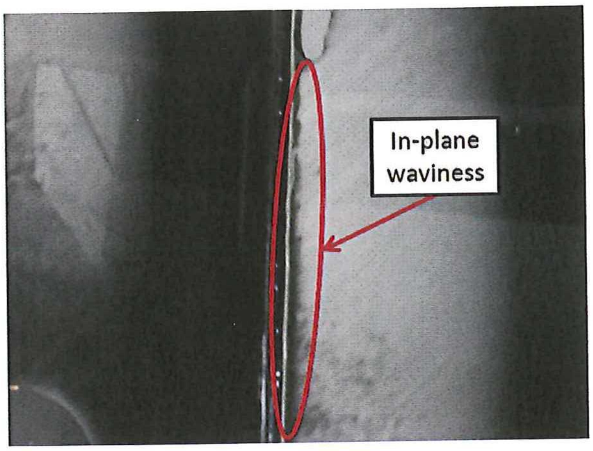


Figure 6.22: In-plane waviness in the web of the stringers near the corner sections

The main defect that can be noticed from the visual inspection is the large number and size of dry spots. They are located on all the stringers on the top and are most severe in the centre of the stringer and are absent at the two ends of the stringer. An overview of these dry spots can be seen in figure 6.23 and 6.24.

Figure 6.23: Dry spots in the stringers

Figure 6.24: Dry spots in the stringers

These dry spots can be easily explained by the mistake to fully enclose the panel with release film and tape so that the panel is closed of airtight and locations where it should not be. That way, there was no possibility for the entrapped air to escape which remained in the panel. All the air gathered in the middle at the top of the stringer, because the pressure that is exerted on the laminate is higher in the web, because of the weight of the core. The air is pushed up to the stringer until it reaches the top and accumulates in the centre of the stringer.
From the visual inspection it can be seen that the dry spots in the stringers with the exact height are on the surface and in between the fibres. However, for the stringer with a lower height, the outer layers are lower and have the entrapped air above it, while the centre plies of the stringer moved up to fill the rest of the cavity. A close-up of the difference can be seen in figure 6.25 and 6.26.

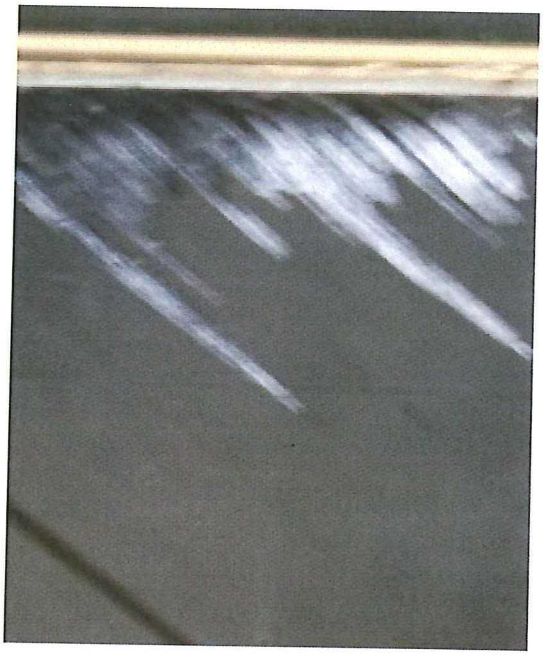


Figure 6.25: Dry spots in the stringers close-up

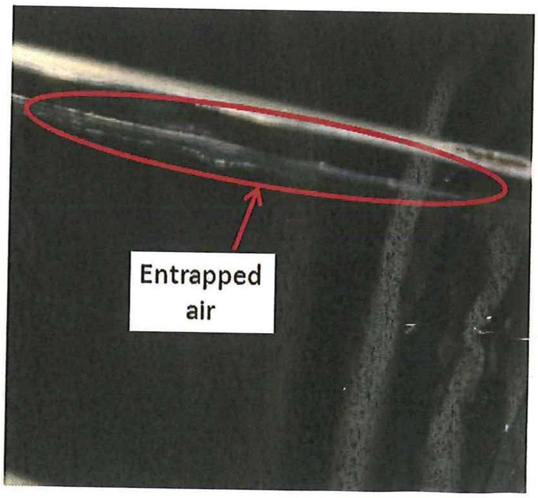


Figure 6.26: Entrapped air above the stringers close-up

For the next panels the alteration is done not to fully enclose the top and sides of the panel with tape and release film, but the close off the top at the top of the stringers and the cores and to enclose the skin together with the outside of the flanges of the outer stringers. The tape on the two longitudinal ends of the panel will not be present anymore so that the air can evacuate through those sides.

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.20. The views are also indicated in that picture. The complete images can be seen in appendix D which include all the thickness measurements of the cross sections.
Comparing the cross sections of panel 3 with panel 1 and 2 immediately shows that a good preforming has been done and that the filler material is located at the right place in the centre of the stringer without it moving upwards. The cross section of the intersection is cross section 4 of stringer 1 and can be seen in figure 6.27.

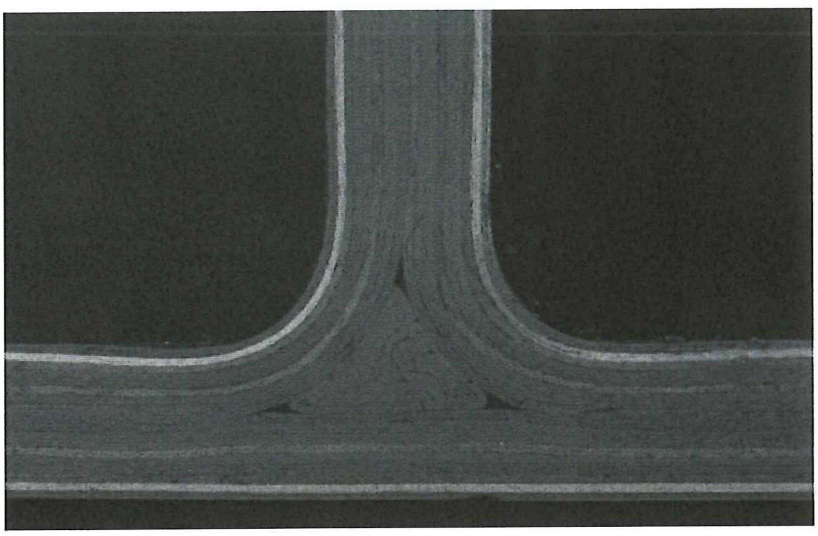


Figure 6.27: Cross section of good quality without any defects in stringer 1

This image shows how the intersection should look like for a perfect panel without any defects. The cross section of stringer 1 and 3 are similar.
When looking at the top of the stringer of the cross section, a difference is noticed between the stringer 1 with an exact height and stringer 3 with an 8 mm lower flange. As described in the outer quality section, the dry spots in the stringer with the exact height are on the surface and in between the fibres. The stringer with a lower height has less high outer layers and has the entrapped air above it, while the centre plies of the stringer moved up to fill the rest of the cavity. This can be seen clearly in the cross sections in figures 6.28 and 6.29.

From now on, the stringers will be made at the exact height of the cores, with the exception of test panel 12, because it better corresponds to the actual production process.

The removal of the Tooltec tape seemed to have no negative effect on the panel quality and will be used for every panel from this panel on. That decision was made based on the assumption that the test panel production will better match the actual production.

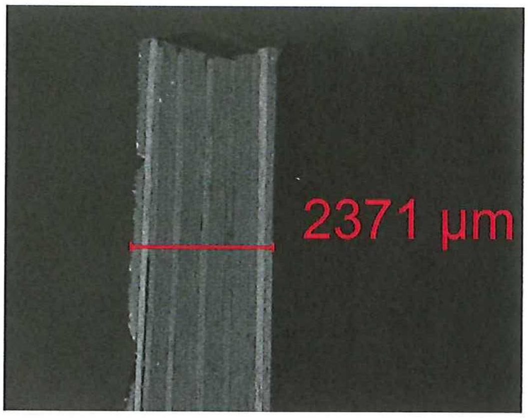


Figure 6.28: Stringer 1 without a cavity, but with dry spots on the left of the stringer

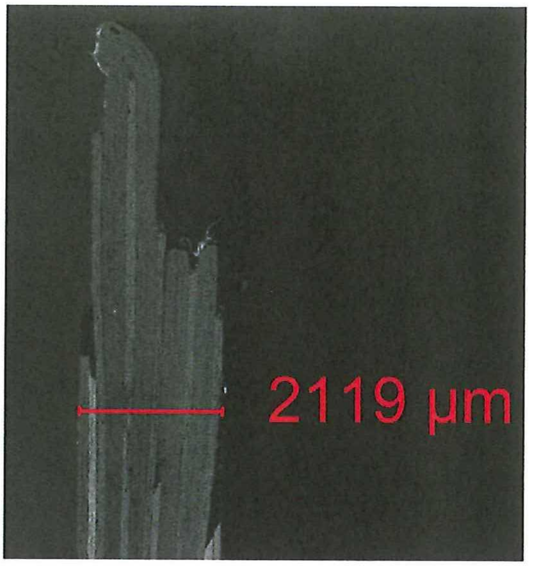


Figure 6.29: Stringer 3 where, the centre plies fill the cavity above the stringer

Thickness measurement

The thicknesses of the skin and stringers are displayed below in figure 6.30 and figure 6.31. The explanation on how the graphs are constructed is explained section 6.1.1.

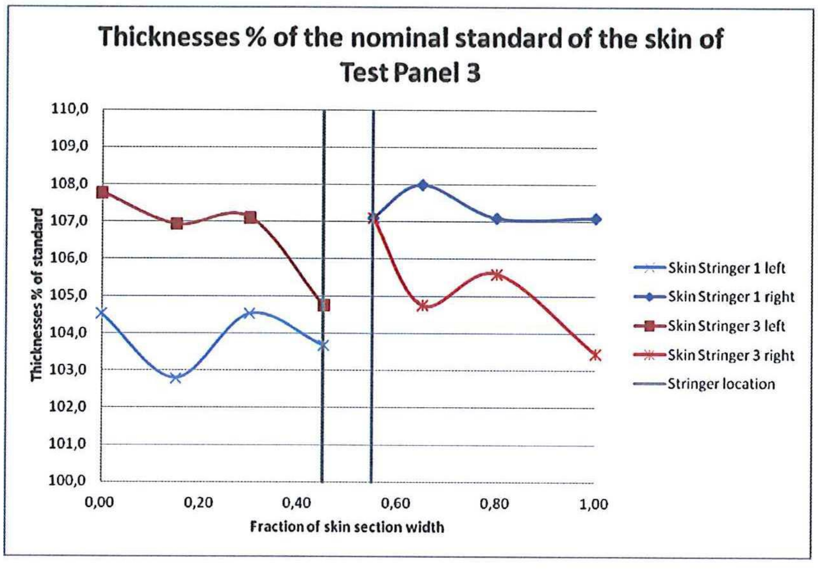


Figure 6.30: Panel 3: Thickness percentage of the nominal of the skin

The thicknesses in the skin are a bit higher than the nominal value. In the skin, the thickness on the left of stringer 1 is more or less constant and similarly to the right side of the stringer. The thickness of the skin of the left side of stringer 3 is larger further away from the stringer and decreasing closer to the stringer. On the right side the thickness is decreasing with an increasing distance from the stringer. This could indicate the interaction of rotation of the two cores 2 and 3 on both sides of the stringers in clockwise direction. In this case, the skin below core 3 is subjected to a higher pressure than in core 2. This can be derived from the lack that the average thickness of the skin below core 2 is higher than that of core 3. However, from an absolute point of view, these thicknesses have a difference between the left and the right side of the stringer of

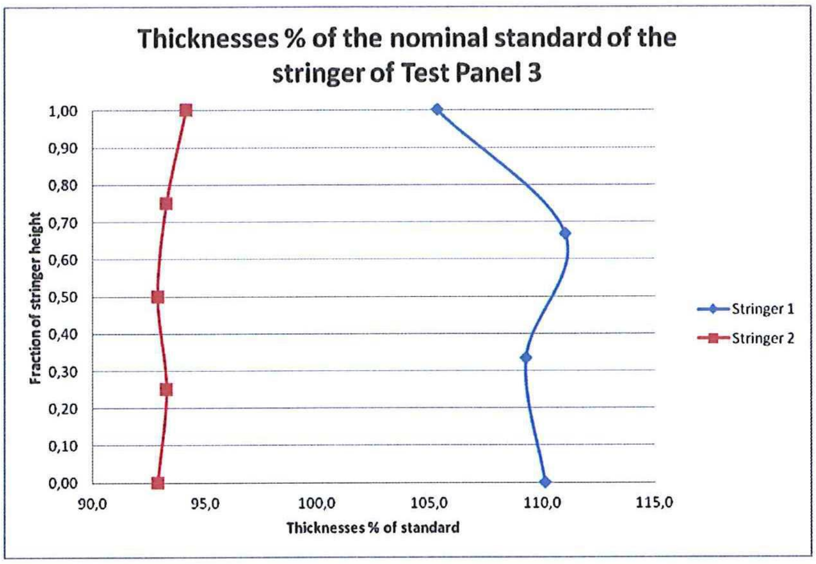


Figure 6.31: Panel 3: Thickness percentage of the nominal of the stringers

only several hundreds of a mm. For that reason, no meaningful conclusions can be drawn about this rotation.

The thickness measurements can be seen in appendix D and the deviations from the tolerances in appendix E. Interesting to notice is that the stringers 1 and 3 have a significant thickness difference between the two. For stringer 1, the thickness is 2,478 mm or 110% at the bottom and at the top 2,371 mm or 105% which is a difference of 0,107 mm. This indicates an almost perfectly straight stringer, which is slightly under pressurized. At stringer 3 there almost no thickness difference for the top and bottom of the stringer where it is 2,090 mm or 93% at the bottom and 2,119 mm or 94,2% at the top and does not make the difference of 0,029 mm significant. However, the stringer is at the bottom 0,010 mm too thin. From a quality point of view this panel would not be acceptable.
The reason that the stringers are thinner is that the laminates were cut 8 mm shorter than the core, but obtained the same height after curing. That means that the carbon fibre in the top is distributed over a larger height, resulting in a lower thickness with an almost constant volume in addition to the dry spots.

Summary and conclusions

This test panel was fully enclosed, leading to dry spots in the stringer which are both visible in the inner, outer and thickness quality inspection. As a deliberate process parameter change, two laminates of the stringers were cut to the exact height of their corresponding cores and two laminates were cut 8 mm lower than the core height. A significant difference is observed between the dry spots of the stringers of the two different heights as well as the thicknesses. For stringer 3, the panel would not be accepted because the thickness is below the tolerance level. The stringers are for other features indifferent and an intersection of good quality was achieved due to the better preforming. The width difference of preform core and autoclave core had little or no effect.

6.2 Panels with tooling alterations

After making the panels of good quality, panels are manufactured where alterations are made to the dimensions and placement of the tooling. In the actual production process there are some variations between the dimensions of the aluminium preform cores and the carbon fibre autoclave cores. Also, the aluminium cores have to be taken out of the panel in order to remove the release film, cut the stringers to the right height and to place the carbon fibre autoclave cores. The dimensional variations and the removal and placement of the cores are assumed to be a cause for many different defects. In panels 4 and 5 described in sections 6.2.1 and 6.2.2, the preform core is made less wide than the autoclave core. In panel 6 and 6, sections 6.2.3 and 6.2.4, a hanging core is simulated, where, the cavity between two stringers is not wide enough to fit the last autoclave core. Finally, in panel 8 (section 6.2.5) the preform core is made wider than the autoclave core.

6.2.1 Test panel 4: Preform core width smaller than autoclave core width

The fourth test panel that is manufactured will have the process variation that the preform core is smaller than the autoclave core. There are some variations in the current process between the dimensions of the aluminium preform cores and the carbon fibre autoclave cores. On average, the preform cores are smaller than the carbon fibre core. The difference in width could have a significant impact on the panel quality and may cause some of the defects present in the flaps. The alteration that the preform cores are smaller than the autoclave core for the test panels will simulate this difference.

Manufacturing

As stated in the introduction, the panel will be made with a different preform core size as the autoclave core size. The preform core will have the normal steel core size and the autoclave core will be made wider using Tooltec tape. First of all, the average tool geometry difference needs to be found. At an early stage of the thesis, all the carbon fibre cores were measured by hand using a digital calliper. The measured values are shown in appendix B and are compared to the width values from the CAD model of the cores. The aluminium cores fit these CAD model dimensions accurately, but the carbon fibre cores do not, though they should. The average width difference of all the NEO carbon fibre cores compared to the CAD model for the upper left shells is 0,43 mm larger and for upper right 0,70 mm larger. On average for the upper shells the difference is 0,56 mm where the carbon fibre cores are wider than the preform cores.
To simulate this width difference, Tooltec layers are applied on the flanges of the autoclave cores. The thickness of a layer of Tooltec is 0,115 mm, so per core a total number of 4,9 layers need to be applied. This number is rounded off to five layers of tape per core, meaning three on one side of the core on one flange and two on the other flange. These layers are applied to all the cores. The resulting situation for the manufacturing alterations is shown graphically in figure 6.32.

From the defects that occurred in panel 3 in terms of the dry spots, the process is now adjusted to exclude the tape on the ends of the stringers to allow for proper evacuation of the entrapped air. Also, a release film will be present on the inside of the stringers.

The overview of the front and back of the panel after curing is shown in figure 6.33 - 6.34.

Visual Inspection of the part

By visual inspection, the following defects are observed:

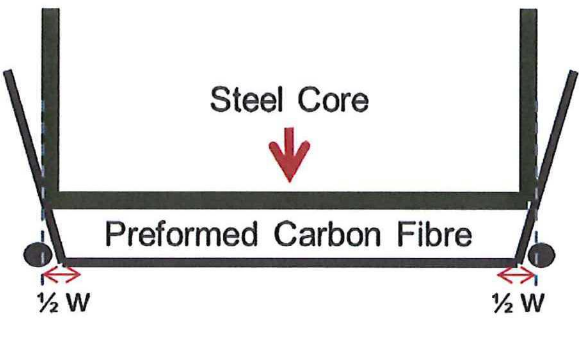


Figure 6.32: Schematical overview of the manufacturing alteration where the steel autoclave core is wider than the preform core

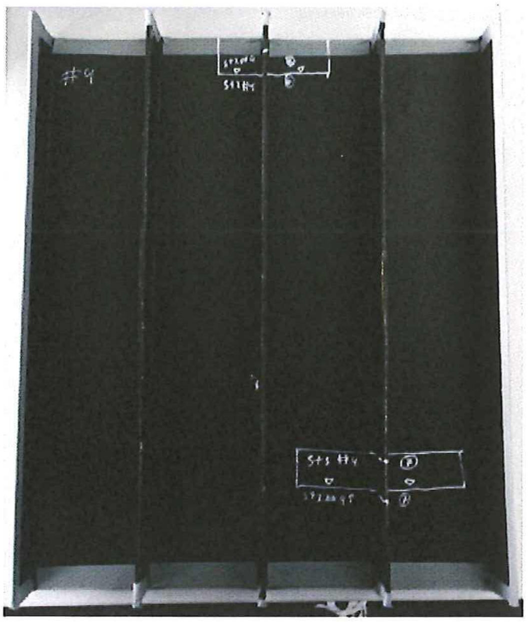


Figure 6.33: Panel 4: finished panel front view

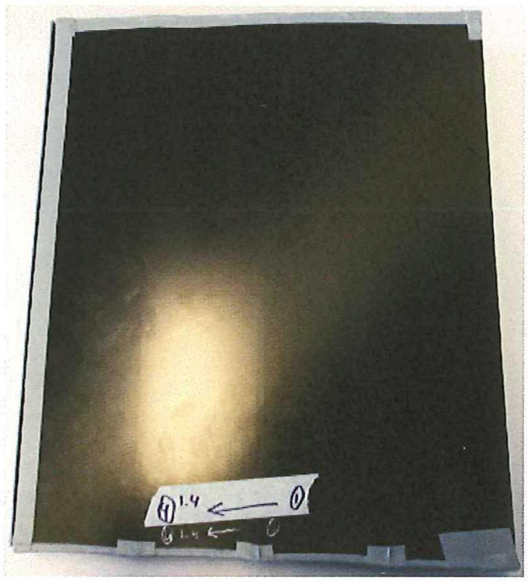


Figure 6.34: Panel 4: finished panel back view

- In-plane waviness in the corner sections
- Enclosed release film

Next to the standard in-plane waviness in the laminate, also extra in-plane waviness present in the web of the stringers originating from the corner sections. This is shown in figure 6.35.

The waviness is present to a larger degree than in test panel 3. In addition to the waviness in the corner sections, there is also release film enclosed in the corners of cores 2, 3, and 4. In core 2, the release film is still present and irremovable. The enclosed release film can be seen in figure 6.36.

The wider autoclave cores combined with the autoclave pressure caused the stringers to be pushed down because the bottom width had increased, see figure 6.32. In order to make the tool fit, extra resin from the stringers was 'used' to widen the bottom surface creating the in-plane waves in the corner sections. This also caused the release film to wrinkle, which was then enclosed in the corner sections by the resin in the autoclave. However, this does not show at the top of the stringers in the form of slipped stringer plies as would be expected. This would

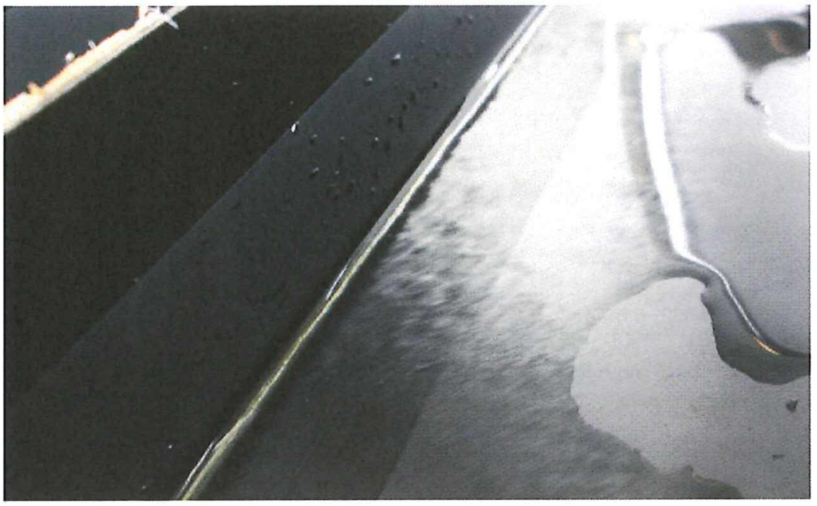


Figure 6.35: In-plane waviness in the web of the stringer originating from the corner sections

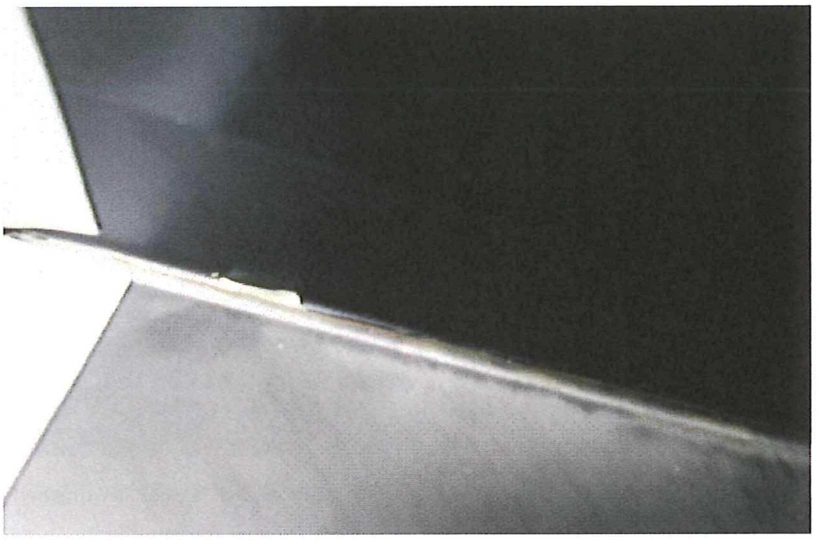


Figure 6.36: Enclosed release film in the corner section

means that only the resin and not the fibres are used to widen the bottom.

For the rest, the panel appeared to be of good quality by visual inspection. Even the filler indentations on the back of the panel on the skin surface can hardly be seen.

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.63.
Cross section 6 at stringer 2 was taken at the location where the release film was enclosed in the corner section that is shown in figure 6.36. Looking at the cross section, it is interesting to notice that the release film is not enclosed in a wrinkle of the prepreg, but in the resin that accumulated on top of the laminates corner. The cross section can be seen in figure 6.37.

From the cross section it is also seen that the filler material is slightly off set from the centre line of the stringer. This phenomenon can be seen even more clearly in cross section 7 at stringer 3 where the offset is almost 1 mm and is shown in figure 6.38.

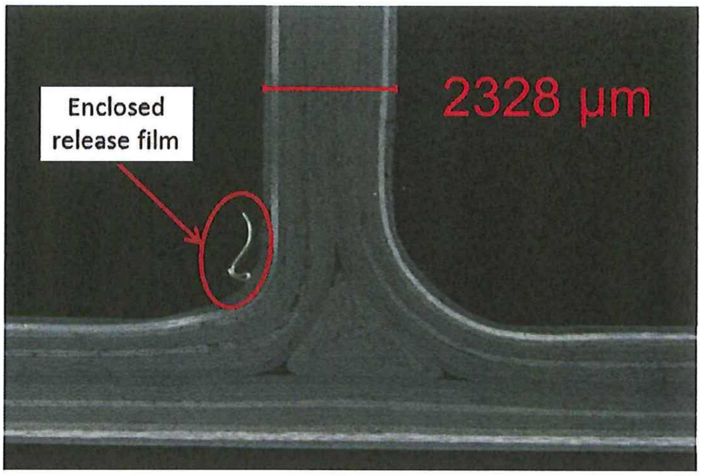


Figure 6.37: Enclosed release film in the corner section

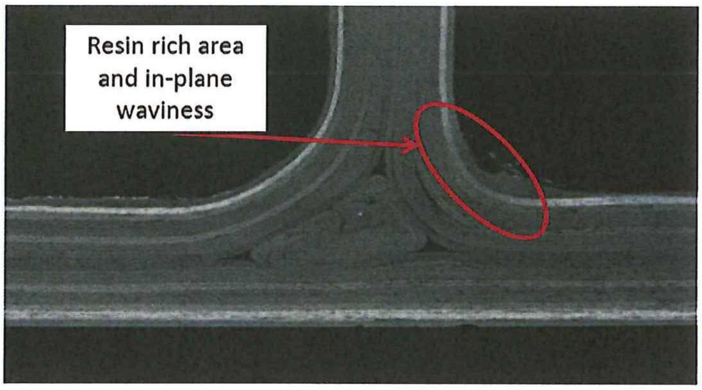


Figure 6.38: Horizontal filler movement in stringer 3 with an offset of almost 1mm

The cause of the filler misalignment in horizontal direction is clearly caused by the difference in preform and autoclave width. Comparing the cross sections and figure 6.32, it can be explained that the autoclave core pushes the stringer over the filler material and shifts the location of the stringer. In figure 6.37, the enclosed release film can be seen in the left corner section of the stringer. In both cross sections, the release film is enclosed on the side where there is less filler material on the U-profile web. The laminate has to fill the cavity due to the absence of filler material and the release film starts to wrinkle due to compression. The film is as a result enclosed in the resin. The way that the stringer shifts, either to the left or the right depends on which core is put in first. The first core pushes the stringers on both sides outwards or just one if it is not properly placed in the centre. This has in its turn also effect on the following cores that are placed in. The radiuses in the corner sections do not change, only the compaction of the fibres changes. If the radius would be different, it could also mean that the flanges are bending, since the outer contour of the finished panel follows the contour of the steel tooling if no dry spots are present. Therefore, the filler misalignment cannot be viewed from the outside. Next to the filler misalignment, the in-plane undulations in the corner section on the right side are also visible in the cross section. The light grey/white colour from the 90 degree ply in layer 2 in the right corner changes to an almost identical colour as the 45 degree ply. That means that the plies also change orientation, e.g. in-plane undulations. This indication is based on experience in examining the cross sections.

Thickness measurement

The thicknesses of the skin and stringers are displayed below in figure 6.39 and figure 6.40. The explanation on how the graphs are constructed is explained section 6.1.1.

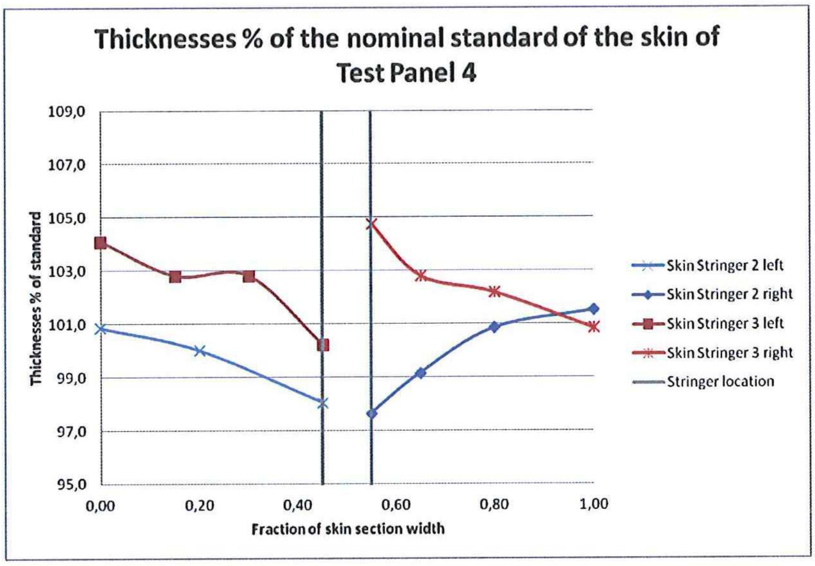


Figure 6.39: Panel 4: Thickness percentage of the nominal of the skin

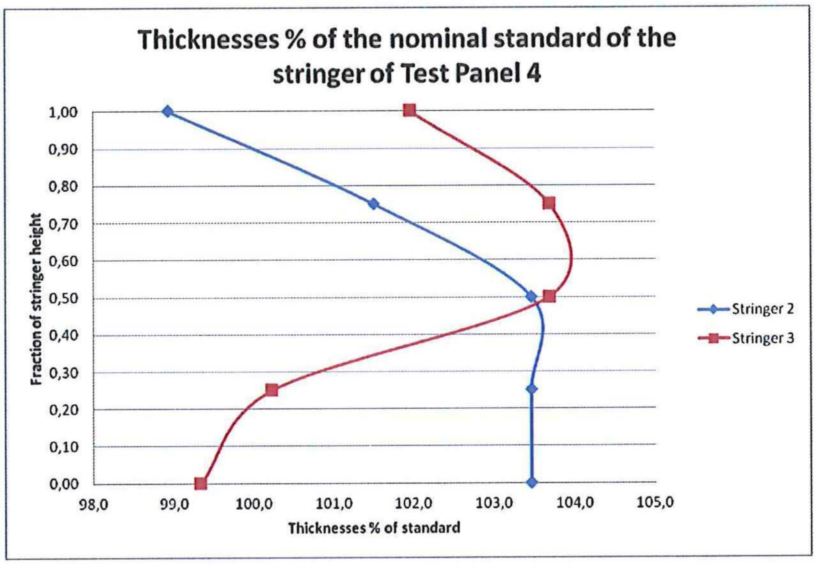


Figure 6.40: Panel 4: Thickness percentage of the nominal of the stringers

The thickness measurements can be seen in appendix D and the deviations from the tolerances in appendix E.
By looking at the thickness of the skin next to the stringers, it is noticed that for stringer 2. The thickness gets smaller in the vicinity of the stringer. This could mean that the corners of the cores are being pressed in the corners of the laminate. This also results in a stringer that is compressed more on the top than on the bottom. This corresponds with the thickness measurements of the stringer that are discussed after. On the left side of stringer 3, the thickness is decreasing with an increasing distance to the stringer. On the right side of stringer 3, the thickness is decreasing with an increasing distance from the stringer. This could indicate the interaction of the two cores 3 and 4 on both sides of the stringers in clockwise direction.

However, the differences are small, so these conclusions serve as assumptions.
However, from an absolute point of view, these thicknesses have a difference between the left and the right side of the stringer of only several hundreds of a mm. The difference of the skin thicknesses of the skin in stringer 3 has differences of up to 4%, which is a larger difference than in part 3. Still, no real meaningful conclusions can be drawn about this rotation and it serves as an indication only.

Interesting to notice is that the stringers 2 and 3 have a significant thickness difference between the two, especially because stringer 3 is thicker at the top than at the bottom, which is the other way around for stringer 2. For stringer 2, the thickness is 2,328 mm or 103,5% at the bottom and at the top 2,226 mm or 98,9% which is a difference of 0,107 mm. This indicates an almost perfectly straight stringer, where the values are well within the tolerances. Stringer 3 has a thickness of 2,235 mm or 99,3% at the bottom and 2,294 mm or 102,0% at the top and does not make the difference of 0,059 mm too significant.

Summary and conclusions

For this test part, the alteration was done that the autoclave cores are bigger than the preform cores. This is also the case in the actual process and it showed that it had an effect on the panel quality. The defect of the sideways filler misalignment was demonstrated to have a cause in using a bigger autoclave core than preform core. The misalignment of the filler can only be proven by evaluating the cross sections. However, an enclosed release film in the corner section and corresponding in-plane waviness originating from the corner section can be indications that the filler is misaligned. The in-plane waviness can be observed, both from outer and evaluation of the cross sections. The thicknesses of the skin and stringers isn‘t varying significantly and are all within the set tolerances.

6.2.2 Test panel 5: Preform core width smaller than autoclave core width

The fifth test panel that is manufactured will have the process variation that the preform cores are smaller than the autoclave cores. This process variation is similar to that of panel 4 where the same variation was introduced. In panel 4, only a small width difference was introduced between the preform and the autoclave cores of two layers of Tooltec per core. The main result of that variation was that the stringer was pushed over the filler material. The assumptions for increasing the width difference is that the plies of the stringers will be dragged down, causing slipped stringer plies and undulations instead of only the misalignment of the filler material.

Manufacturing

The manufacturing of the panel is similar to panel 4. Since the mould has constraints on both sides with maximum spacing between the edge bars, it was chosen, to have only two cores with width differences. The width difference is simulated in the same way as in the panels before by placing Tooltec tape on the cores after the preforming has been done. Core 1 has no width difference, core 2 has a width difference of 0,92 mm(4 layers of tape on each side), core 3 has a width difference of 1,84 mm(8 layers of tape per side) and core 4 has also no width difference. With these width differences, the maximum spacing between the edge bars was reached. The reason that those width differences were chosen was to have a doubling series, by combining panel 4 with 2 layers and in this panel with 4 and 8 layers. The graphical description of the situation, which is the same as for panel 4, is given again in figure 6.41.

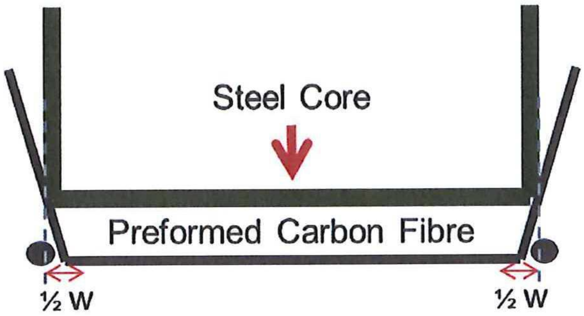


Figure 6.41: Schematical overview of the manufacturing alteration where the steel autoclave core is wider than the preform core

Core 1 is placed first, followed by core 4 and 2 and finally core 3. The order in which the cores are placed has an effect on the defects. The first core that is placed is able to have full contact with the web surface and will cause the stringer to shift outwards if the core is too wide. Then, the final cores will not be able to fit perfectly and will result in a hanging core. This is similar to the test panels 6 and 7, only the core is now resting on the filler material instead it is clamped by the flanges of the stringer. The higher placed cores 2 and 3 are shown in figure 6.42, including the simulated width difference in the autoclave cores.

Figure 6.42: Higher placed cores with a gap between core and laminate

The overview of the front and back of the panel after curing is shown in figure 6.43 and figure 6.44.

Visual Inspection of the part

By visual inspection, the following defects are observed:

- In-plane waviness
- Out-of-plane waviness
- Slipped stringer plies
- Dry spots (very few in the skin at core 2 and 3)

In addition to the standard in-plane undulations, in- and out-of-plane undulations are strongly present in the web skins 2 and 3, with the most present in the core 3 section. Because the

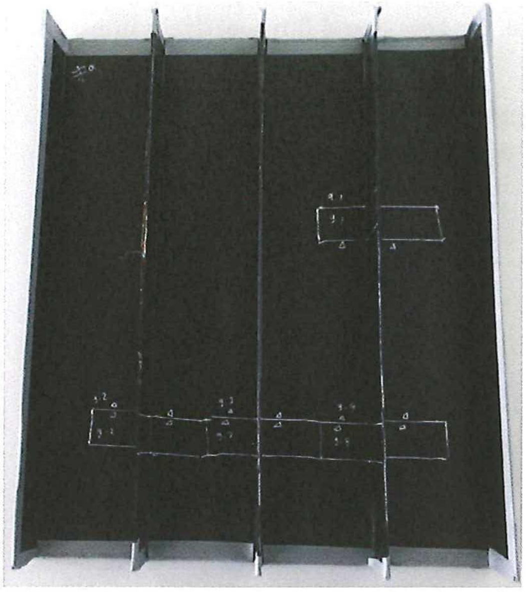


Figure 6.43: Panel 5: finished panel front view

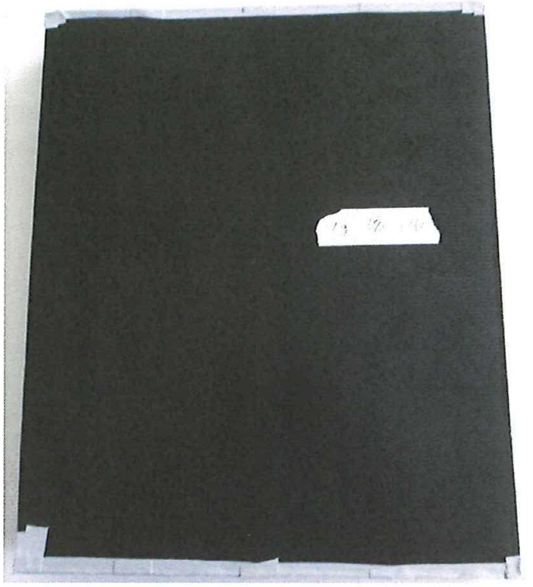


Figure 6.44: Panel 5: finished panel back view

autoclave cores are bigger than the preform cores, they don't fit properly on the skin. They are resting on the corner sections and as soon as the panel goes in the autoclave, the cores are pressed down, dragging the outer plies with them. This is similar to the 'hanging core' principle of panel 6 and 6. Therefore, also slipped stringer plies can be seen, although they are less severe than those of the previously manufactured panels. The slippage distance is about 2-3 mm for the inside of the flanges of the stringer sides adjacent to core 2 and 3. The slipped stringers plies are shown in figure 6.45.

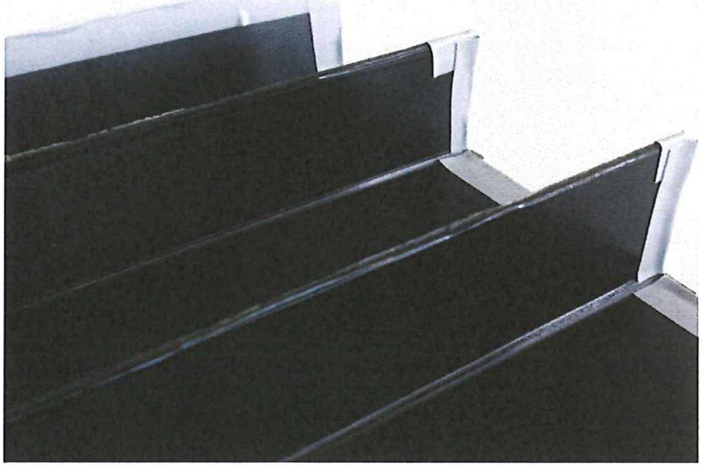


Figure 6.45: Slipped stringer plies in stringer 2 and 3

A difference to the undulations is that they are more strongly present on one side of the core than on the other side. This could originate from the order in which the cores are placed. As soon as the first core is placed, it pushes the stringer outwards, because of the width mismatch. This also goes for the next cores. When the stringer is shifted sideways, it is likely that undulations start to form on the convex side of the moved stringer due to the pressurization of the corner section. On the concave side, the corner is stretched out, resulting in fewer undulations. This would also indicate that the filler material might have shifted sideways. The in-plane waviness is shown for both the 4 and 8 layer width difference, for core 2 and 3 respectively in figure 6.46 and figure 6.47.

Figure 6.46: In-plane waviness in the skin on the inner mould line at core 2

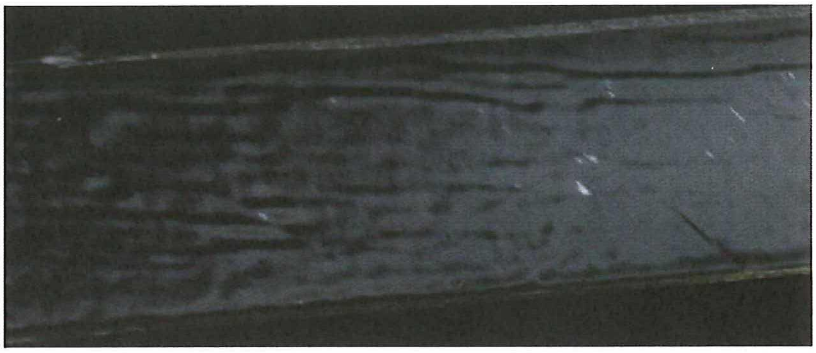


Figure 6.47: In-plane waviness in the skin on the inner mould line at core 3

When turning the part, the out-of plane undulations can be seen better due to a different deflection of the light and they correspond also to the in-plane undulations. They can be seen in figure 6.48 and figure 6.49.

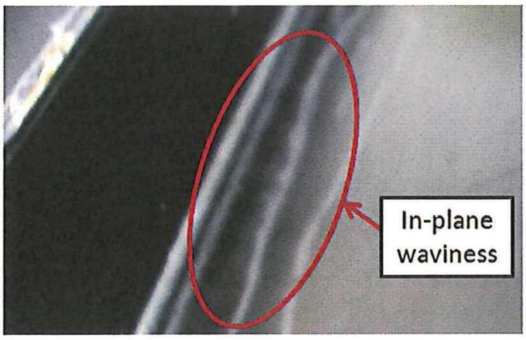


Figure 6.48: Out-of-plane undulations near the corner sections of core 2

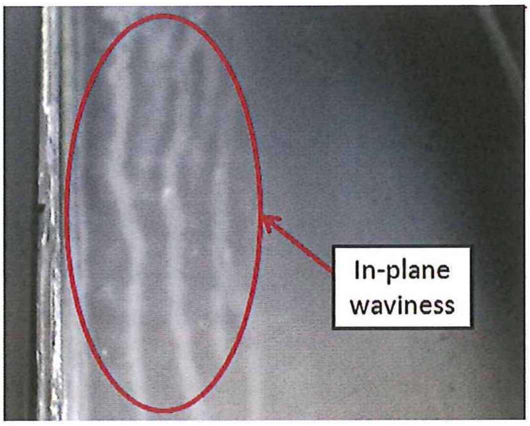


Figure 6.49: Out-of-plane undulations near the corner sections of core 3

Next to the slipped stringer plies and the in- and out-of-plane undulations, also dry spots are present in the web of core 2 and 3, but only to a small degree. These are caused by improper evacuation of the entrapped air, because the cores were not fully in contact with the laminate. This makes the compacting more difficult.

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.43.
The cross sections were taken in one plane for stringer 1, 2 and 3 to have a good overview on the defect progression for the different core widths. First of all, the misalignment of the filler material in horizontal direction is present for all the stringers. The misalignment is most severe for stringer 3 at core 3 where the width difference is the largest.
In stringer 1, the misalignment is observed with a large resin rich area on the side where the stringer moved to. Also, the resin rich area on the right side of the stringer corner is more severe than in test panel 4 due to a larger shifting of the stringer. This leads to the fact that the outer layer of the stringer formed a wrinkle in the corner section. The outer layer of the stringer is saturated with resin, because there is a cavity present on the right side of the stringer corner. The outer layer expands in thickness because of the extra space. This can be seen in figure 6.50.

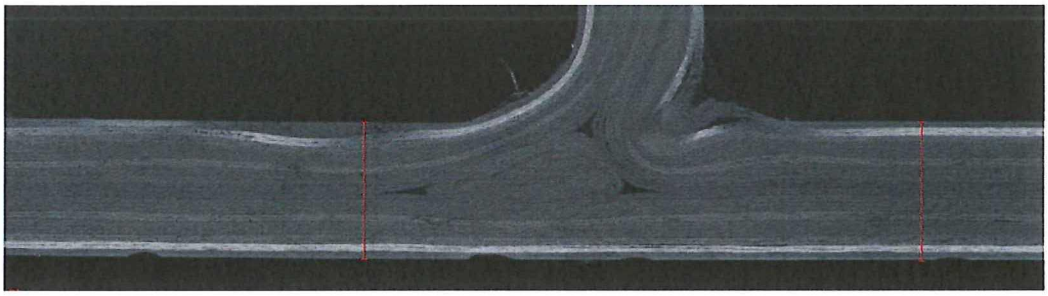


Figure 6.50: Expanding outer layer as well as in- and out-of-plane undulations and wrinkle in the right corner section in stringer 1

In that figure, also the in- and out-of-plane waves are observed, which originate from the corner sections. The in-plane waves are depicted as the colour change of the layers to a different grey scale. There is a lot of in-plane waviness in the middle of the laminate in the corner section, with around a 45 degree ply change orientation in some of the individual plies in the right corner section of figure 6.50. This indication is based on experience in examining the cross sections and is indicative only. On the concave side of the stringer intersection, slipped stringer plies of 3 mm are present on one side of the stringer, namely on the core 2 side. The slipped stringer plies in the stringer are shown in figure 6.51.

In stringer 2 there is a combination of the core width differences on both sides of the stringer. By looking at the intersection of the stringer and skin, more extreme waves and wrinkles and misalignment of the stringer can be seen when comparing to stringer 1. The wrinkles and shifting of the stringer is in the same direction as in stringer 1. This means that the whole core shifted in the direction of core 1. The fact that this stringer has shifted more, and that an extreme wrinkle is present on the side of core 2, corresponds with the fact that core 3 has a larger width than core 2. Core 3 pushed stringer 3 further away from its intended position. The cross section of stringer 2 is shown in figure 6.52.

Next to the larger wrinkle and misalignment of the filler, also in-and-out of plane undulations can be seen in both the corner sections as well as in the skin. When looking at the top of the stringer, the slipped stringer plies can clearly be identified on both sides of the stringer with a slippage of about 2 mm on each side. This is shown in figure 6.53.

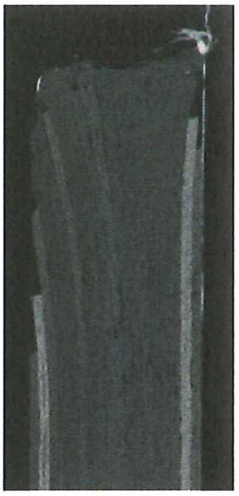


Figure 6.51: Slipped stringer plies in stringer 1 on the side of core 2

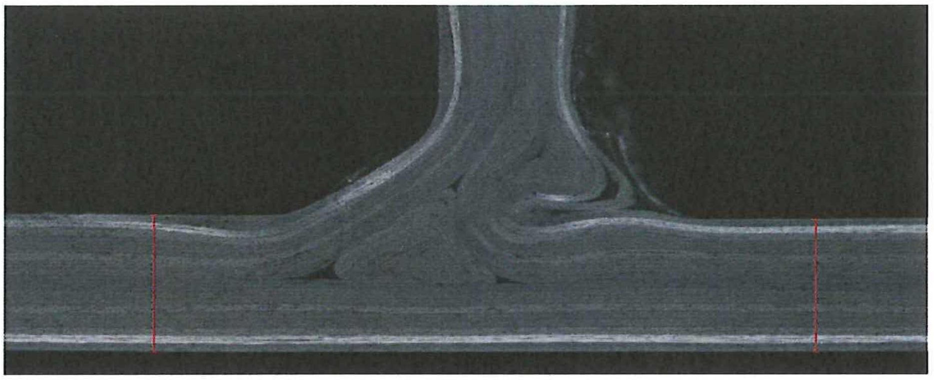


Figure 6.52: In- and out-of-plane undulations and wrinkle in the right corner section in stringer 2

Figure 6.53: Slipped stringer plies on both side of stringer 2

In stringer 3, the wrinkle and filler misalignment is to the other side compared to stringer 1 and 2. The wrinkle and undulations are less severe compared to the ones in stringer 1 and 2, but still present, see figure 6.54. Interesting to see is that the slipped stringer plies of 3 mm are on the other side of the stringer on the side of the core, see figure 6.55.

An explanation for this could be that the core 4 was pushed upwards when the other cores were pressed in. This can also be seen in figure 6.42 on the left side of the image that core 4 is not touching the skin of the laminate. In the autoclave, the outer ply is then pushed downwards,

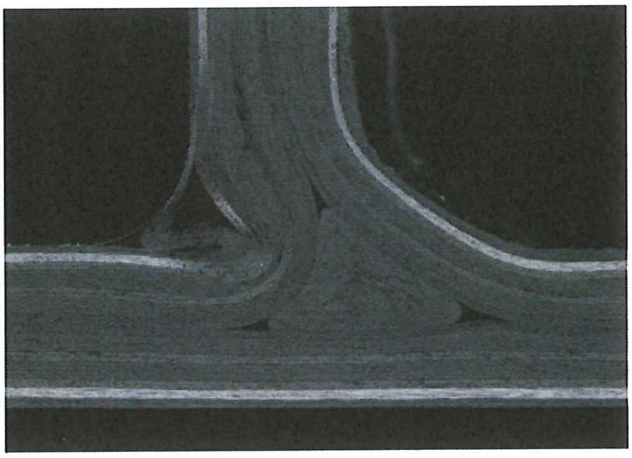


Figure 6.54: Wrinkle and undulations around stringer 3

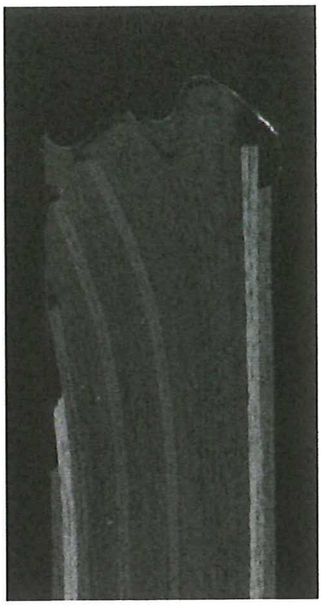


Figure 6.55: Slipped stringer plies in stringer 3 on the side of core 3

creating the wrinkle in the corner section. This shows the interaction between the cores. If one core moves in a direction less or more than the width difference that is present between preform core and autoclave core, it will influence the shifting distance and direction of the other cores.

Thickness measurement

The thicknesses of the skin and stringers are displayed below in figure 6.56 and figure 6.57. The explanation on how the graphs are constructed is explained section 6.1.1.

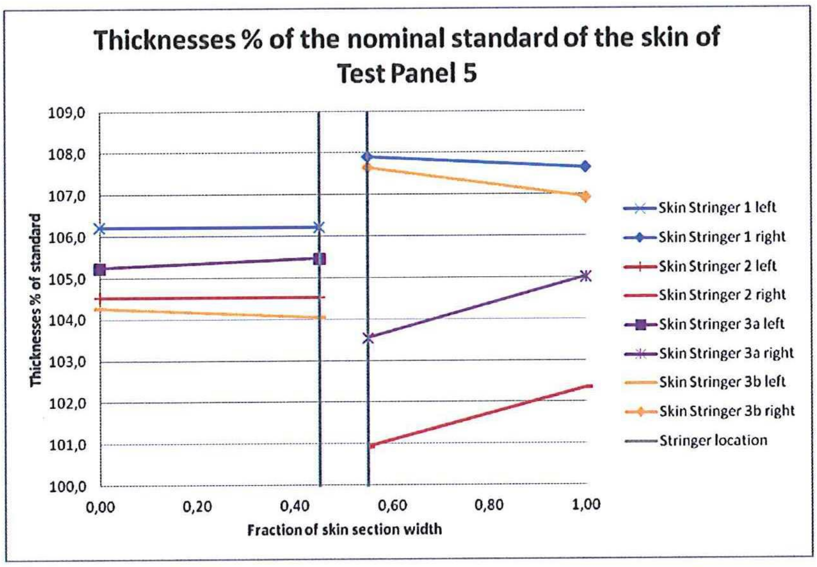


Figure 6.56: Panel 5: Thickness percentage of the nominal of the skin

The thickness measurements can be seen in appendix D and the deviations from the tolerances in appendix E.

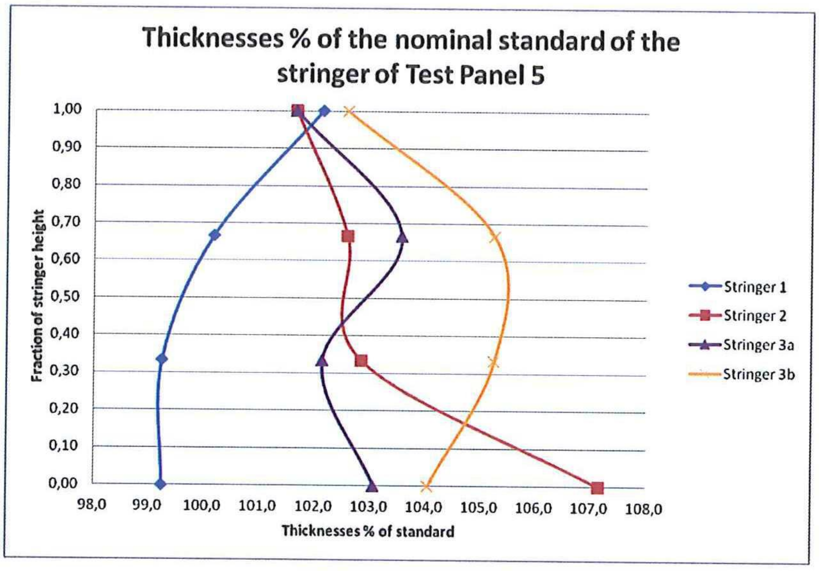


Figure 6.57: Panel 5: Thickness percentage of the nominal of the stringers

In this part, the autoclave core 2, between stringer 1 and 2, is 0,92 mm wider than the preform core and core 3, between stringer 2 and 3, is 1,84 mm wider. For stringer 1, the stringer gets thicker at the top side of the stringer compared to the bottom side. By looking at the skin thickness of the right of stringer 1 and the left side of stringer 2 it is seen that the skin is thicker on the right side of stringer 1. This means that the core has rotated clockwise which also resulted in the thicker stringer at the top.
In stringer 2 there is a large width difference between the bottom of the stringer where the thickness is 2,411 mm or 107,2% compared to 2,287 mm or 101,6% at the top. This is a difference of 0,124 mm. This width difference can be explained by the fact that there is a thicker autoclave core present on both sides of the stringer. As a result, the slipped stringer plies are present on both sides of the stringer, leading to fewer fibres in the top of the stringer compared to the other stringers. This means that the stringer will be thinner at the top. The stringer measurements at section 3a and 3b show similar results where the stringer of 3a is overall a bit thinner than 3b, probably due to the larger slipped ply distance.

Against expectations, the thickness of the skin does not clearly show the amount of undulations present in the skin. From panel 7 it was shown that only when large wrinkles are present in the skin, it becomes clear that there is a relation between the skin thickness and the degree of undulations.

Summary and conclusions

In the manufacture of test panel 5, the variation was introduced that the autoclave cores are wider than the preform cores. This is similar to that of test panel 4, with the change that the width difference is doubled for one core and quadrupled for another. The effects of increasing the width difference for two of the cores are significantly more than for the core width change in test panel 4. In this test part, the cores are resting on the fillers, creating a gap between the web of the steel core and the skin of the laminate. This creates similar defects as for the hanging core in test panels 6 and 7, combined with the defects from test panel 4. Now, in- and out-of-plane undulations are present with an increased severity for an increased width

difference. These undulations are visible from both the visual inspection and the evaluation of cross sections. The undulations are mostly caused by the slippage of stringer plies adjacent to the cores with increased width. The slipped stringer plies can be seen in both the visual inspection and the evaluation of cross sections. Wrinkles and filler misalignment defects are visible with the evaluation of the cross sections only. Similarly to panel 4, the stringer is pushed over the filler material where the core is wider than the skin between stringers. Instead of a resin rich area in the corner section, there are now wrinkles present.
From the thickness measurements, the main conclusion is that the thickness is not correlated to the degree of undulations that are present in the skin.

6.2.3 Test panel 6: Hanging cores

The sixth test panel that is manufactured will have the process variation that the stringer pack will be slightly compressed after the removal of the preform cores when all the cores are placed back in except for one core. The last core is not able to fit properly due to the change in width of the whole pack. As a result the core will be hanging on the flanges of the laminate and be pushed down in the autoclave.

Manufacturing

As stated in the introduction, the panel will be made with a so-called hanging core. The compressing of the pack when not all the cores are inserted back can also happen in the actual production due to the curved mould. With a curved concave mould, gravity could slightly move the cores inwards, making it difficult to insert the last core. Also, the pack could be of slightly different dimensions than the space available between the edge bars. The mismatch between preform and autoclave tooling could also be the reason that tooling does not fit properly and results in a hanging core.

During the manufacturing, the whole pack of stringers is compressed. During this step of the manufacturing process, the web of the U-profile laminates started to show waves. These waves formed when the preform cores were still inside the laminate, so the width dimensions of the laminate match the preform core widths. The reason for the waviness is probably that the clamps were not turned with equal speed, compressing one half first followed by the other. It could have also been because the cores were not lined up properly. The waviness was also clearly visible after turning when the preform cores were removed. At this point, the skin and filler were already stuck on stringer pack. The waves on the in- and outside of the stringer webs can be seen in figure 6.58 and figure 6.59.

All cores are placed back in, except for core 3, the edges are installed and the pack is compressed. As a last step, the remaining core is placed in, which will not fit due to the compression. The core is pushed in by hand as far as possible. This creates the so-called hanging core with a gap underneath the core.
A graphical representation of the situation is shown in figure 6.60.

The hanging core 3 in the actual production of the test panel can be seen for both sides in figure 6.61 and figure 6.62.

The core was hanging with a highest distance of 15 mm above the web of the U-profiles laminate. When examining the pictures, it can be seen that small waves are starting to form in the skin. The core end with the smallest distance from the web was fully pushed down, as soon as the vacuum bag was closed and the vacuum was applied. The side with the largest distance still

Figure 6.58: Waviness of the uncured stringer laminate on the outside of the stringer pack before turning

Figure 6.59: Waviness of the uncured stringer laminate on the inside of the stringer pack after turning

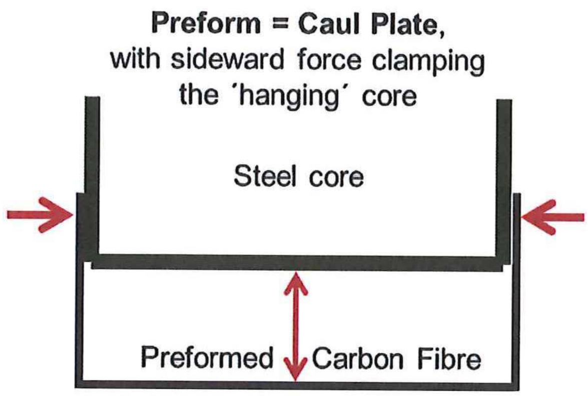


Figure 6.60: Schematical overview of the hanging core production process alteration

Figure 6.61: Hanging core on one side of the core with a height of 15 mm

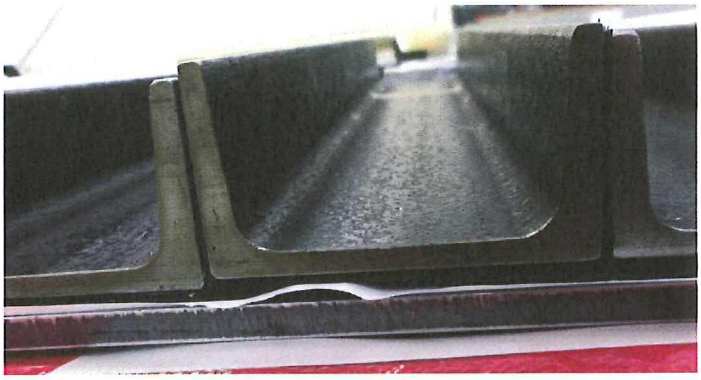


Figure 6.62: Hanging core on the other side of the core with almost no height difference

had a gap underneath it, even with the vacuum applied. By looking at the finished panel and the presence of the defects, it is clear that the gap is still present when the autoclave pressure is applied. As soon as the resin becomes liquid, the core is pressed down and the gap is closed.

The overview of the front and back of the panel after curing is shown in figure 6.63 - 6.64.

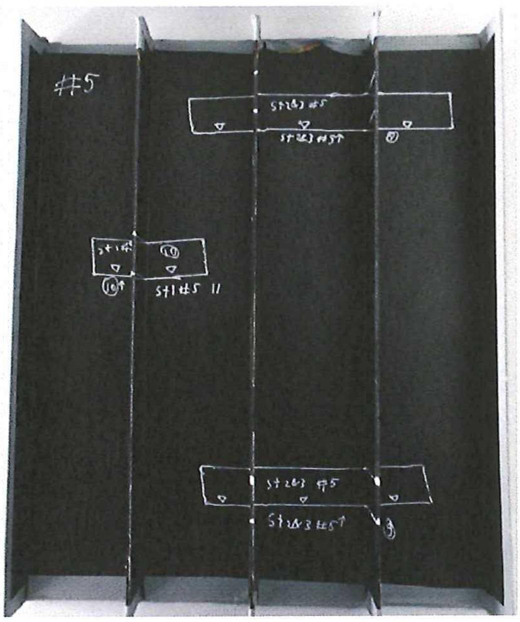


Figure 6.63: Panel 6: finished panel front view

Figure 6.64: Panel 6: finished panel back view

Visual Inspection of the part

By visual inspection, the following defects are observed:

- In-plane waviness between stringer 2 and 3 (core 3) in both the outer skin and web of the stringer U-profile
- Out-of-plane waviness between stringer 2 and 3 (core 3) in both the outer skin and web of the stringer U-profile

- Slipped stringer plies in stringer 2 and 3 at core 3

There is in- and out-of-plane waviness present in the web between stringer 2 and 3 where the hanging core 3 was introduced. This can be observed in both the outer skin on the outer mould line of the ground plate and the skin between the stringers on the inner mould line of the steel cores. A detailed view of the in-and out-of-plane waviness in the skin can be seen in figure 6.65 and the out-of-plane waviness in the outer skin can be seen in figure 6.66.

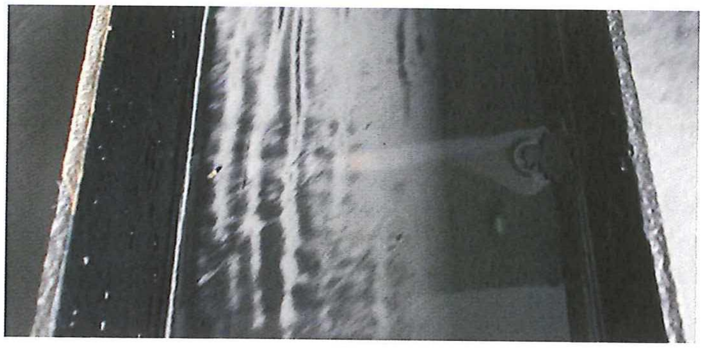


Figure 6.65: In-and out-of-plane waviness on the web of the stringer on the inner mould line

Figure 6.66: Out-of-plane waviness on the outer skin on the outer mould line

As soon as the vacuum was applied before the panel went in the autoclave, one side of the core was forced down already, but the other halve was still hanging. The in- and out-of-plane waviness can clearly be seen in both sides in the skin however they have different causes. On the outside of the skin, the out-of-plane waviness that is present is most noticeable. After compressing the pack with one core left out, the skin was also compressed and started to show waviness before the core was placed back in, see figure 6.61 and figure 6.62, because the skin was constrained on the sides it was not allowed to expand and straighten out in the autoclave. That is also why the waviness can be seen over the entire length of the core.
On the inside of the skin, both in- and out-of-plane waviness is observed. The cause for this waviness is that the core was clamped between the stringer flanges, because of the dimensional mismatch due to the compression. As soon as the temperature was increased in the autoclave and the pressure was applied, the outer (2-3) plies of the stringer started to slip downwards due to the friction with the core. Because the skin of the stringer was constrained on the two sides by the down pressing force of the adjacent cores, waviness starts to form both in- and out-of-plane

direction. The slippage of the plies can also be seen clearly at the top of the stringers on the side where the core was hanging. Here, the maximum slippage distance is 6 mm. The slipped stringer plies are shown in figure 6.67.

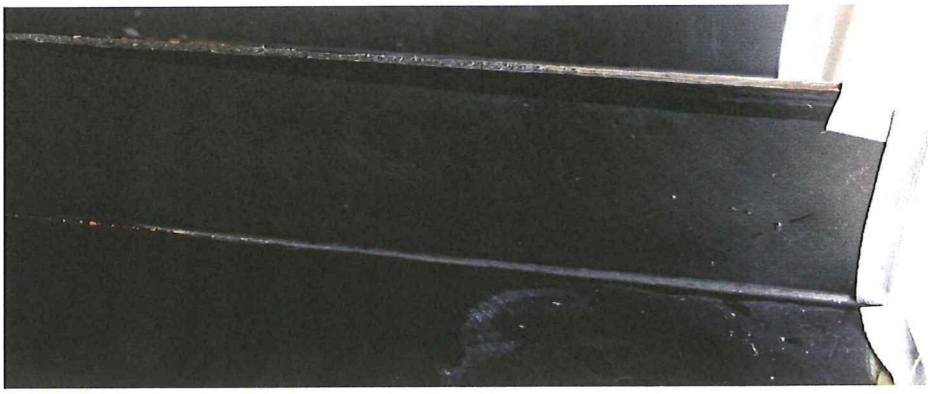


Figure 6.67: Slipped stringer plies on the stringer with the hanging core

As a comparison, the laminate at the other cores appears to be of a good quality with no defects present.

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.77.
The cross section at stringer 1 was examined as a reference that is used to check if the inner quality in the rest of the panel without waviness was affected by the hanging core. The cross section of stringer 1 is shown in figure 6.68.

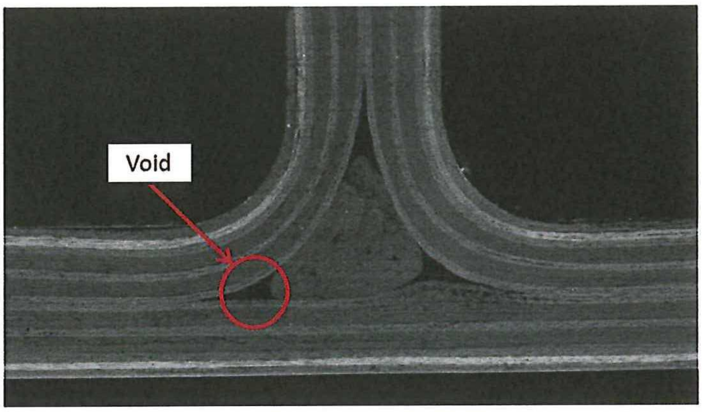


Figure 6.68: Cross section of the intersection of stringer 1 as a reference without the hanging core

The filler is in the correct location in the centre of the intersection. However, a small void can be seen on the left corner side of the filler. Apart from the void, the panel quality of stringer 1 is good, with no other defects. The reason of the presence of the void is most likely caused by the entrapment of air when the filler was placed on the pack and covered by the skin. The void is considered to be accidental and not representative of the overall stringer quality. On the other side of the cross section, there is no void present and it therefore considered to be a local phenomenon.
When looking at the cross sections of the stringers at core 3 where there are no slipped stringer plies present on the side where the core was not hanging, no defects can be seen. The waviness present in that section is hardly visible in the cross section. From the visual inspection for the

outer quality, it could however be seen that undulations were present. These undulations are therefore not caused by the slipped stringer plies, but by the constraining of the whole pack.

When the cross section of core 3 is examined on the side where the core was hanging, defects in the form of slipped stringer plies, stronger out-of-plane undulations and wrinkles in the corner section on both sides of the core in stringer 2 and 3 can be observed. These defects are shown in figures 6.69-6.71.

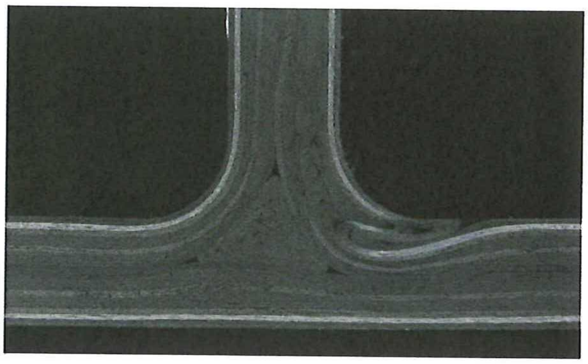


Figure 6.69: Wrinkle/fold in the corner section of stringer 2 where the hanging core was present

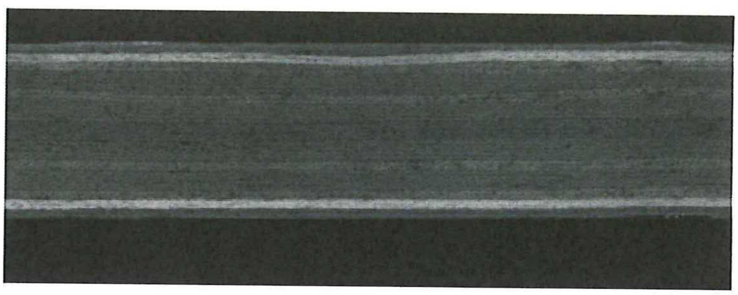


Figure 6.70: In- and out-of-plane waviness in the top layers of core 3 with the hanging core

Figure 6.71: Slipped stringer plies of 6 mm in stringer 2 with the hanging core

In the figure with the slipped stringer plies (figure 6.71), it can be seen that the outer two plies slipped the most. The slippage of the plies is directly translated in wrinkles and undulations, because the material needs to go somewhere. The explanation of the cause of the defects is explained in the outer quality section.
In figure 6.70, both the in- and out-of-plane undulations are present, where the in-plane waves are visible by the grey scale change in the top outer layer. The waviness in the panel is noticeable, but does not have a strong influence on the panel quality. Out-of-plane waviness does become a problem when the orientation of the plies greatly changes. As soon as forces are applied, the

plies cannot take up the loads properly, since they are not loaded in tension directly. Then, delaminations can then occur due to the inter laminar forces. The red line in figure 6.71 was used for the thickness measurement at that location

Thickness measurement

The thicknesses of the skin and stringers are displayed below in figure 6.72 and figure 6.73. The explanation on how the graphs are constructed is explained section 6.1.1.

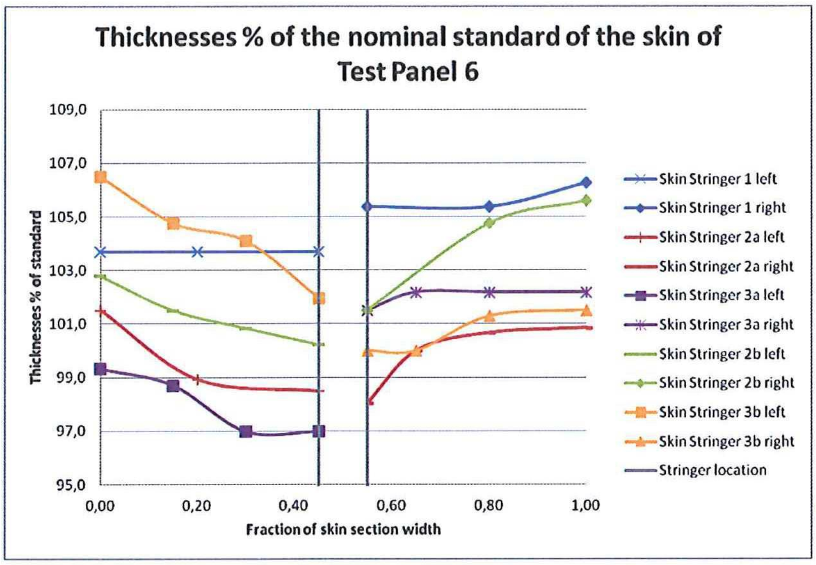


Figure 6.72: Panel 6: Thickness percentage of the nominal of the skin

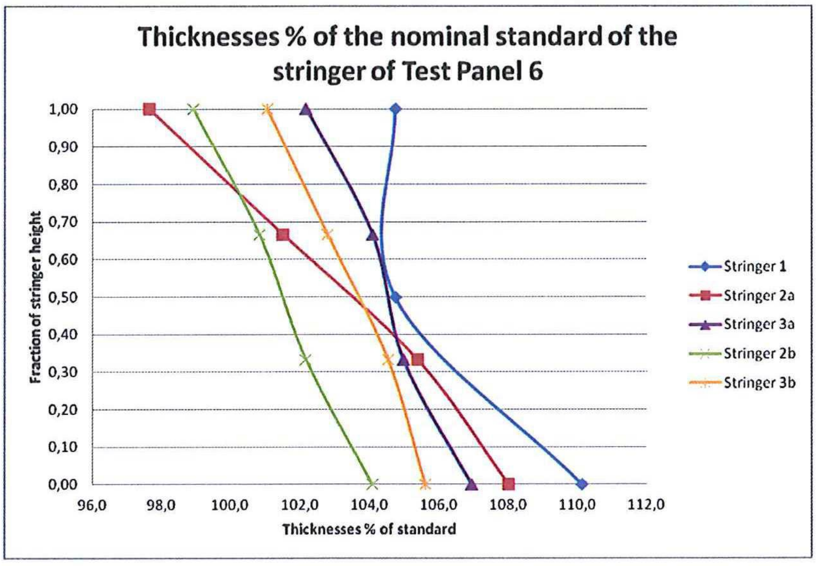


Figure 6.73: Panel 6: Thickness percentage of the nominal of the stringers

The thickness measurements can be seen in appendix D and the deviations from the tolerances in appendix E.

In this part, five different cross sections were examined of which the cross section in stringer 1 serves as a benchmark since no process alterations are induced in that stringer. The assumption is done that this stringer is influenced by the process alteration to a negligible extend. This assumption is validated by checking the inner quality, where no defects are detected in stringer 1, as can be seen in appendix D.
From both thickness graphs it can be seen that the thickness of the skin is almost perfectly straight on both sides. The stringer is however thicker on the bottom side compared to the top side. This panel is the first panel where the thicknesses are measured for all the stringers in the width direction. From these measurements, the thickness distribution over the entire width of the panel is monitored. A new unexpected effect is observed that occurs in the autoclave. When looking at core 3, which was also introduced as the hanging core, the thickness of the skin near the stringer is getting smaller on the right side of stringer 2a and 2b as well as on the left side of stringer 3a and 3b. In the middle of the core the thickness gets larger. The same is true about the other sides of the stringers 2 and 3.
However, from an absolute point of view, these thicknesses have a difference between the left and the right side of the stringer of only several hundreds of a mm. The difference of the skin thicknesses of the skin in stringer 3b has differences of up to 4,5%, At this value the skin thickness deviations start to become significant. Since the thickness deviations are consistent around all the stringers, where the skin is thicker in the middle of the skin compared to the thickness of the skin near the corner sections, the thickness deviations are suitable to draw conclusions.

As can be seen in figure 6.73, the stringers all are thicker on the bottom than on the top. The cores have the perfect shape before the autoclave with 90 degree angles in the corner section. However, the panel takes over the same shape as the core, because the core gives the outer shape to the part. From the observations that are made in the previous sentences, the core could not be rotated around the x-axis, because the corner sections on both sides of the core are pressing the skin in the corners and under pressing in the middle. Therefore, the conclusion is made that the shape of the cores changes in the autoclave either due to the increased temperature or due to the high pressure of 7 bars. As soon as the resin becomes liquid, the core is able to deform to a certain degree. If pressure is acting on the flanges of the core, they will rotate outwards, bending the web of the core. Due to the autoclave pressure that is also acting on the web, the core is pushed down in the corner section, resulting in a lower thickness. The cores have by then obtained a W-shape due to the finite stiffness of the cores. From here onwards, this effect is referred to as the W-effect and can be seen in figure 6.74.

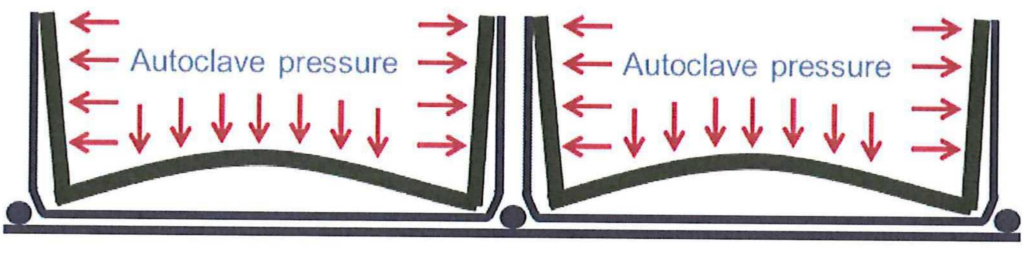


Figure 6.74: W-effect where the steel cores deform elastically due to the autoclave pressure

In the panels that are produced hereafter, the effect is observed even more clearly and can even lead to defects as for instance in panel 14. In addition to the applied pressure in the autoclave, the non uniform thermal expansion or the higher temperature in general can also play a role in the deformation. Further studies have to be performed to examine the effects of the cores in the autoclave and which parameters have an influence and to what degree. The effect is also observed to a certain degree in the actual panels, where also U-profiled cores are used, but since a different material (different stiffness, thermal expansion coefficient, etc) is used for the cores, different effects and severity of the deformation will occur. To monitor the W-effect and the severity of it, the recommendation is to do further testing with these and the actual carbon fibre cores

The process alteration that was introduced in this panel is the hanging core. Wrinkles are present in the corner section of that core as well as slipped stringer plies in the stringers. Comparing stringer 2a with 2b and 3a with 3b, it is seen that the thickness of the skin on average is much higher on the right side of the stringer in figure 6.72 of 2b and the left side of 3b compared to the same locations in 2a and 3a. With the highest thickness in the left of 3b of 2,396 mm or 106,5% compared to the same location in 3a of 2,235 mm or 99,3%. This is a difference of 0,161 mm. The extra thickness is a result from the hanging core and the extra plies that are present in the skin in the form of wrinkles. Also the two stringers at locations 2b and 3b are thinner on average compared to 2a and 3a.This can be explained by the slipped stringer plies, which causes to thinner stringers due to less material present.

Summary and conclusions

In this part, a hanging core was introduced in the production. This process alteration leads to defects, in the section where the core was hanging, in the form of slipped stringer plies and undulations in the in- and out-of-plane direction in both the skin and the web of the U-profile. The undulations in the skin are however caused by constraining the skin on both sides and the undulations in the web are caused by a combination of the slipped stringer plies and the constraining of the whole pack. These defects can be observed with both the inner and visual inspection of the part. In the evaluation of the cross sections, wrinkles in the corner sections are also present around core 3. The stringers are on average thinner with slipped stringer plies due to less material and the skin is thicker when wrinkles and undulations are present due to more material. The degree and distance of slipped stringer plies directly correspond to the degree of presence of wrinkles and undulations. So if slipped stringer plies are present, the inner quality has a significant chance of being affected negatively.
Also, the W-effect was found, whereby the core elastically deforms in the autoclave due to the pressure and/or temperature.

6.2.4 Test panel 7: Hanging cores

The seventh test panel that is manufactured will have the same process variation as panel 6 that one of the cores will be hanging. The reason that again a panel is manufactured that features a hanging is that the defects with the hanging core are reproducible. Secondly, some variations to panel 6 are introduced to see the effect on the severity of the defects. This time, two cores are present in the panel when it is being compressed instead of the previously used three, to see if the panel quality differs greatly from panel 6. The distance between the core and skin is now also increased.

Manufacturing

The manufacturing of test panel 7 is similar to that of panel 6, but as said before it will have some small deviations compared to that panel. It has the difference that both core 2 and 3 are taken out. This is done to see if the removal of two cores has an effect on the defects in the part. The pack is compressed and secured with the two cores taken out, followed by the placing in of core 2. Since core 3 is not present at the moment, core 2 was able to fit better due to the ability to push stringer 2 away than the core in test panel 6. Core 3 is inserted last, with the change that the hanging core will be at a height from the laminate skin of 24 mm on one side and 2 mm on the other, compared to 15 mm and 0 mm of panel 6. So the main deviation is that the gap will be wider to see how the severity of the defects increases with a higher hanging core. Core 3 can be seen in figures 6.75 and 6.76.

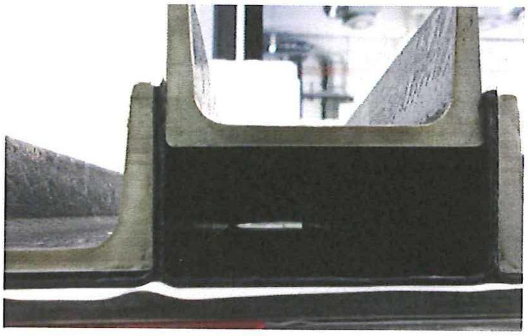


Figure 6.75: Hanging core with a height of 24 mm, front view

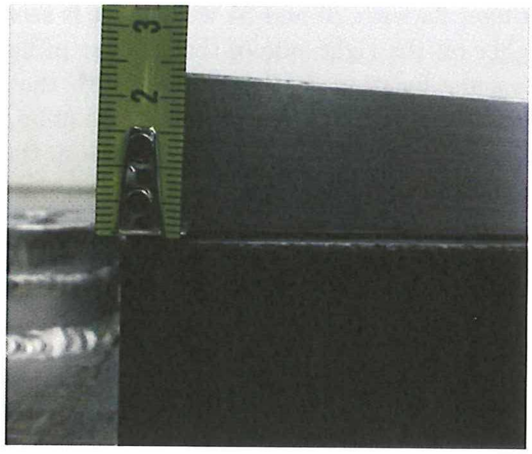


Figure 6.76: Hanging core with a height of 24 mm, side view

In figure 6.75 it can be seen that core 2 on the left is not completely touching the skin of the laminate, due to the lack of available space for the core to fit completely.

The overview of the front and back of the panel after curing is shown in figure 6.77 and 6.78.

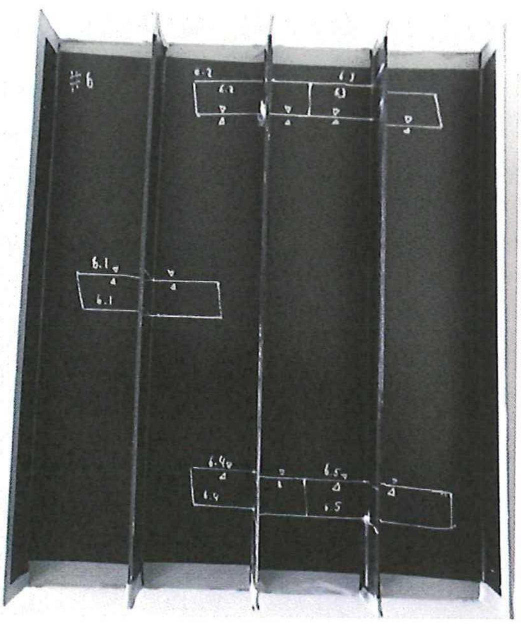


Figure 6.77: Panel 7: finished panel front view

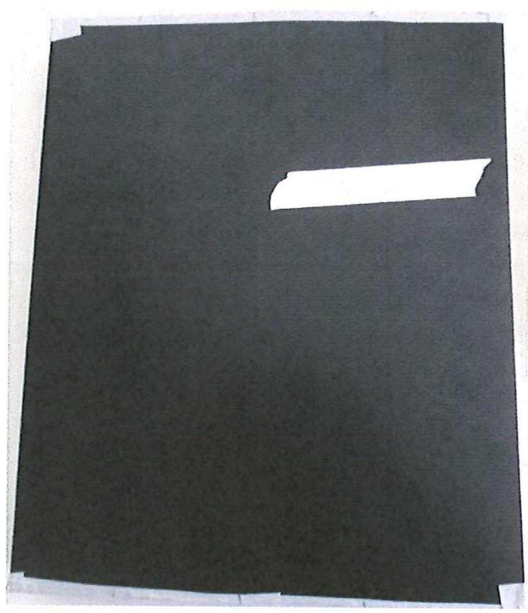


Figure 6.78: Panel 7: finished panel back view

Visual Inspection of the part

By visual inspection, the following defects are observed:

- In-plane waviness
- Out-of-plane waviness (very strongly)
- Slipped stringer plies (very strongly)
- Dry spots

The panel showed no defects in the area of core 2 when looking at the outside. At core 3, the same defects as for the hanging core in panel 6 can be seen. The slipped stringer plies are present on both stringers 2 and 3 on the side of core 3 and can be seen in figure 6.74, for stringer 3. The distance over which the outer ply slipped has 20 mm, which is 4 mm less than the height of the core 3 above the laminate skin. The difference is assumed to occur by the autoclave pressure, pushing the core down 4 mm. As soon as the resin becomes liquid, the plies start to slip until the core touches the laminate skin and can be seen in figure 6.79

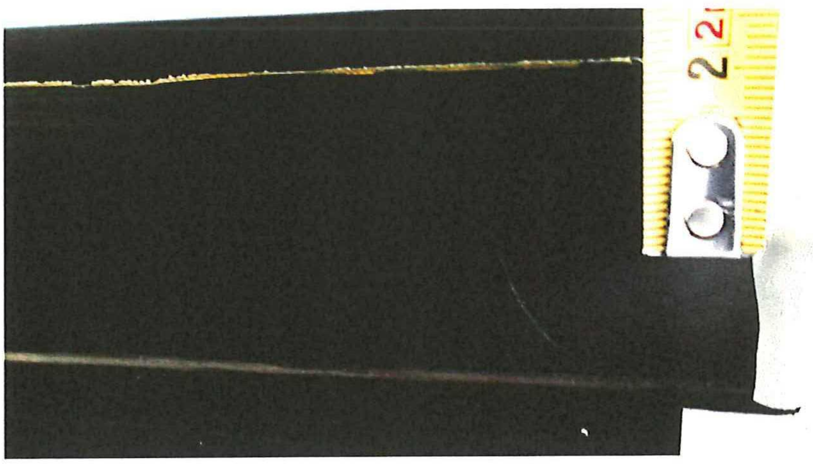


Figure 6.79: Slipped stringer plies in stringer 3 with a distance of 20 m

Additionally, out-of-plane undulations are present to a higher degree than in test panel 6. This is also the same for the in-plane undulations. These results prove that the in- and out-of-plane waviness is reproducible with the hanging cores and intensifies when a hanging core has a larger distance from the skin. Additionally, dry spots are observed on the inner skin of core 3. This can be explained by the fact that the core was hanging higher than for panel 6 and that the core was not able to compact the laminate properly to evacuate the air out properly. The in-plane, out-of-plane undulations and the dry spots in core 3 can be seen in figures 6.80 and 6.81.

The in-plane undulations are better visible in figure 6.80 and the out-of plane undulations in figure 6.81.The undulations are more intense near the corner sections of the stringer than in the centre and the dry spots are located more in the centre of the laminate.

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.77. The in-plane undulations in the skin can clearly be seen in the cross sections, in several layers, in figure 6.82.

Figure 6.80: In-plane, undulations and the dry spots in the web of the stringer at core 3 where the hanging core was present

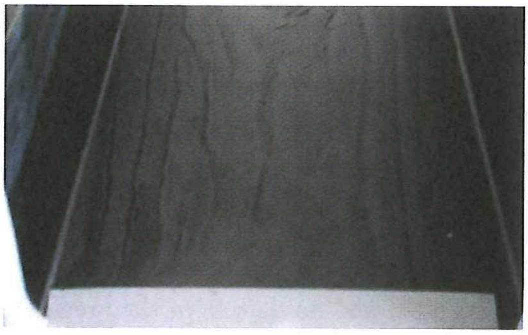


Figure 6.81: Out-of-plane undulations and the dry spots in the web of the stringer at core 3 where the hanging core was present

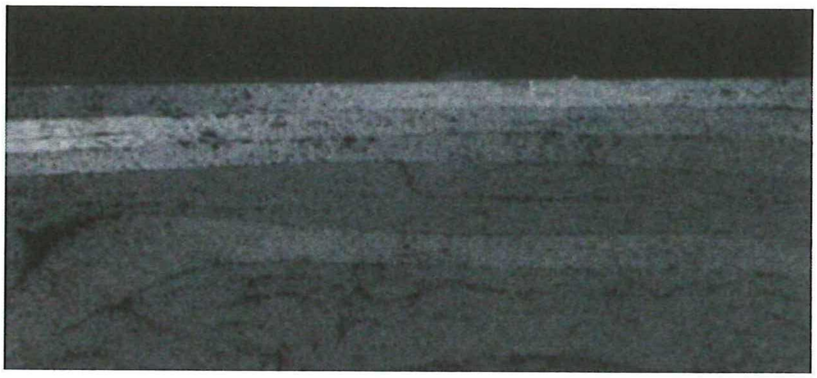


Figure 6.82: In-plane undulations in the layers

The top layer is changing from a 45 degree layer to a 90 degree layer by looking at the change of colour from dark grey to very light grey. The reverse happens in the second layer, where the 90 degree layer changes either to - or + 45 degrees. The layers thereafter are also changing to a different orientation. This indication is based on experience in examining the cross sections.

The out-of-plane undulations are dominant throughout the skin and even form wrinkles in some locations. The undulations are however only present in the top half of the skin laminate which was previously the web of the U-profile and not the skin laminate (bottom 9 layers). That is logical since the plies of the stringer are being forced down, creating the undulations, and the skin remains unaffected. The skin laminate is however compressed less or more depending on the location across the width of the part. The out-of-plane, together with in-plane undulations are shown in figure 6.83.

In the top of the stringer cross section, the slippage of the stringer plies is clearly portrayed on the side of core 3 of stringer 3. The slippage is shown in figure 6.84.

In total, more than halve of the stringer plies have slipped, with the outer ply slipping 17,2 mm and the second ply 14,6 mm. The open space above of the slipped plies is filled with the other, non-slipped, plies that bend towards core 3. The material, just as in core 5, is pushed down and creates the undulations in the skin. Next to the undulations, wrinkles are formed in the

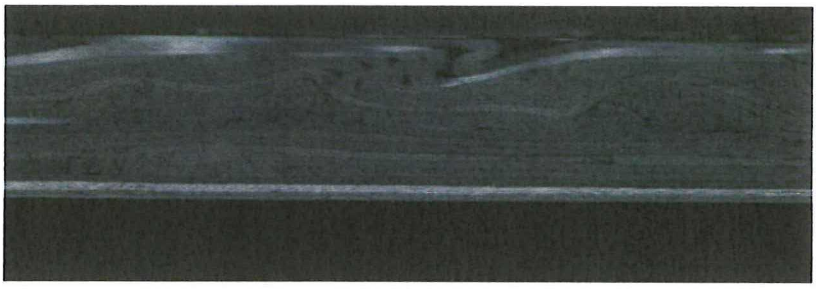


Figure 6.83: In- and out-of-plane undulations in the layers

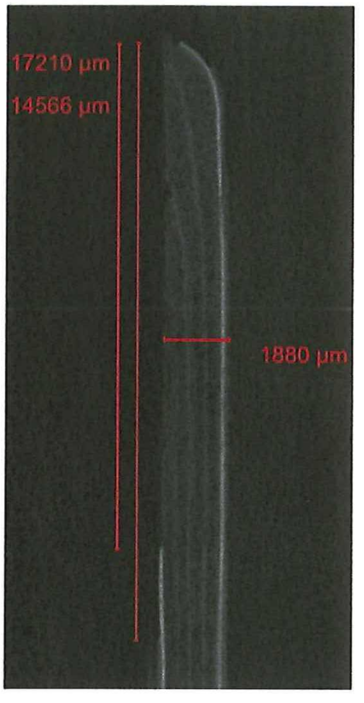


Figure 6.84: Slipped stringer plies in stringer 3 over a distance of 17,2 mm

corner sections. As can be seen in figure 6.85, not only wrinkles are formed with the outer plies, but also the quality of the inner plies is affected. Large internal undulations are observed in the centre of both the stringer and the web of the U-profile.

Thickness measurement

The thicknesses of the skin and stringers are displayed below in figure 6.86 and figure 6.87.

The thickness measurements can be seen in appendix D and the deviations from the tolerances in appendix E. In this part, also five different cross sections were examined of which the cross section in stringer 1 serves as a reference benchmark since no process alterations are induced in that stringer. It is assumed that this stringer section is affected to a negligible extent. These cross sections are at similar locations as in panel 6.

The process alteration that was introduced in this panel is also the hanging core but then with a height of 24 mm compared to 15 mm. Wrinkles are present in the corner section of that core as well as slipped stringer plies in the stringers.

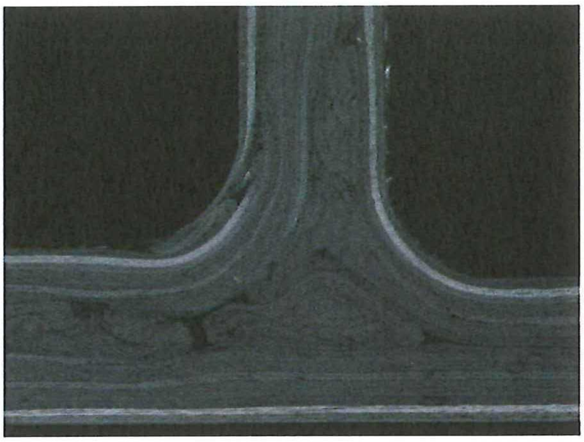


Figure 6.85: Wrinkles and large internal undulations present in the intersection of stringer 3

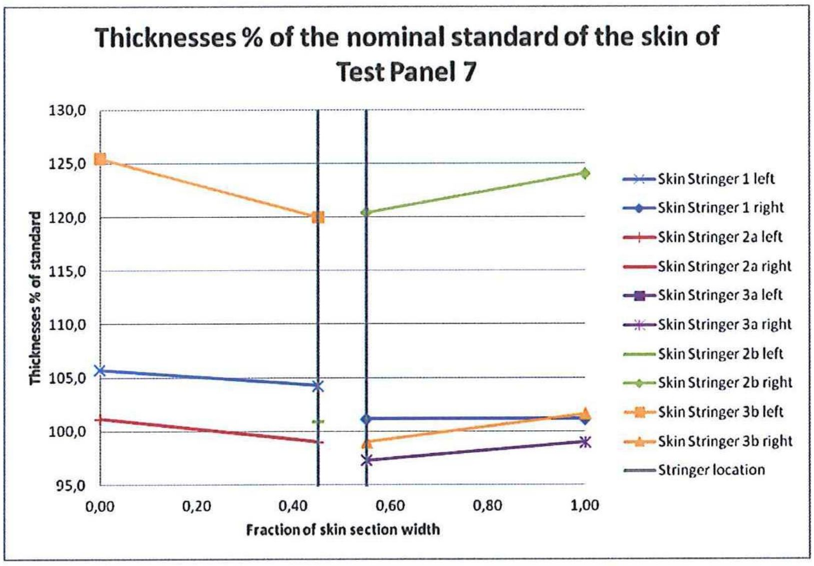


Figure 6.86: Panel 7: Thickness percentage of the nominal of the skin

Comparing stringer 2a with 2b and 3a with 3b, it is seen that the thickness of the skin on average is much higher on the right side of 2b and the left side of 3b compared to the same locations in 2a and 3a. This is an identical behaviour as for panel 6, but with a larger thickness between the hanging side of the core and the non-hanging side. The highest thickness is in the skin on the left of 3b of 2,823 mm or 125,5% compared to the same location in 3a of 2,276 mm or 101,2%. This is a difference of 0,547 mm. The extra thickness is a result from the hanging core and the extra plies that are present in the skin in the form of wrinkles and large out-of-plane undulations. Also the two stringers at locations 2b and 3b are much thinner on average compared to 2a and 3a.This can be explained by the slipped stringer plies, which causes thinner stringers due to less material present. In core 3, the W-effect is also observed since the core presses down in the corner section and is thicker in the centre of the skin.

Summary and conclusions

In this test part, a hanging core was introduced, similar to test panel 6, with the difference that the panel was compressed with two cores present. The last core that was placed in was hanging with a height of 24 mm above the laminate skin before the vacuum was applied. It is assumed

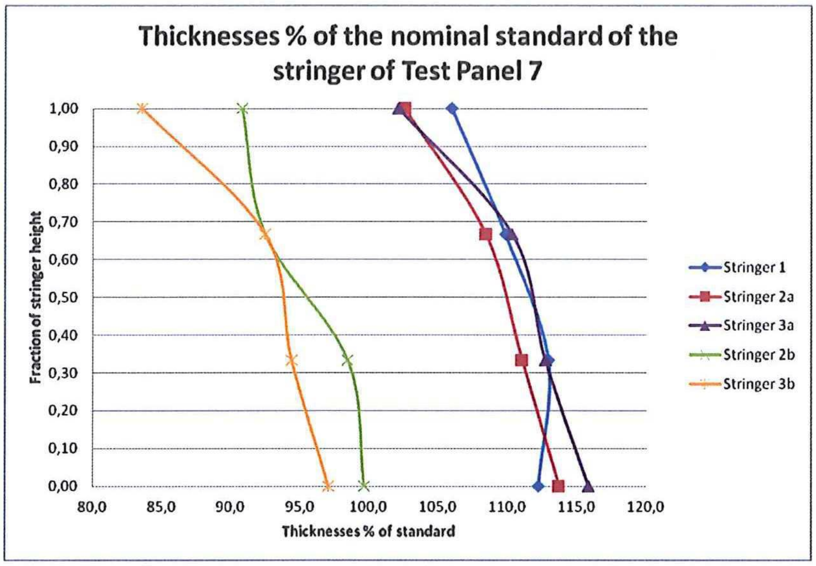


Figure 6.87: Panel 7: Thickness percentage of the nominal of the stringers

that in the autoclave it was pressed down to a height of 20 mm by visual inspection. From that point the resin becomes liquid and the individual plies start to slip. This leads to large undulations. These, together with additional dry spots, can be observed from during visual inspection. The undulations are more severe than for test panel 6, but of the same order. When evaluating the cross sections, there are a lot more undulations in the top half of the skin which was previously the web of the U-profile compared to panel 6. In panel 6, only the top layers are affected slightly with waviness. In this part, wrinkles are present in the corner sections and in the top half of the skin. As a conclusion, it is stated that the inner quality cannot be seen by visual inspection, because of a similar outer quality compared to panel 6 and a different inner quality. The only indications that the inner quality shows undulations is the larger thickness of the skin at the hanging core section compared to the thickness of the skin where the core is not hanging. This is to a larger degree when comparing the defects to panel 6.

6.2.5 Test panel 8: Preform core width larger than autoclave core width

The eighth test panel that is manufactured will have the process variation that the preform cores will be larger than the autoclave cores. The reason that this process variation is considered is because of the tooling dimensional mismatch between the preform cores and autoclave cores in the actual production. Another reason is to simulate the dimensional mismatch of different thermal expansion coefficients between the two tools.

Manufacturing

The manufacturing process is identical as the panels before. The simulation of this panel can be seen as an extension of the test panel 3, where the preform cores were also slightly bigger than the autoclave cores. The change in test panel 3 was introduced to compensate for the expansion of the steel cores compared to the actual carbon fibre cores. The principle is the same with this panel and Tooltec material is placed onto the flanges of the preform cores and is removed when they are placed back for the autoclave cycle. In panel 3, only one layer of Tooltec of thickness 0,115 mm per layer was placed on the flanges. This principle was also introduced in the panels

thereafter.
For these panels, width differences of 0,46 mm(2 layers of Tooltec tape per side) in core 1 and 2 and 0,92 mm(4 layers of tape per side) in core 3 and 4 are introduced. A graphical overview of the process alteration is given in figure 6.89, where w is the width difference between the preformed laminate and the autoclave core.
How the width difference looks in the actual manufacturing of the panel is shown in figure 6.88, for the width difference of 0,46 mm.
The overview of the front and back of the panel after curing is shown in figure 6.90 and figure 6.91.

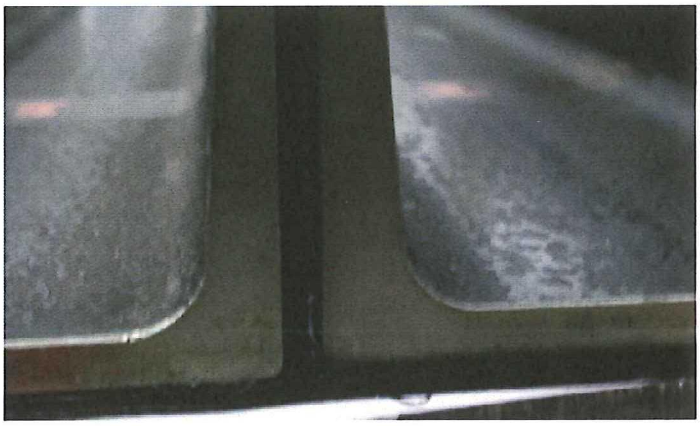


Figure 6.88: Width difference in the production of the test panel after inserting the autoclave cores

Figure 6.89: Graphical overview of the process alteration for when the steel autoclave cores are less wide than the preform cores

Visual Inspection of the part

By visual inspection, the following defects are observed:

- In-plane waviness
- Filler indentations

In the bottom skin of the panel, it can be seen that there are slight dents along the length of the filler location which are shown in figure 6.92.

This could indicate that the filler material has shifted upwards, because the indentations look similar to the indentations seen in test panels 1 and 2.

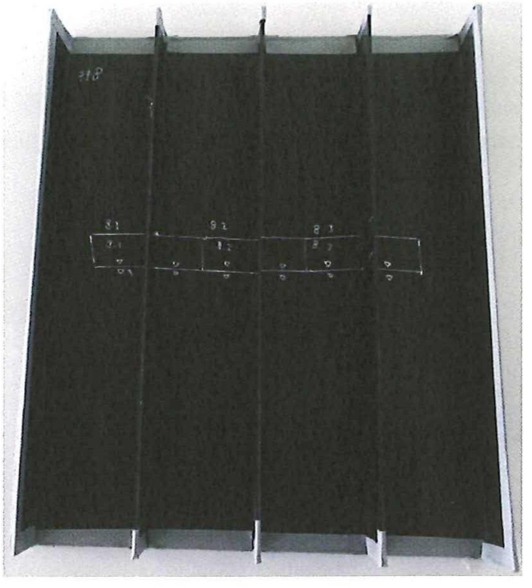


Figure 6.90: Panel 8: finished panel front view

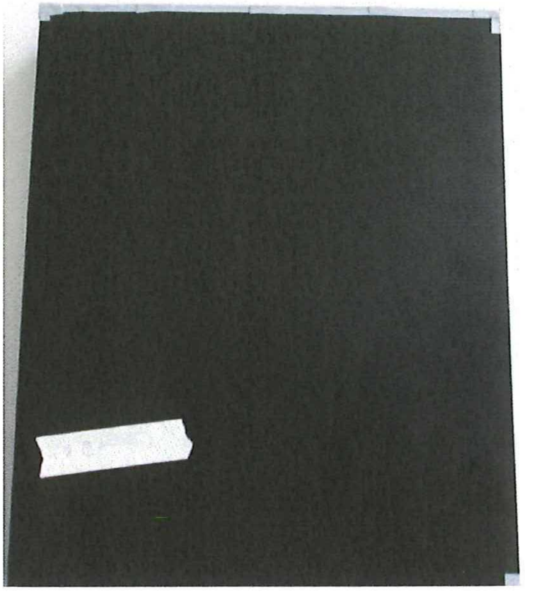


Figure 6.91: Panel 8: finished panel back view

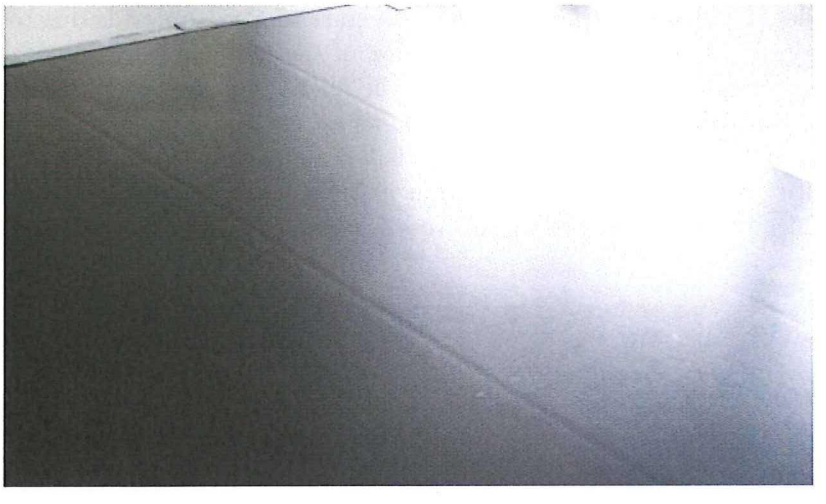


Figure 6.92: Indentation at the location of the filler on the back of panel on the outer mould line

Similar to test panel 12 with the pushing down of the stringer, in-plane undulations are observed in the stringers instead of the skin. The presence of the undulations can be explained by the fact that the preform core is larger than the autoclave core. From figure 6.89, it is visualised that with the cavity present and the autoclave pressure pushing from the right side, panel of the skin laminate, filler and the stringer want to be pushed to the left. As soon as the width difference w is 0 mm, the skin, filler and stringer material is pushed upwards. By the movement of the fibres from the skin into the stringer, the amount of fibres starts to build up. Since it is constrained from movement on the top and the movement of fibres upward, they start to show waviness. The waviness is stronger for the stringer 1 with the width difference w of 1 mm, compared to stringer 3 with the width difference w of 2 mm. Both stringers and their corresponding waviness are shown in figure 6.93 and figure 6.94.

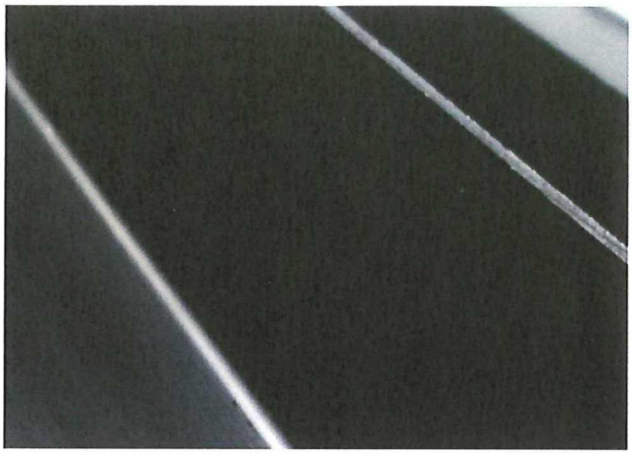


Figure 6.93: In-plane waviness in stringer 1

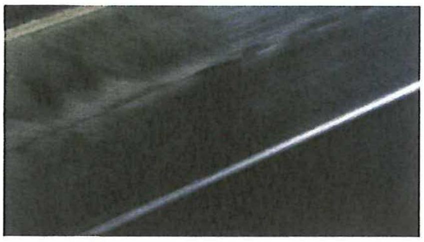


Figure 6.94: In-plane waviness in stringer 3

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.90. Looking at the cross sectional image it can be seen that the filler material has shifted upwards. This happens for a similar reason as for test panels 1 and 2. As soon as the autoclave pressure is applied and the temperature is increased, the stringers will be pressed together to fill the cavity between laminate and core. The stringer plies together with the filler and skin start to move upwards due to the decreased viscosity of the resin as was explained as the cause of the in-plane waviness in the stringers in the outer quality section. The end result is that the filler is not located at its intended position anymore. Also, the skin underneath the filler shows an extreme wave that follows the contour of the stringers and filler on one side and the flat ground plate on the other side. This can also be seen clearly from the visual inspection as the filler indentation on the skin. This is explained graphically in figure 6.89 and the cross section of the shifted filler material in stringer 3 in figure 6.95.

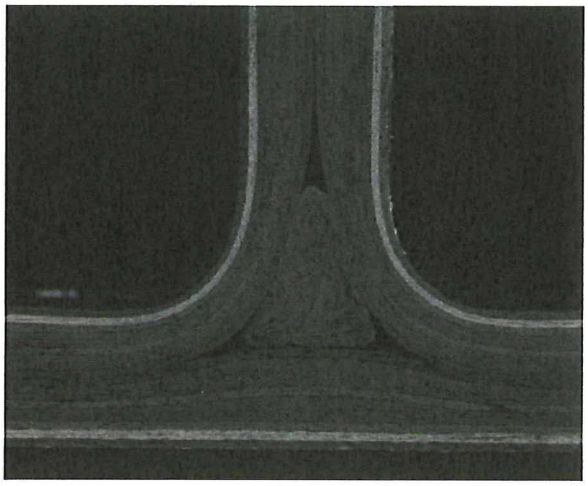


Figure 6.95: Indentation at the location of the filler on the back of panel on the outer mould line

Surprisingly, there is not that much difference between the shifting of the filler materials in the three different cross sections for the two different width differences.
Examining the cross sections of the stringers, the in-plane waviness is observed in the outer ply. This is similar as for test panel 12, where the stringer is pushed down. In this case the stringer is pushed up with extra material from the skin because of the width difference between

the cores, but the compressive forces are the same. The cross sectional images of the stringer and the corresponding waviness are shown in figure 6.96 and figure 6.97.

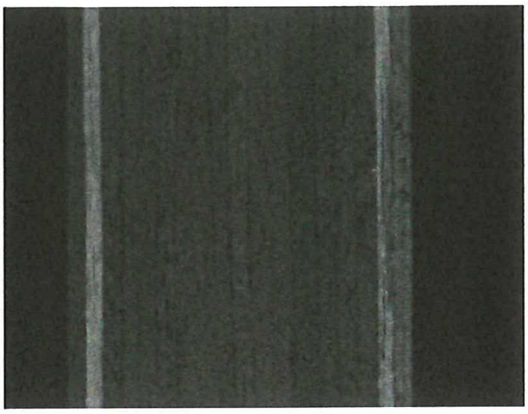


Figure 6.96: In-plane waviness in stringer 1 seen from the cross section

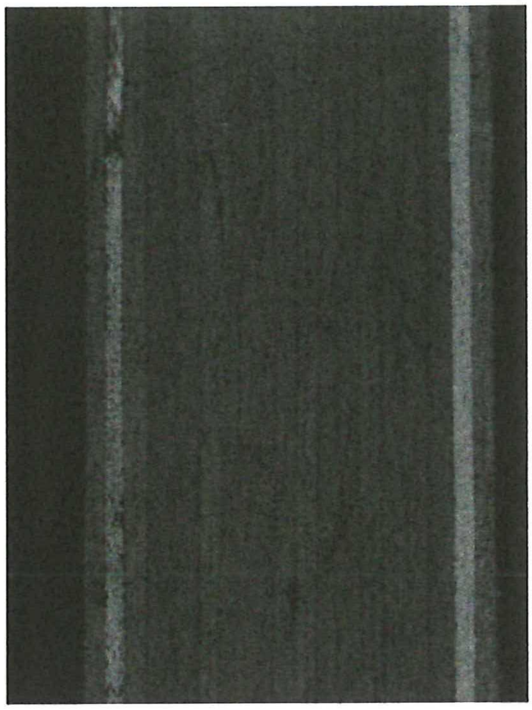


Figure 6.97: In-plane waviness in stringer 3 seen from the cross section

Thickness measurement

The thicknesses of the skin and stringers are displayed below in figure 6.98 and figure 6.99. The explanation on how the graphs are constructed is explained section 6.1.1.

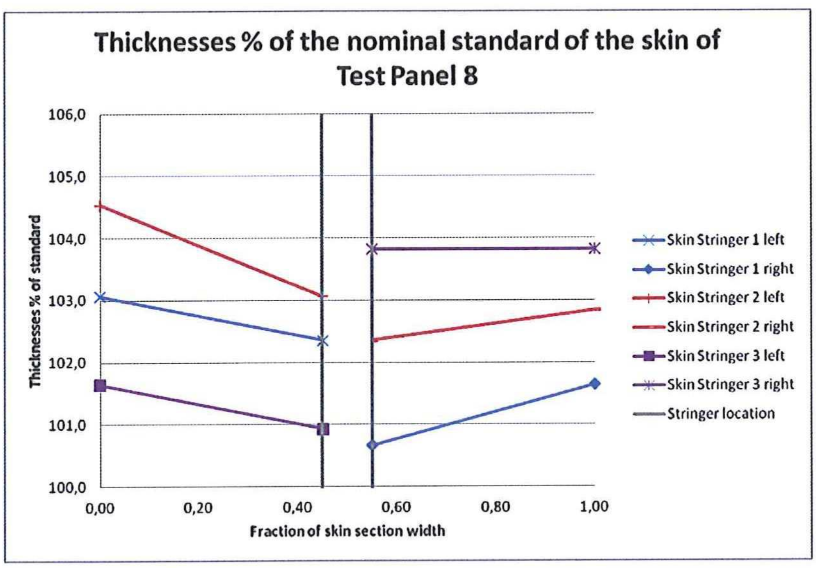


Figure 6.98: Panel 8: Thickness percentage of the nominal of the skin

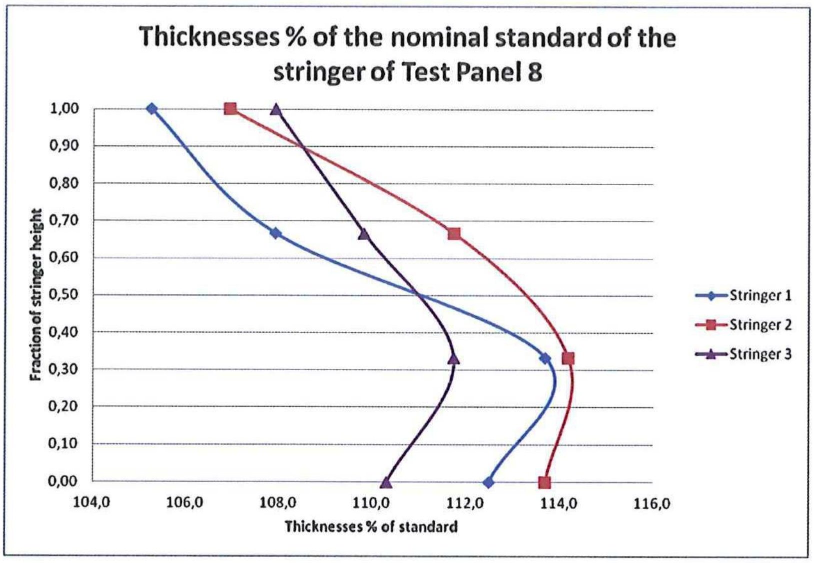


Figure 6.99: Panel 8: Thickness percentage of the nominal of the stringers

The thickness measurements can be seen in appendix D and the deviations from the tolerances in appendix E.
For these panels, width differences of 0,46 mm in core 1 and 2 and 0,92 mm in core 3 and 4 are introduced. The thicknesses of the skin are similar for the three cores, but they are all above the nominal thickness. In all the three cores, the W-effect can be seen, since the cores are pressing down more in the corner sections of the skin and less in the middle of the skin.
Of main interest for this process alteration are the stringer thicknesses. From a certain point of view is this process alteration of having smaller autoclave cores than preform cores similar to that of having too high stringers as in panel 12. The cores are pressed together to fill the cavity, forcing the stringer upwards. The stringer is compressed from the top and this also causes the undulations in the stringers as described before. The same thickness variations are observed in the stringers as for panel 12. The stringers are thickest in the centre of the stringer instead of the bottom or the top. Comparing stringer 1 and 3, it is seen that stringer 1 is thicker at the bottom with a thickness of 2,531 mm or 112,5% compared to the thickness at the bottom of stringer 3 of 2,482 mm or 110,3%. This is a difference of 0,049 mm. For the top of the stringers it is the opposite that stringer 1 is thinner than stringer 3 with a thickness of 2,368 mm or 105,2% for stringer 1 and a thickness of 2,428 mm or 107,9%. In other words, the thickness variation of stringer 1 is more extreme than for stringer 3, even though that the width difference is smaller of the cores. The assumption is that the cores have an effect on each other, where for instance the width difference influences the there neighbouring laminate thicknesses. If one core does not shift, then the other core needs to shift twice as much in order to fill the hole.
The same explanation is given for that the stringers are thicker in the centre than at the top or the bottom as for panel 12 The assumption is that the stringer is compressed from the top, resulting in the compaction of the stringer in the centre.

Summary and conclusions

In this test part, the preform cores were wider than the autoclave cores to simulate the mismatch in tooling geometry in production. From the defects it can be concluded that, next to wrong preforming, the filler material shifting upwards can also be caused by having a wider preform compared with the autoclave core. Indications for the shifting of filler material can be noticed on the outer quality of the panel in the form of filler indentations and small in-plane undulations in the corner sections. These are only indications and it can only be said with certainty that the filler movement is present in the panel if the cross section is checked. The presence of the in-plane undulations in the stringer indicates that there is an axial compressive force acting on it. In the case of this panel it is caused by the pushing up of extra material from the skin. These undulations can be seen both in the inner and outer quality check. In addition to the similar undulations as for panel 12, the same thickness variations in the stringers are observed where the stringers are thickest in the centre compared to the top and the bottom.

6.3 Panels with core movement

In the actual production process, the autoclave cores can be either misplaced in longitudinal direction or shift in the autoclave due to the autoclave pressure. These core movements and misplacement are assumed to be the cause of several of the defects that are currently present in the actual panels. In panel 9, described in section 6.3.1, the cores are misplaced before the autoclave cycle in x-direction. In panels 10 and 11 respectively, the cores are rotated in the autoclave in the xy-plane (section 6.3.2 and are shifted in the autoclave in y-direction (section 6.3.3.

6.3.1 Test panel 9: Core movement in X-direction with ramps

As the first panel of the new series, defects are simulated in the x-direction of the panel which is in the length direction of the stringers as can be seen in figure 5.10. In the actual flaps there are ramp ups in the panel where the thickness of the laminate is increased locally by adding plies between the skin and the web of the U-profile. The increased thickness gives an increased strength and stiffness to the section where the mounts are located that connects the flap to the rest of the wing. A possible cause for the defects in the flaps is that the cores are shifted in x-direction and when they are misplaced.

Manufacturing

The manufacturing of the test panel to simulated the shifting of the cores in x-direction is done is a similar way as for the previous panels, with the difference that a ramp needs to be build in the laminate as well as its negative shape on the tooling cores, to contour the section. This needs to be done in a precise way in order to mimic the accuracy of the lay-up and tooling of actual production. In actual production there are three ramps present with different layups. Every 15 mm in x-direction there is a ply step. So the length of a ply is 30 mm longer than the one on top of it. In the original part, the shortest and thus, the top layer of the ramp is 365 mm. Since the test panel is only 400 long, the ramp needs to be sized, keeping the same distance for the ply steps. In the ramp section test layup, 12 layers are present, which corresponds to 5 ply steps. In the total test panel, 6 ply steps are present, because the ramp is placed on the skin laminate leading to an extra ply step from ramp to skin laminate. The 5 ply steps for the ramp correspond to a length of 75 mm for one side. This means that for the ply steps a total length of 150 mm needs to be considered. The remaining 250 mm is divided in 80 mm skin length with the ramp on either side of the ramp, which leaves 90 mm for the smallest top ply of the ramp instead of the original 365 mm. The lay-up and the length of the plies that are used for the test panels can be seen in table 6.2.
The ramp is installed in the middle across the entire width between the skin and stringer laminates. Therefore, the ramp section has a total outer surface of 240x320 mm. The laminated ramp section is shown in figure 6.100.

Table 6.2: Lay-up and length of the plies of the ramp

Ply nr (from the top)	Orientation (degrees)	Length of the ply(mm)
1	45	90
2	45	90
3	90	120
4	-45	120
5	90	150
6	-45	150
7	90	180
8	90	180
9	-45	210
10	90	210
11	-45	240
12	90	240

Figure 6.100: Laminated ramp section

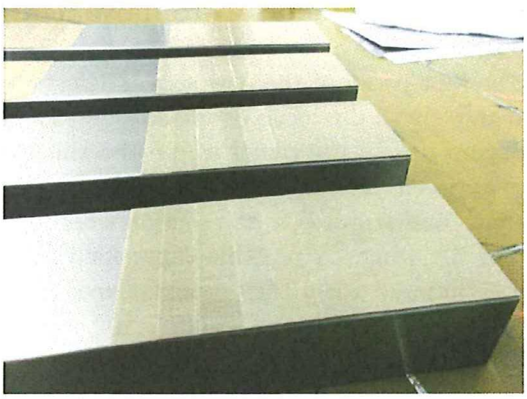


Figure 6.101: Inverted ramp on the tooling

The negative shape of the ramp is the surface of the tooling. This inverted ramp is constructed using Tooltec tape. These ramps are identical for each of the cores and can be seen in figure 6.101.
The rest of the build-up is identical to the previous panels and the laminates of the U-profiles are preformed with the ramps in the tooling present. The ramp will have an influence on the shape of the flanges of the U-profiles of the laminate, but since these are cut to length after the preforming the presence of the ramp will not influence the shape of the stringers. After the cores have been compressed, the filler material is placed in followed by the ramp and the skin. The placement of the ramp is shown in figure 6.102.

The main alteration in the production process is that the cores are being shifted. Core one will be the reference core, with no movement and the other cores will be shifted a distance that corresponds to a calculated thickness increase of the ramp. The overview of a perfectly fitting ramp is showed in figure 6.103 as well as what happens if the ramp is shifted in x-direction by

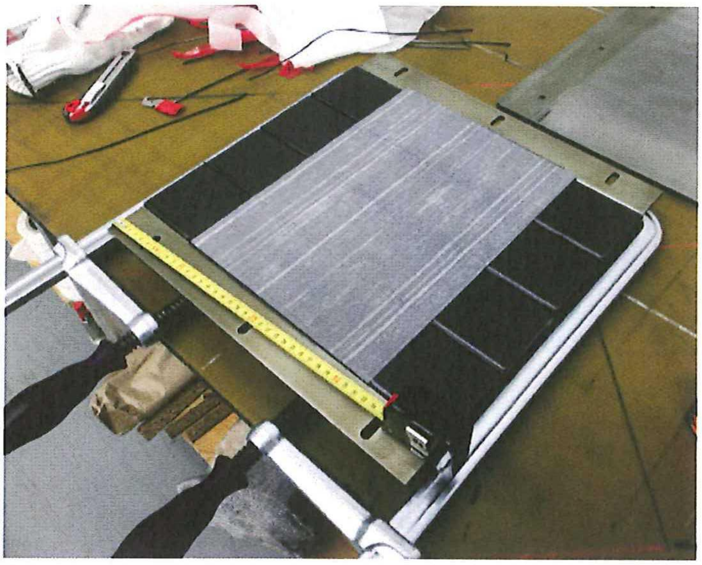


Figure 6.102: Placement of the ramp

a distance w in figure 6.104.

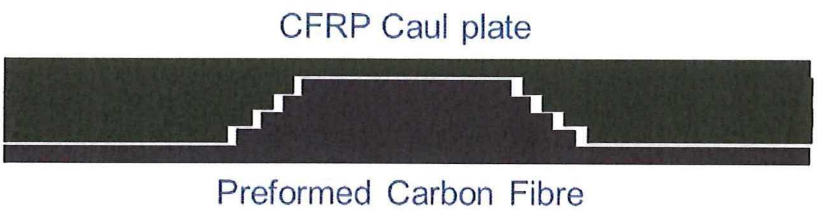


Figure 6.103: Overview of a perfectly fitting ramp

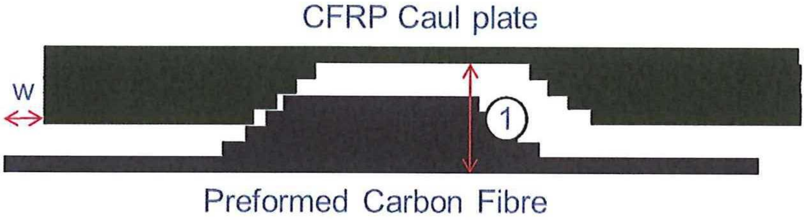


Figure 6.104: Overview of the shifted ramp in x-direction

It can be seen that as soon as the tool is shifted in x-direction, a cavity arises at location one, because the core is also moved up. The tools are shifted before the autoclave cycle so that resin will fill the cavity. The distance w that the tools should shift is dependent on the thickness increase at point 1. There will however also be cavities present on both sides of the ramp. The assumption is that increasing the thickness will lead to movement of fibres leading to defects. A visual representation of the shifting of the tooling is shown in figure 6.105.

In order to achieve a thickness increase, w needs to increase in order to increase t%. In order to calculate the theoretical thickness increase, the angle of the tooling (θ) is kept constant. This angle is calculated to be 1,15 degrees by using l=75,0 mm and t is 0,125x12=1,5 mm. The corresponding calculated values of w for a thickness increase of the ramp laminate of 0%, 5%,

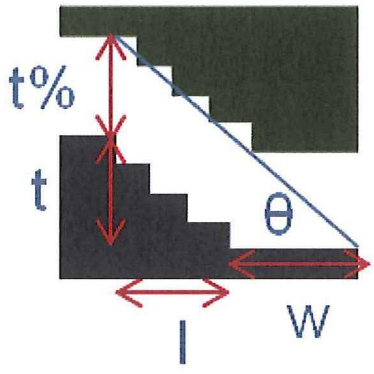


Figure 6.105: Overview of the dimensions for the shifted core

Table 6.3: Shifting of the cores compared to the thickness increase

Core	Thickness increase	W (mm)
1	0%	0
2	5%	6,4
3	10%	12,8
4	20%	25,6

10% and 20% in cores 1, 2, 3 and 4 respectively is shown in table 6.3. In the actual production, shifting of the cores has been observed that have values of 15 mm, so the shifting distances that are examined are assumed to be realistic.

The shifting of the cores on the test panel is shown in figure 6.106. After the shifting of the cores, the vacuum bagging is done in the identical way as was done for all the other panels.

Figure 6.106: Shifting of the cores in the test part

The overview of the front and back of the panel after curing is shown in figure 6.107 - 6.108.

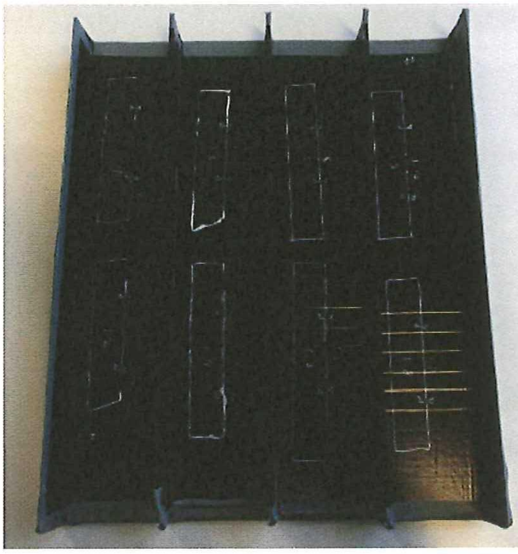


Figure 6.107: Panel 9: finished panel front view

Figure 6.108: Panel 9: finished panel back view

In these images, cross sections are also indicated on the front side. In this part, the defects are examined in x-direction, so no cross sections are taken from the stringers.

Visual Inspection of the part

By visual inspection, the following defects are observed:

- In-plane waviness
- Dry spots
- Resin rich areas

The increase in thickness leads to an increase in fibre undulations and dry spots. The dry spots start occurring in the stringer in core 3 and to a small degree in the ramp section with the cavity. In core 4, the dry spots are also present on the end of the core in addition to large dry spots in the ramp section. The dry spots in core 3 and 4 are shown in figure 6.109 - figure 6.111.

These dry spots in the ramps are explainable since the core has a cavity present, which increases for an increasing distance w. However, the core also rotates slightly due to the misplacement when the autoclave pressure is exerted on the core. The visual representation of the rotation is shown in figure 6.112.

A cavity is present on one side of the ramp at location 4 and 5, so the core will rotate down until it rests on the laminate. This leads to a cavity on the other side of the mould, resulting in dry spots and undulations. These in-plane undulations can also be seen in figure 6.110 It is also noticed that the ramp with the cavity becomes darker brown for an increasing shifting distance of the respective cores, see figure 6.112. Cured resin has a brown colour, so a darker brown colour means that there is more resin present in that area, which corresponds to the fact that the resin is filling the cavity.

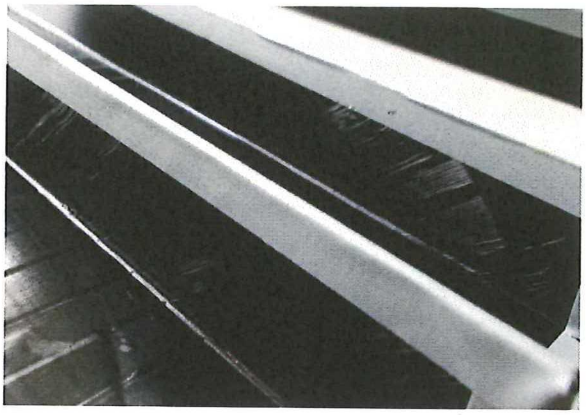


Figure 6.109: Dry spots in the stringers

Figure 6.110: Dry spots at location 1 in core 4

Figure 6.111: Dry spots at location 4 in core 4

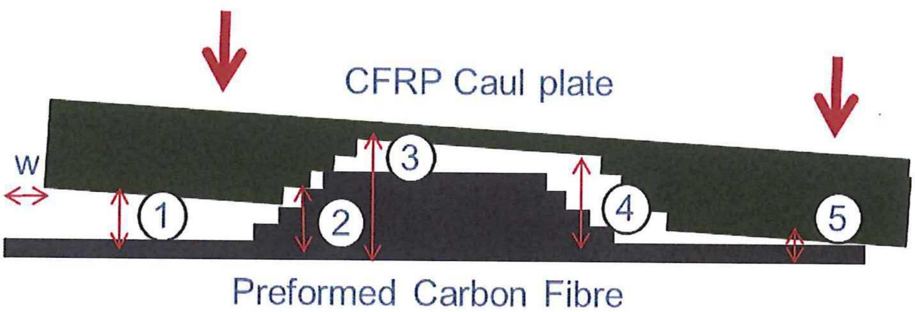


Figure 6.112: Overview of the rotation of the core due to the shifting

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.107. The views are also indicated in that picture. The complete images can be seen in appendix D which include all the thickness measurements of the cross sections.

As for the inner quality of the part, the most noticeable is that the location of the ply steps corresponds less with the location of the matching ramp on the tooling with an increased shifting distance w. This is of course logical, since the shifting of the tool will lead to a different location of a ramp with respect to the ply step location. The distance between the tooling ramp location

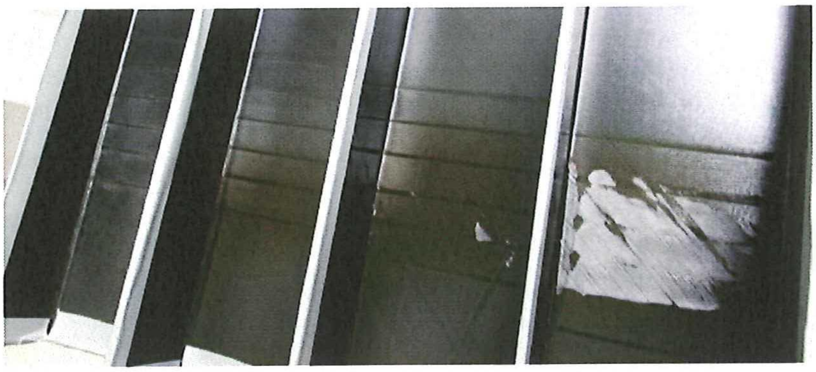


Figure 6.113: Increasing severity of brown areas for an increasing shifting distance

and the ply step in the laminate corresponds directly to the shifting of the tool. An overview of the shifting of the ply step locations and the ramp location differences is given in appendix D and in the thickness analysis below. The shifting is obviously the most severe in core 4. As an example the ramp with the cavity in cross section 1.1 is shown in figure 6.114. The red line in the figure comes from the thickness measurement, and has no further meaning with respect to the defects.

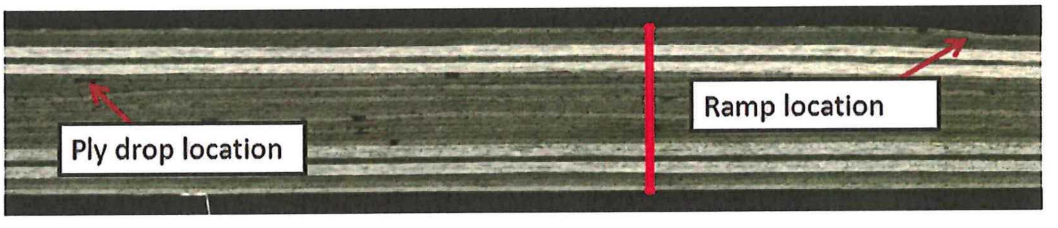


Figure 6.114: Mismatch of ply step location and tooling ramp location in core 4

The distance between the ply step location in the laminate and the ramp from the tooling are clearly identifiable. As a result also some out-of-plane waviness is present after the ply step, since the number of plies decreases but the thickness does not. This happens for all the mismatches in ply step and ramp location for all the ramps of all cores. However, this is a local phenomenon, because the out-of-plane undulations are only occurring after the ply step location and decrease in intensity with an increasing distance from the ply step.

In addition to these undulations, the dry spots in the top layers as well as cavities in the deeper layers are present by looking at these cross sectional images. Interesting to see is that there are not only surface dry spots, but that the lack of pressure also leads to cavities in the rest of the laminate. These dry spots and cavities are present in location 4 of core 3 and 4 and in location 1 of core 4. Location 4 of core 4 is shown as an example in figure 6.115.

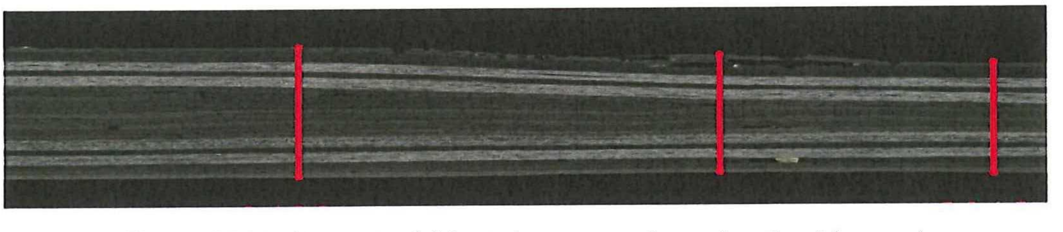


Figure 6.115: Dry spots visible at the cross section at location 4 in core 4

Core 1 is the reference core which should serve as a benchmark for the other cores since no shifting of the cores takes place. Nevertheless, some quality issues are present in these sections. On points 1, 2 and 3, the ramp locations of the tooling matches perfectly with each other as can be seen in figure 6.116.

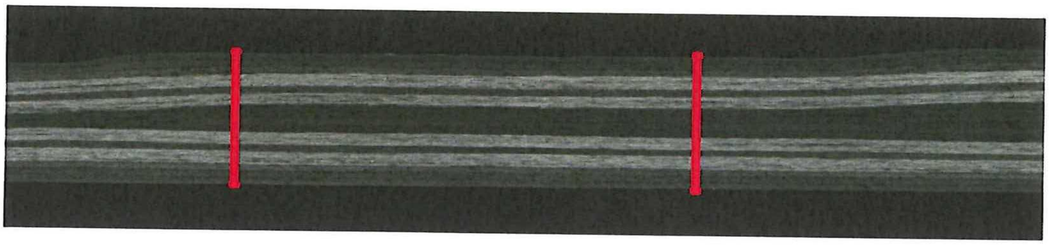


Figure 6.116: Matching ply step and tooling ramp locations in core 1

However, on the side of the core with the cavity at location 4, the distance between the ramp location of the tooling and the ply step locations increases with an increasing distance from the first ply step on top of the ramp. These distances are shown in appendix D and are displayed graphically in the graph below in figure 6.117. In the graph, ramp/ply step number 1 is on the top of the ramp and 6 is at the bottom of the ramp.

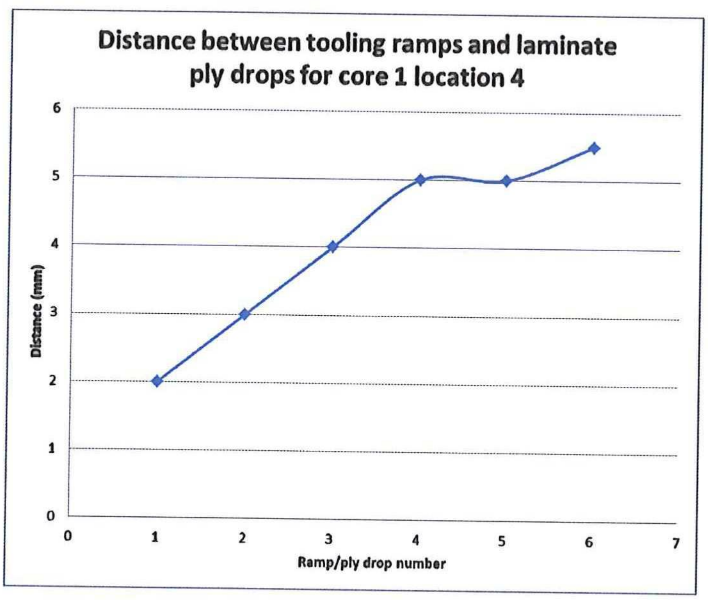


Figure 6.117: Distance between tooling ramps and laminate ply steps for core 1 at location 4

A reason for this could be an inaccurate lay-up of the ramp section. However, in location 2 all the ramps in the tooling and the ply steps match perfectly. So a more plausible explanation would be that the layers in 0 degree direction elongate in the autoclave in x-direction when the pressure is applied. Since the fibres have little straining capability in length direction, the assumption is that the 90 and ± 45 degree ply show shifting behaviour. The reason that the ramps and ply steps match at location 2 is that the ramp is under a slight angle in the beginning, matching the ramps and cavities. As soon as the pressure is applied, the core is pushed down, squeezing the layers in the opposite direction. A visual representation of this situation is shown in figure 6.118.

It can than also explain why the mismatch of the bottom ply step is 2,75 times more than the top ply. The length of the top ply is 90 mm and the bottom one is 240 mm as described

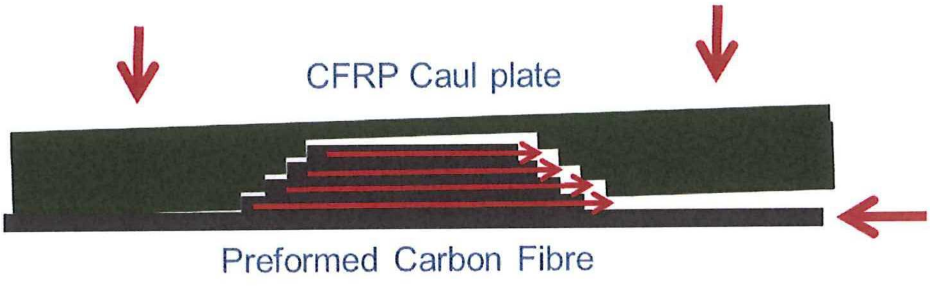


Figure 6.118: Expansion of the layers in x-direction due to the applied pressure

in table 6.2. This difference is 2,67 times as much, with a linear relation for the ply steps in between. Therefore the plausible conclusion can be drawn that the mismatch is due to unequal pressurization of the two sides of the core.
As a result of these shifted locations and the squeezing of the plies sideways, out-of-plane undulations formed in the section without ramps. These undulations are shown in figure 6.119 and cannot be observed with the visual inspection.

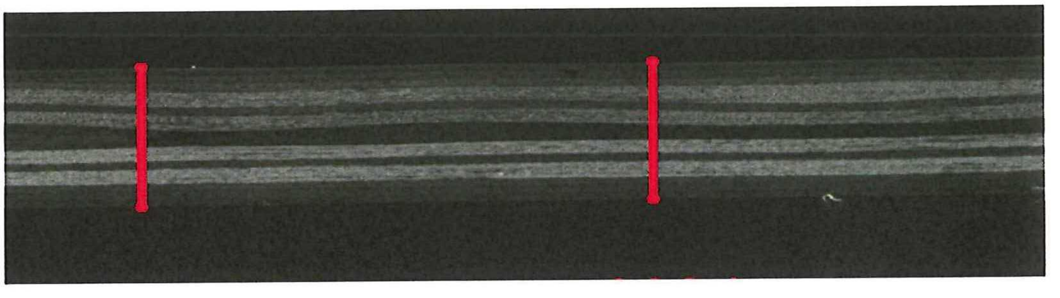


Figure 6.119: Out-of-plane undulations caused by the expansion of the layers in x-direction

The explanation of these undulations lays the squeezing of the plies and the pressure that is pushing from the other direction as shown in figure 6.118. This results in waves being formed and only in the top half of the laminate of the stringer web. This panel of the laminate is placed over the ramp and is also subjected to the squeezing from the one side of the core, while the bottom half remains straight and has no sideward force from the ramps acting on it.

Thickness measurement

Using the thickness measurements from the cross sectional images, some additional conclusions can be drawn with respect to the panel quality. The values of the thickness measurements are found in appendix E and are derived from appendix D. As a first visual representation, the measured thicknesses are plotted at the location in the x-direction as a fraction of the test panel length, since not all the thickness measurement points are at the same locations. It is done this way to have a general overview of the shape of the laminate with respect to the supposed thicknesses according to both the ply steps in the laminate and the ramps in the tooling, since these locations also differ from one another. For every point that is measured in the part, there is a corresponding thickness of what the panel should be according to the ramps in the tooling and the play steps in the laminate. Ideally, the two values are the same, which would mean that the locations match perfectly. However, since the cores are shifted, these locations will match less with an increased shifting distance. The graphs for the four cores are shown below in figures 6.119 - figure 6.123.

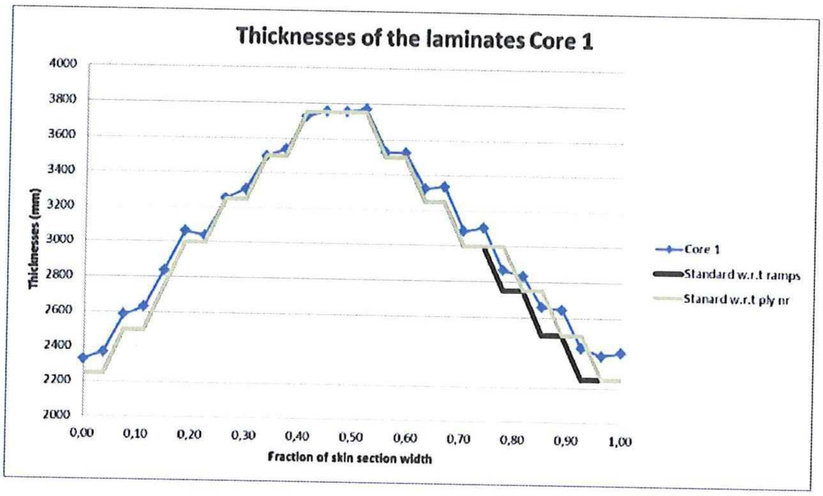


Figure 6.120: Thicknesses of the laminate in core 1

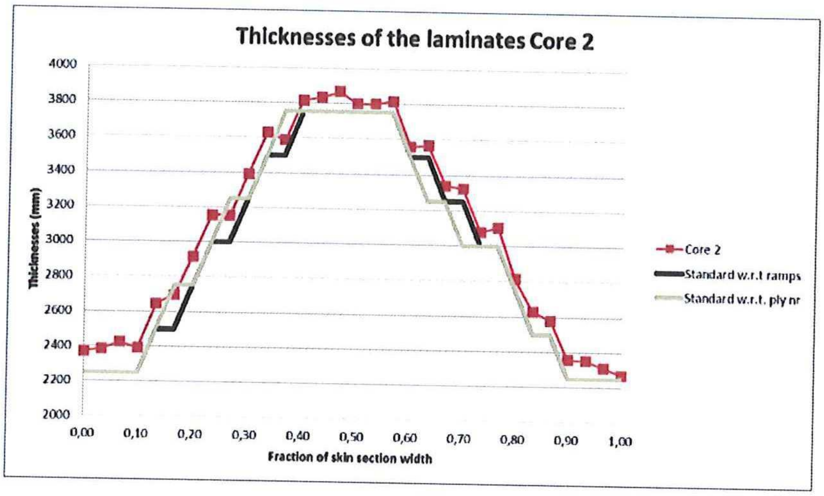


Figure 6.121: Thicknesses of the laminate in core 2

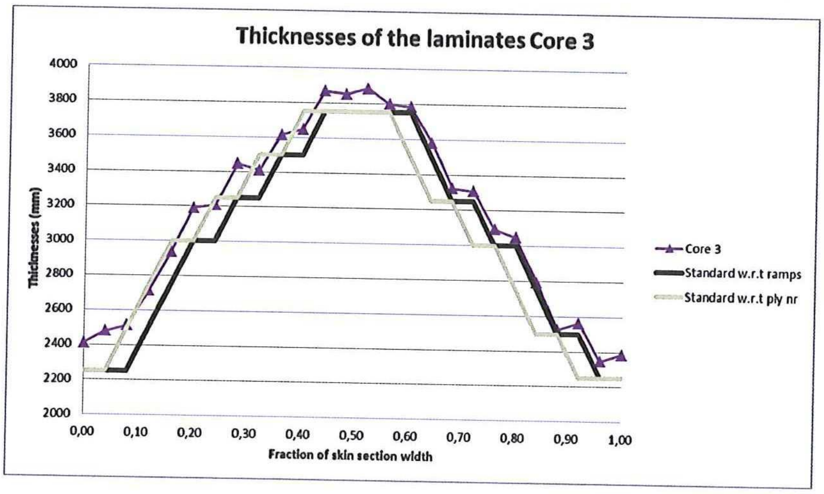


Figure 6.122: Thicknesses of the laminate in core 3

In core 1 it can be seen that the locations of the tooling ramps and the ply steps almost match perfectly well for the ramp up and the actual thicknesses are also in the close vicinity. As

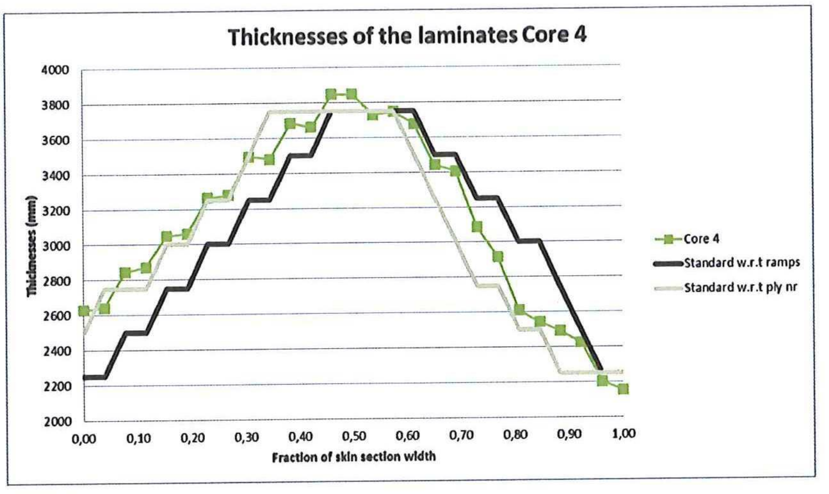


Figure 6.123: Thicknesses of the laminate in core 4

explained in the evaluation of the cross sections section, the ramp down at location 4 is not matching with an increasing deviation with an increasing distance from the top. The shifting of the ramp thickness curve is shifting more to the right compared to the curve of the ply step thickness. This difference increases for an increasing shifting of the cores. This is consistent with the expectations. However, the measured thicknesses show a different image than the expectations of local increased thickness compared to figure 6.112. At location 1 of the figure (0-0,1 fraction of skin section width in the graph) it is expected to have a larger thickness than the nominal thickness. This is true for all the cases and is increasing with an increased shifting of distance w. At point 2 of the figure (0,1-0,4 fraction of skin section width in the graph) it is expected that the thickness will be smaller due to extra pressure on the laminate by the core at that location (no cavity). However, it is relatively similar or sometimes even a bit larger than the nominal thickness of the ply steps in the laminate and at an increased shifting or a lot more for the nominal according to the ramps. In addition to these graphs, the data can also be combined in a graph where the thickness percentage is compared to the nominal thickness according to the ramps and to the ply steps in the laminate to get a better overview of the dependence. These two graphs are shown in figure 6.124 and figure 6.125

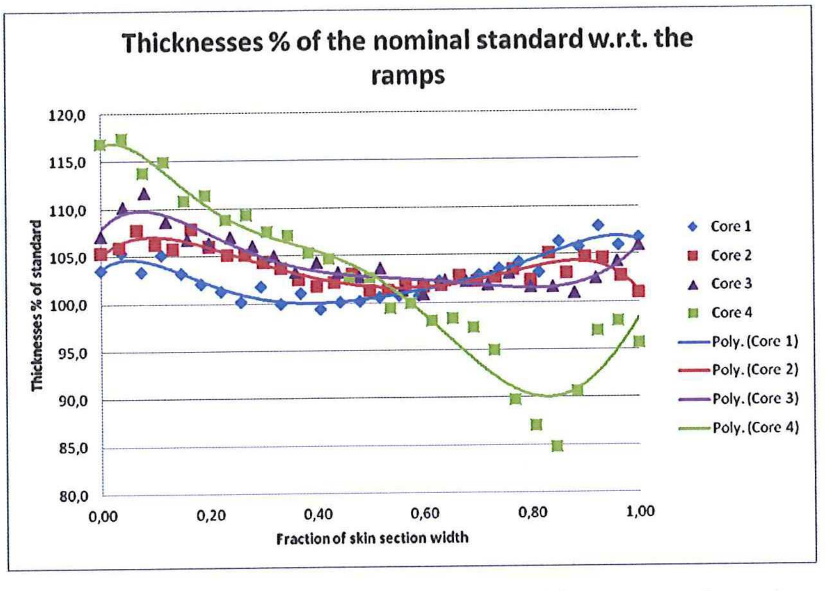


Figure 6.124: Thicknesses percentage of the nominal with respect to the tooling ramps

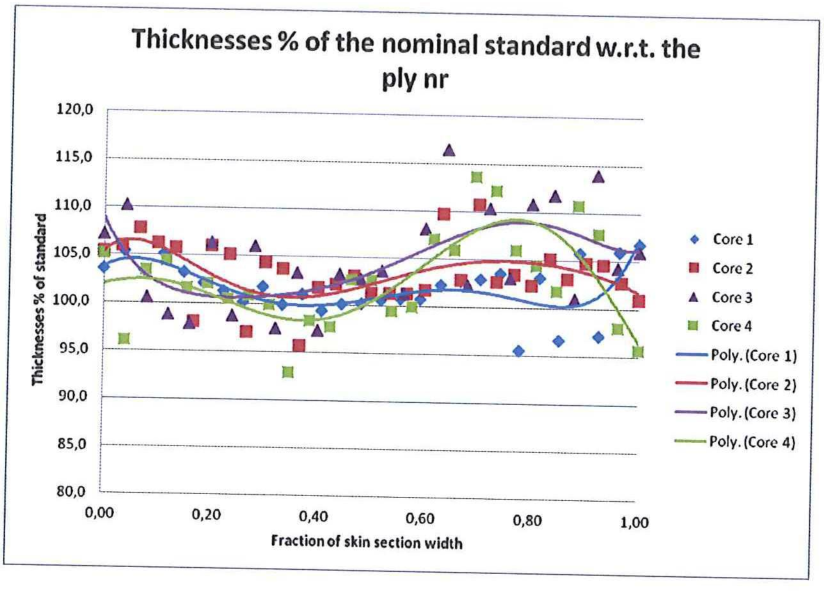


Figure 6.125: Thicknesses percentage of the nominal with respect to the ply steps

In both graphs, polynomial trend lines are added of the sixth order to get a clearer overview of the situation. Polynomial trend lines are suited best when the data fluctuates and the higher the order, the better the points match the trend line. The reason that the points are more scattered in figure 6.125 is that the total thickness of the laminate does not change immediately when there is a ply step. The thickness that the laminate should have does however change immediately with a ply step. This also results in a different value of the thickness percentage of the nominal with respect to the ply steps in the laminate.
With these two graphs it can be seen that the thicknesses at point 2 are increasing with respect to the tooling ramps for an increasing shifting distance w. This contradicts the theory of the compression that is present, but when looking at figure 6.125 it can be seen that the trend lines are quite similar with core 4 being the lowest, followed by core 3. So the reason that the laminate is thicker at the location where it should be thinner has purely to do with the number of plies at that location.
At location 3 at the top of the ramp it is seen from figures 6.120 - 6.123 that the laminate is thicker on the left of the flat panel than on the right. At these sections, the thicknesses with respect to the tooling ramps and the laminate ply steps is the same in the middle (0,45-0,55 fraction of skin section width in the graph), because there are no ply steps. The thickness difference is larger for an increased shifting difference and fully supports the theory of figure 6.112.
At location 4 (0,45-0,90 fraction of skin section width in the graph) the thickness should be larger than the nominal according to the theory of figure 6.112. For the thickness with respect to the ramps in the tooling, no large deviations seem to occur when looking at figures 6.120 - 6.123 and figure 6.124. This is true for cores 1,2 and 3, but for core 4, the thickness steps to 84,8% with respect to the ramps in the tooling. This can be explained by the formation of the dry areas at this location. The laminate is not in contact with the tooling, so there is still a gap filled with air between the tooling and the laminate. A lower thickness is the result.
In the contrary, by looking at the thicknesses with respect of the ply steps a great increase in the thickness percentage is observed for an increasing shifting distance. Because there is a gap present at location 4, the laminate is free to expand through the thickness, resulting in a thicker laminate compared to the ply step thickness. This means that the fibre volume content is lower, because more resin is present and the amount of fibres is constant. Referring to the outer quality of the part, the conclusion can be made that the brown ramps at location 4 indeed means that more resin is present there. In location 5 (0,90-1 fraction of skin section width in the graph)

the actual thickness is lower than in location 1 when looking at figures 6.120 - 6.123. However, there is no major difference when comparing the thicknesses of the different cores with different shifting distances. The explanation for that is that close to the ramp, the pressurization is not occurring yet and there is even a small cavity present. That is also why all laminates are thicker than the nominal, except for core 4. The reason that this thickness is deviating is because of the dry areas that are present in the ramp and the skin.

As an example, when looking at the thicknesses percentages with respect to both the ramps and the ply number of core 3, it is noticed that for a large shifting of the cores(larger than 12,7 mm) the two graphs are mirrored. This can be seen in figure 6.126

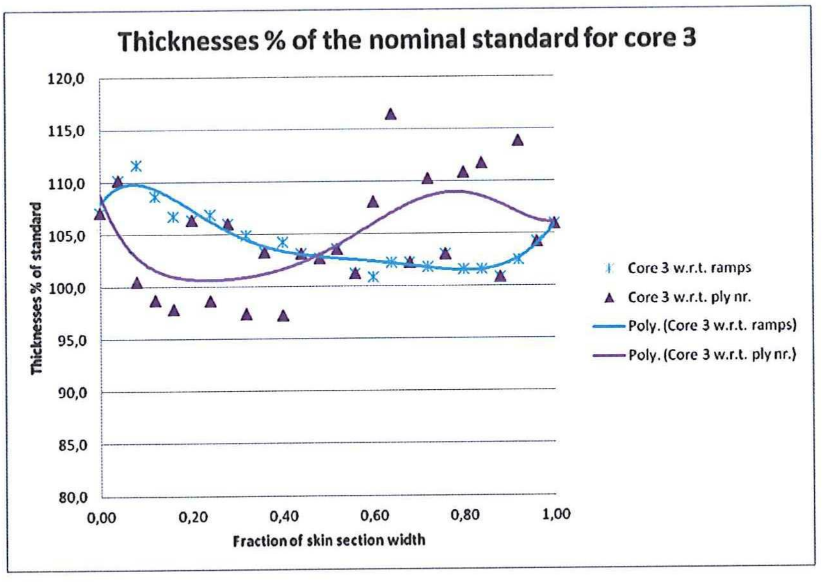


Figure 6.126: Thicknesses percentage of the nominal comparison for core 3

The larger the shifting difference, the more the small mismatch effects are removed, which are for example clearly present in core 1. It is logical that the graph becomes globally mirrored for the deviations with respect to the nominal thickness, because the tooling ramps outline thicknesses are mirrored compared to the ply step thicknesses. In other words, when there is for example a cavity present of 1 mm, the thickness of the panel compared to the ply step thickness should be 1 mm thinner (the panel is too thick) and with respect to the tooling ramps 1 mm thicker (the panel is too thin). However, as is seen from the other graphs, this is not always the case, due to the locations of the measurement points, the elongation of the plies and dry areas.

Summary and conclusions

The manufacturing alteration that was simulated in this panel was the shifting of the cores in x-direction with ramps present in the laminate. As a summary, the defects that were found with the outer quality visual inspection were in-plane waviness and dry areas. The in-plane undulations only occurred in the panel close to the dry areas of the skin with the core with the largest shifting of the core. When evaluating the inner quality, in-plane undulations are observed with an unshifted core. The explanation for this is that the web of the stringer is squeezed to one side due to an uneven pressure. Since it is constrained on the other side by applied pressure, the laminate is loaded in compression causing the waves.
The main conclusion is that the outer surface and contour of the panel are formed by the tooling, but that the actual thickness of the laminate and the ramps are determined by the number of

plies without a cavity present and by the tooling shape when there is a cavity present. During the application of pressure, the laminate is difficult to squeeze more even if the shape of the tool is promoting it to be squeezed. With the cavity present, the resin will fill the cavity together with the expanding fibres up till a certain maximum. This leads to a decrease in fibre volume content. If the maximum fibre volume content is exceeded, dry areas start to form and the laminate is no longer in contact with the tool.

6.3.2 Test panel 10: Core rotation around the z-axis

In this part, the simulated process alteration is to rotate the cores in the autoclave around the z-axis. The z-axis is the axis in the direction of the height of the stringers. The coordinate system is shown in figure 5.10. In actual production, there is the assumption that the carbon fibre cores might rotate in the autoclave due to misalignment and misplacement of the edge bars. The misplacement of the edge bars can be either a manual mistake or due to that the laminate and cores are misplaced, leaving less space for the edge bars. If the edge bars are misplaced they are pushed to the left or right to align them with the contour lines on the skin mould surface and to match the orientation of the cores. Another cause of the rotation is that the bottom of the edge bar rests on a slope. When the autoclave pressure is applied, it is pushed down, squeezing the laminate underneath, but also moving the edge bars and cores in x-direction due to the slope. This movement can be either rotational if only one side of the bar moves or lateral. The shifting occurs in the autoclave, because the resin becomes liquid and the laminate deforms easier. Another test panel is made to simulate the lateral misplacement of the edge bar in test panel 11.

Manufacturing

The cores need to be rotated individually around their respective z-axis during the autoclave cycle to simulate the rotation of the stringer pack due to misalignment of the edge bars. In order to achieve this rotation, one core is removed from the pack and a panel will be made with one full stringer less. A silicone rubber expansion block is inserted in the location of the removed core between the edge bar and core number 3. The laminate of core 3 will have an L-shaped profile (figure 6.127), so that the expansion block will press against the core flange and not against the laminate.
Since there is no full block of silicone available at Airbus, one is composed by adding individual layers of a silicone mat together. The mat is 2 mm thick and the space it needs to fill due to the absence of one core is 65 mm. So, 32 layers of the mat will be used with the surface dimensions of one layer being 400 mm x 45 mm. The silicone rubber has a thermal expansion coefficient of $342,0 \cdot 10^{-6} K^{-1}$. The free expansion of the silicone rubber in width direction with a temperature difference, from 23 degrees heating up to 180 degrees, of 157 degrees and a width L of 65 mm is calculated as follows:

$$\delta L_{steel} = L \alpha_{steel} \delta T = 3,34mm \tag{6.3}$$

In addition to this lateral expansion, the block will also expand in the other directions. The autoclave pressure is constraining this expansion and even compressing the block from the two ends and the top further. However, the calculated expansion is the free expansion when the rubber is not under compression and free from expansion constraints. If the rubber is compressed, the expansion will be less, but it will accumulate internal build-up stresses.

In order to achieve the rotation, one edge bar is rotated around its z-axis and secured, so that the block can expand till the maximum value that is set by securing the edge bars. The cores will then be rotated in order to match the new contours. A visual representation of the setup is shown in figure 6.127 with the image of the actual production in figure 6.128.

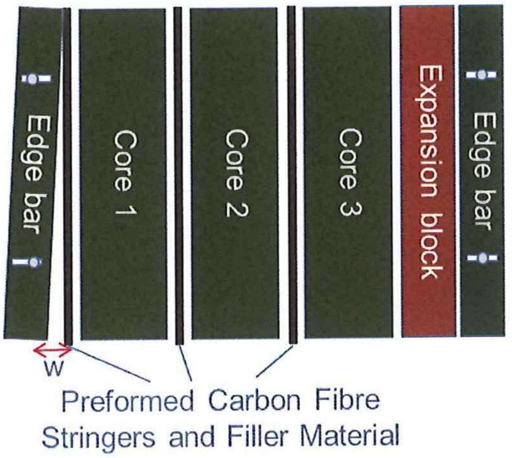


Figure 6.127: Overview of the process alteration of rotating the cores

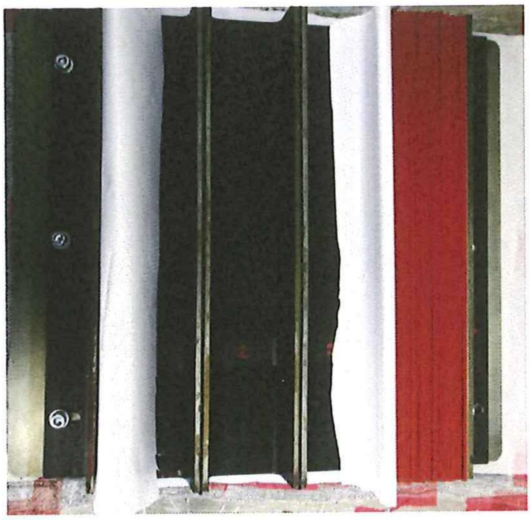


Figure 6.128: Overview of the process alteration in the production of the test part

A small triangular cavity of width w is left open on the side of the other edge bar and the half stringer with the widest being 3 mm on the bottom and 0 at the top. The manufacturing of the test panel will be for the rest identical to the standard production method.
In the autoclave, the expansion block will expand due to the increase in temperature in a triangular way and will exert pressure on the core pack. Since the cavity is present on the other side and the resin becomes liquid, the cores will rotate to fill the cavity. This situation is shown in figure 6.129.

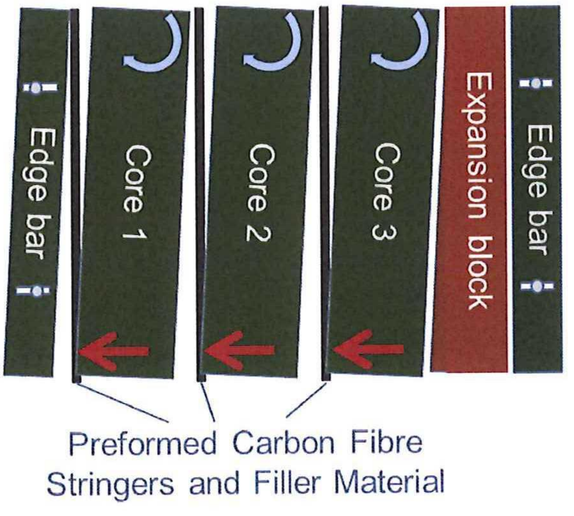


Figure 6.129: Theoretical rotation of the core with an expansion block

At the top where there is the rotation point, the cores will push the stringers to the right side in the direction of the expansion block. At the bottom, the cores will push the stringers to the

left side away from the expansion block.
After the autoclave, it was clear that the expansion block did indeed expand, because the individual layers of the block were separated and the gap between core 1 and the edge bar had disappeared. The separation of the layers indicated expansion in the autoclave due to the increased temperature and shrinkage after curing due to the cooling down of the expansion block. The expansion block after curing is shown in figure 6.129.

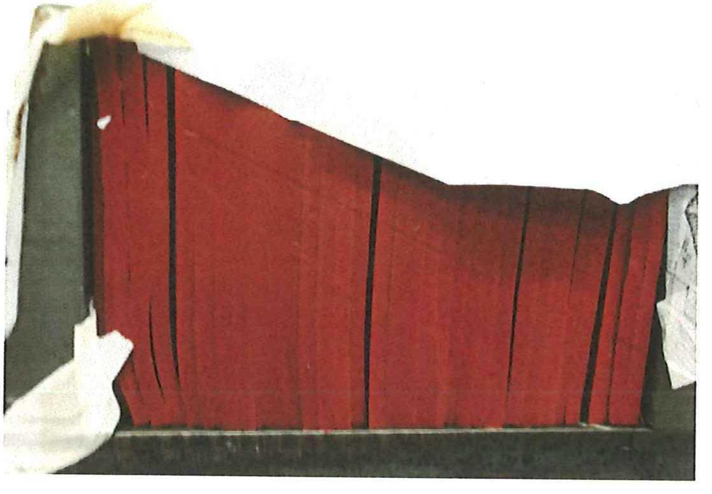


Figure 6.130: Expansion block after curing

The overview of the front and back of the panel after curing is shown in figure 6.131 - 6.132.

Visual Inspection of the part

By visual inspection, the following defect is observed:

- In-plane waviness

The only observed defect is that there are small undulations present in the skin in the corner sections of the stringer. This could indicate that the filler material has shifted. For the rest, the panel has an expectable quality according to the visual inspection. The small in-plane waviness in the corner section of, in this case stringer 2 core 3, is shown in figure 6.129.

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.131.
The first defect that is observed by looking at the cross sections is the in-plane waviness in the skin near the corner sections. As an example, the waviness at stringer 2 at location a on the top of the panel, on the right side where core 3 is present is shown in figure 6.134.

The colour change of the top layer from darker grey in the stringer, to light grey in the skin, indicates the change of fibre orientation in that layer from 45 degrees to almost 90 degrees. This indication is based on experience in examining the cross sections. In stringer 1 at location a, at the top side of the panel, a resin rich area is identified on the right side of the stringer on the

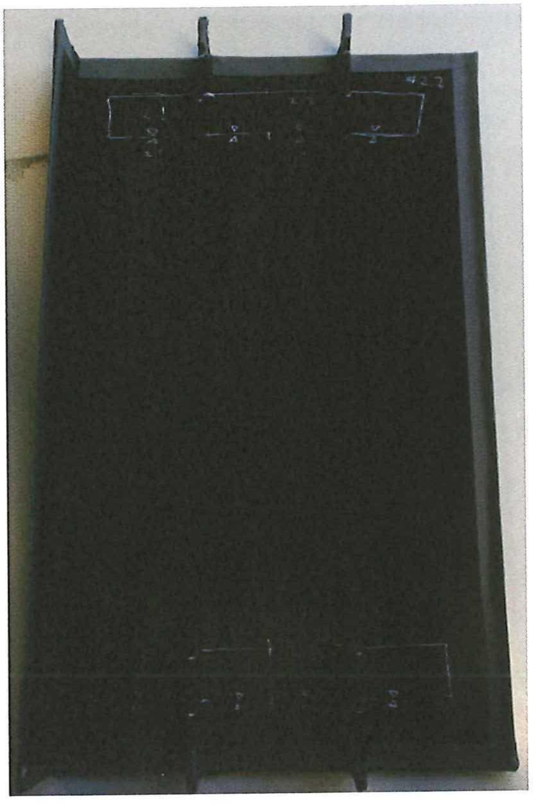


Figure 6.131: Panel 10: finished panel front view

Figure 6.132: Panel 10: finished panel back view

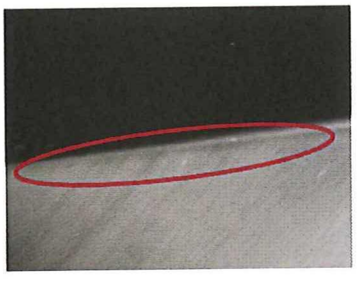


Figure 6.133: In-plane waviness in the corner section in stringer 2

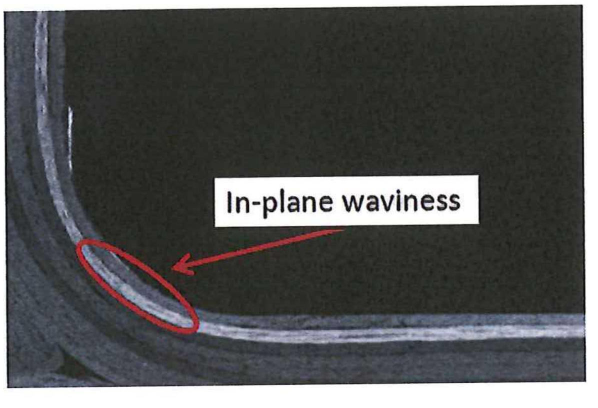


Figure 6.134: Cross sectional image of the in-plane waviness in the corner section in stringer 2

side where the core rotates the stringer. The cross sectional image is show in figure 6.135.

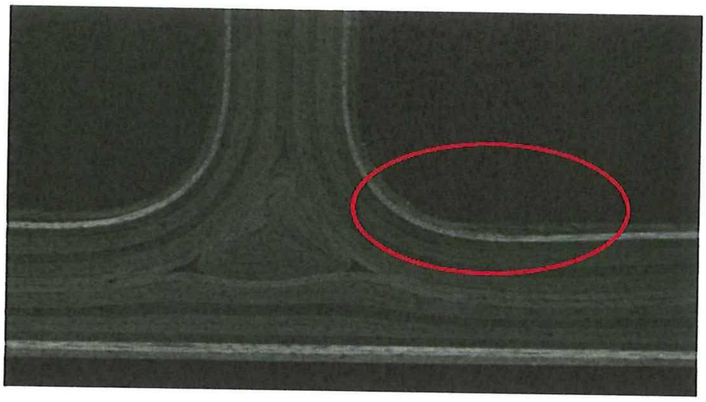


Figure 6.135: Resin rich area on the right side of stringer 1

The shape of the resin rich area further propagates to the layers below it and gives the indented shape of the other layers, compared to the left hand side. The resin rich area indicates that the core pack has indeed rotated.
Other, unexpected defects are also present in this part. For cross sections at location b in stringers 1 and 2 at the bottom of the panel where the cavity was present, the filler has shifted upwards significantly. For stringer 2 in cross section location b in stringer 2, the upward shifting of the filler material is as much as 4,5 mm. This intersection with the filler material shifting is shown in figure 6.136.

Figure 6.136: Vertical filler movement in stringer 2

The shifting of the filler material in stringer 1 and 2 occurs in the side of the panel where the gap of 3 mm was present. Together with the thickness analysis that is further explained in the next section, it can be concluded the laminate was local lack of pressure on that side of the part. First of all a gap of 3 mm was present, which the expansion block was supposed to fill by pushing the core pack into the gap. The theory is that the expansion block did expand, but not enough to completely pressurize the laminate at the end. This led to the filler material moving upwards instead of the expected sideways movement, since there was space available for the stringer to expand dragging the filler material along with it. To monitor the effect of the rotating cores, only the one side with the good compression is taken into account. This can also be seen from the thickness measurements. The panel that is not under enough pressure is regarded as a manufacturing defect in the production of this test part.

Thickness measurement

In addition to the defects in the cross sections, it can also be noticed that there is a significant thickness deviation in the stringer thicknesses, even within the same stringer at different locations. The thicknesses of the skin and stringers are displayed below in figure 6.137 and figure 6.138.

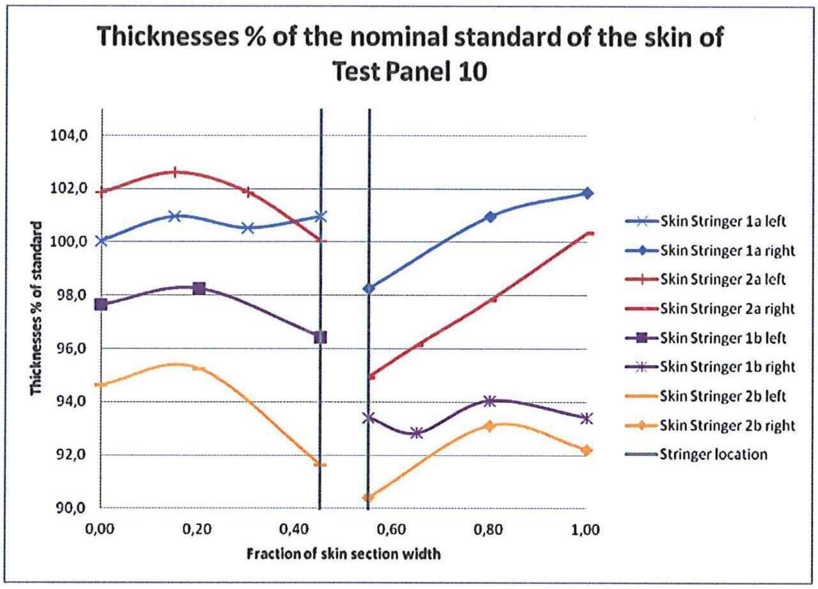


Figure 6.137: Panel 10: Thickness percentage of the nominal of the skin

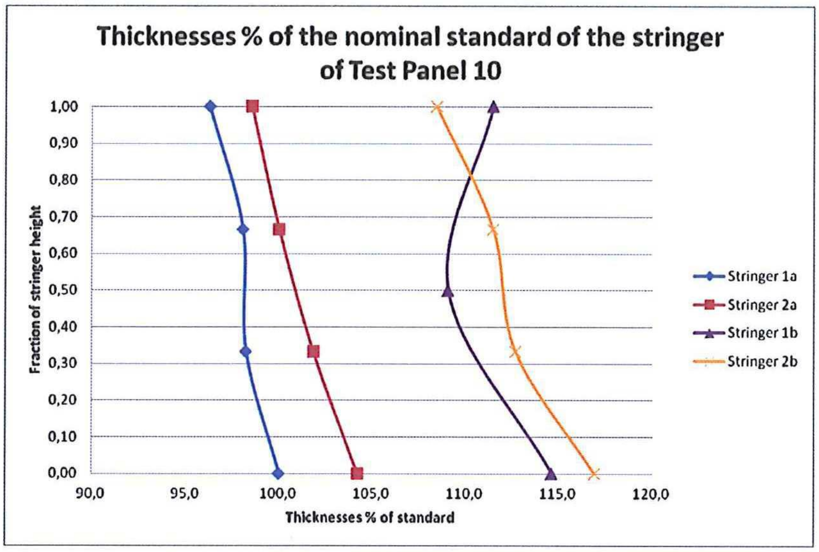


Figure 6.138: Panel 10: Thickness percentage of the nominal of the stringers

The thicknesses in the skin are close to the nominal value. In this section, 1a is the location a in stringer 1 on the top of the panel and 1b location b on the bottom side of the panel where also the gap is present (see figure 6.127).This is the same for 2a and 2b, but then for stringer 2. The skin at stringer 1b and 2b, which are located on the side of the panel where the gap was

present, is thinner on average than for the skin in stringers 1a and 2a. In all skins section the thickness is decreasing closer to stringer.
The lower thickness in the skin next to stringers 1b and 2b compared to 1a and 2a can be explained by looking at the stringer thicknesses. First of all, all of the stringer cross sections are thicker at the bottom than at the top. This corresponds with the skin thicknesses, which are decreasing near the stringer. The cores next to the stringer rotate inwards in opposite directions, compressing the stringer at the top. For stringer 1a, the thickness is 2,251 mm or a value of 100,0% at the bottom and at the top 2,167 mm or a value of 96,3% which is a difference of 0,084 mm. For stringer 2a, the thickness is 2,346 mm or a value of 104,3% at the bottom and at the top 2,218 mm or a value of 98,6% which is a difference of 0,128 mm. So the thickness difference between bottom and top is slightly larger for stringer 2a, which could correspond to a more evenly distributed compression of the stringer. The difference between the thickness differences is however only 0,044 mm, so no solid conclusion can be drawn from this difference.

As explained in the evaluation of the cross sections section, the stringers 1b and 2b are much thicker than 1a and 2a at the side where the gap was present. Combining the thickness results with the stringer thicknesses, it can be concluded that resin from the skin close to the stringer was pushed into the stringer to fill the cavity with insufficient pressure. In stringer 2b, the thickness difference between skin and stringer is most severe, with skin thickness to the right of the stringer of 2,034 mm or a value of 90,4%, compared to 2,631 mm thickness in the bottom of the stringer or a value of 116,9%. This value decreases to 2,441 mm or a value of 108,5%, which is still high. However, the values of the stringer thicknesses are still within tolerances, while the skin thickness is outside of the tolerances.

Summary and conclusions

The production change that was introduced for this panel is the rotation of the cores around the z-axis in the autoclave to simulate the mismatch and sideways movement of the edge bars. An expansion block was used that expands in the autoclave with a temperature increase. This pushes the cores on one side in lateral x-direction where a gap is present between the core and edge bar, causing them to rotate with the lateral movement constrained on the other side of the core.
The only defect that was found with the outer quality visual inspection was in-plane waviness. The waviness was also visible with the evaluation of the cross sections. Furthermore, resin rich areas are present in the corner sections due to the rotation. Additionally, a manufacturing defect was present on the side where the gap was present. That side was not pressurized sufficiently due to the presence of the gap, which caused the filler material to shift upwards, the stringers to increase thickness and the skin to decrease in thickness near the stringer. The manufacturing defect of the vertical filler movement is specific to this individual panel and the setup on how to achieve the rotation and does not portray the production alteration in the actual production.

6.3.3 Test panel 11: Core movement in Y-direction

In this test part, the manufacturing variation is done where the cores are shifted horizontally in y-direction. The coordinate system is indicated in 5.10. This is a variation of the test panel that was created in test panel 10. There, the cores were rotated to simulate an uneven shifting of the edge bars. The edge bars shift due to misplacement and the bars moving sideways due to their placement on a slope and the autoclave pressure acting on it. As said before, the even shifting is simulated where only lateral movement of the cores will take place.

Manufacturing

The stringer pack has to be shifted in y-direction during the autoclave cycle, to simulate the misalignment of the edge bars. A similar approach is used in order to shift the stringer pack in one direction as for the rotation in panel 10. One core is removed to place the expansion block and the laminate at core 3 will have an L-profile shape instead of a U-profile. The same expansion block is used as before, with the alteration that there is not a triangular gap present, but a rectangular gap with a width of 3 mm on the top and bottom between the core and edge bar. The gap of 3 mm is used, because of the calculations on the thermal expansion of the expansion block done for test panel 10. A visual representation of the setup is shown in figure 6.139 with the image of the actual production in figure 6.140.

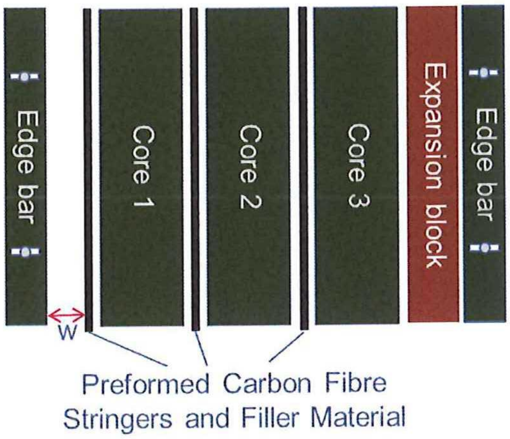


Figure 6.139: Overview of the process alteration of rotating the cores

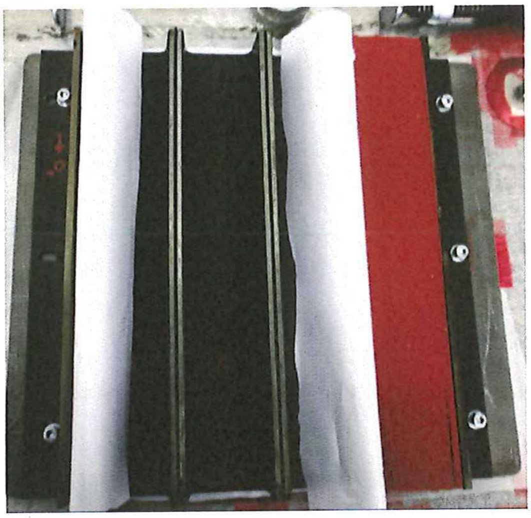


Figure 6.140: Overview of the process alteration in the production of the test part

In the autoclave, the expansion block will expand, shift the core pack in y-direction and fill the gap on the other side as is shown in figure 6.141. The cores will theoretically push the stringers away from the expansion block.

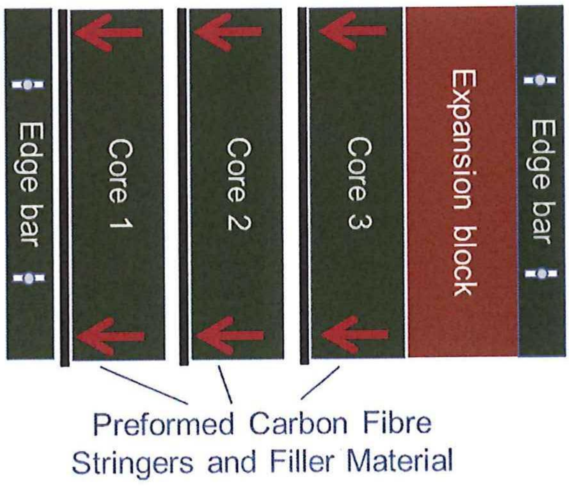


Figure 6.141: Theoretical movement of the cores using an expansion block

After the autoclave, it was clear that the expansion block did indeed expand, because the individual layers of the block were separated and the gap between core 1 and the edge bar had disappeared. This is identical to test panel 10. The expansion block after curing is shown in figure 6.142.

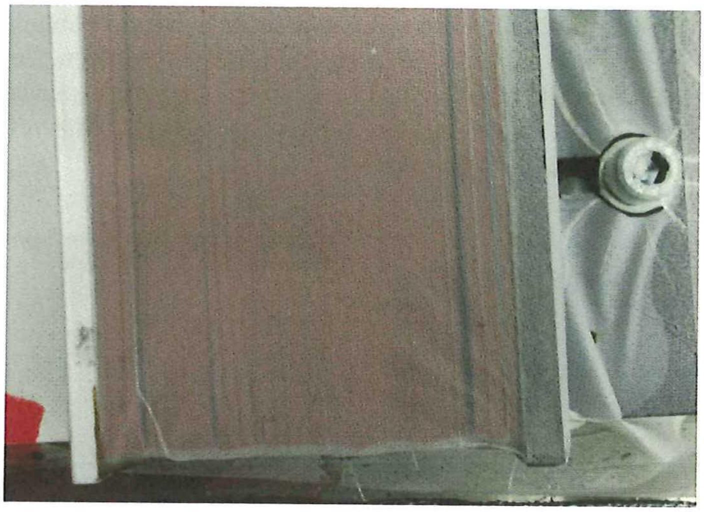


Figure 6.142: Expansion block after curing

The overview of the front and back of the panel after curing is shown in figure 6.143 - 6.144.

Figure 6.143: Panel 11: finished panel front view

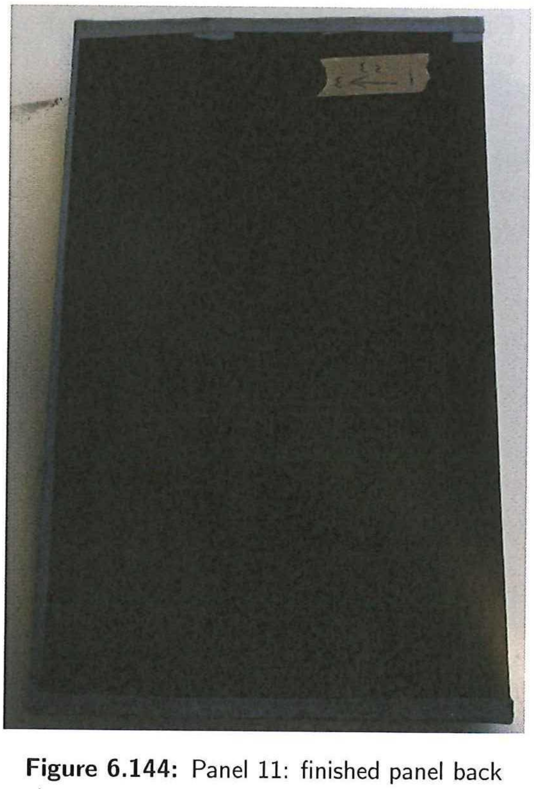


Figure 6.144: Panel 11: finished panel back view

Visual Inspection of the part

By visual inspection, the following defect is observed:

- In-plane waviness

The in-plane undulations that are observed in this panel are similar to that of test panel 10. The only observed defect is that there are small undulations present in the skin in the corner sections of the stringer. However, these in-plane undulations are more severe than for panel 10. This could indicate that the filler material has shifted more or that larger resin rich areas are present near the corner sections. For the rest, the panel has an expectable quality according to the visual quality inspection. The small in-plane waviness in the corner section of, in this case stringer 1 core 2, is shown in figure 6.145.

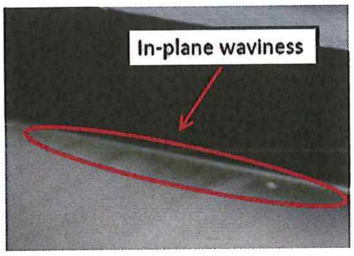


Figure 6.145: In-plane waviness in the corner section of stringer 1

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.143. The views are also indicated in that picture. The complete images can be seen in appendix D which include all the thickness measurements of the cross sections.
The first defect that is observed by looking at the cross sectional images is the in-plane waviness in the skin near the corner sections. As an example, the waviness at stringer 1, on the right side where core 2 is present is shown in figure 6.146.

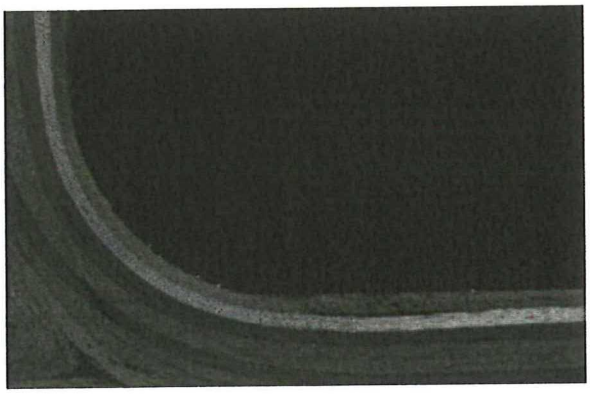


Figure 6.146: Cross sectional image of in-plane waviness in the corner section of stringer 1

The colour change of the top layer is clearly noticeable in the radius of the cross section as well as in the skin in the vicinity of the corner. The brightness of the top layer changes from darker grey in the stringer, to light grey in the corner section and skin. This indicates the change of fibre orientation in that layer from 45 degrees to almost 90 degrees. This indication is based on experience in examining the cross sections. Also a resin rich area is identified at this location on the right side of the stringer on the side where the core pushes the stringer to the left. In the other cross section of stringer 1 at location b at the bottom of the panel, two resin rich areas are present on both sides of the stringer. The cores were pushed from right to left and it is show in figure 6.147.

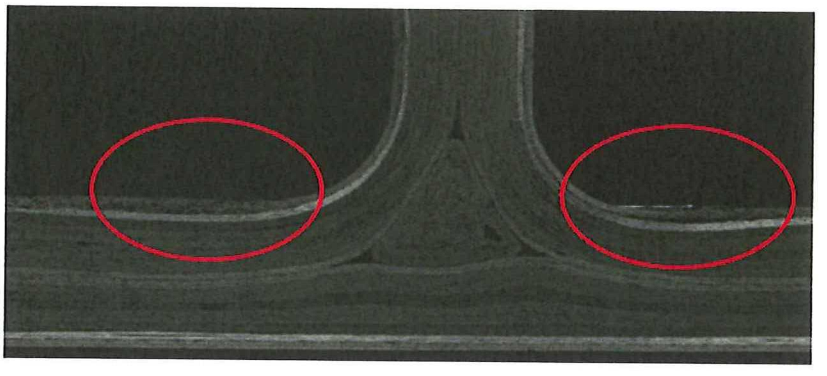


Figure 6.147: Resin rich areas in the corner sections of stringer 1

The shape of the resin rich area further propagates to the layers below it on the right side of the stringer just like in test panel 10 and gives the indented shape of the other layers, compared to the left hand side.
In addition to the in-plane waviness and resin rich areas, filler material has also shifted 0,5 mm in stringer 2 at the top side of the panel. The filler misalignment is shown in figure 6.148.

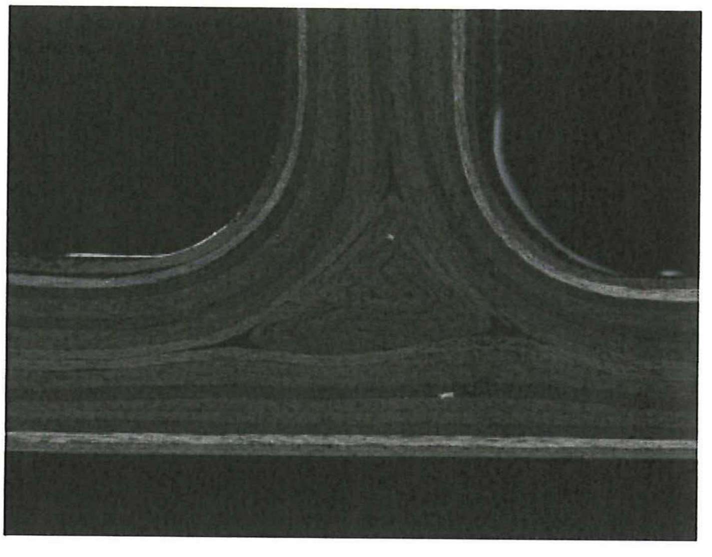


Figure 6.148: Horizontal filler misalignment in stringer 2

The core is pushing from the right side, so there is a force acting on the stringer and filler material that pushes them to the left. The filler material is compressed on the right hand side due to this force and pressed between the stringer web and skin laminate on the left side. This is a completely different situation for the shifting of the filler material than when the autoclave core is bigger than the preform core in test panel 5 (section 6.2.2). In that situation the force is acting more from above pressing the stringer more outwards and over the filler material, followed by exerting pressure on the filler material. In the case of the shifting of the cores however, the force is acting sideways pressing the filler material and the stringer instead of only the stringer. The filler misalignments, together with the resin rich areas, indicate that the core pack has indeed shifted.

Thickness measurement

In addition to the defects in the cross sectional images, it can also be noticed that there are some thickness deviations in the skin thicknesses, even within the same skin section of a core at different locations. The thicknesses of the skin and stringers are displayed below in figure 6.149 and figure 6.150.

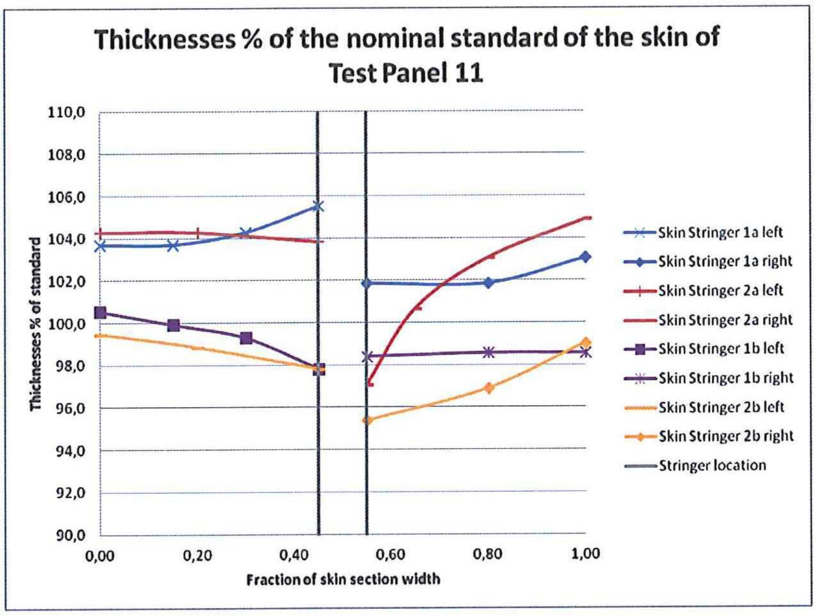


Figure 6.149: Panel 11: Thickness percentage of the nominal of the skin

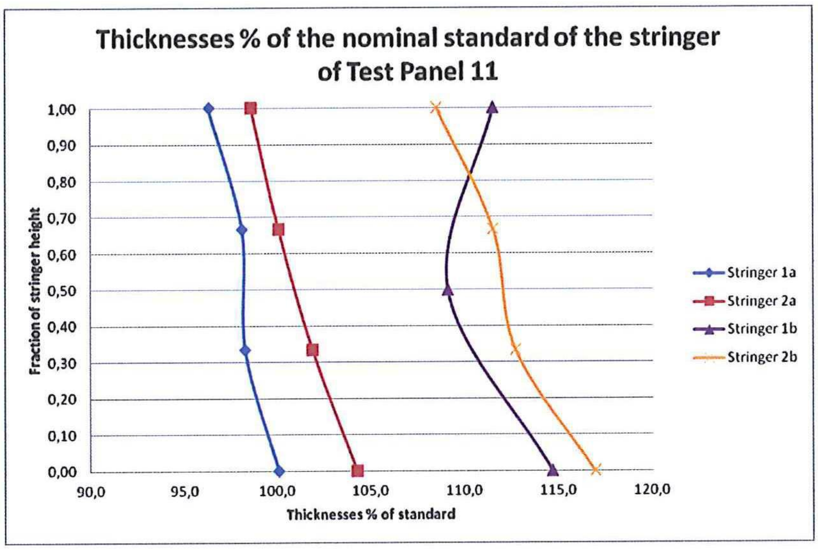


Figure 6.150: Panel 11: Thickness percentage of the nominal of the stringers

The thicknesses of the skin in stringer panels 1a and 2a (on the top of the panel) are on average higher than of 1b and 2b (on the bottom of the panel). In stringers 1a and 2a, there is a more significant presence of the resin rich areas compared to 1b and 2b. This means that there is more resin in the skin present, which explains the increased thickness. The thicknesses of the skin and stringers 2a and 2b match quite well and show a similar shape. Core 2 and 3 are slightly rotated inwards with core 2 having a clockwise rotation and core 3 a counter clockwise. This inward rotation causes the stringer to be thicker at the bottom and thinner at the top. For stringers 1a and 1b there is on the other hand a difference between the shapes of the stringers and the thicknesses of the skins. The left panel of the skin is higher near the stringer for panel 1a, implying that the core is rotated slightly counter clockwise. The corresponding stringer is almost perfectly straight with a width at the bottom of 2,262 mm or 103,7% of the nominal and 2,262 mm as well at the top. On the other hand, at the other side of stringer 1 at location 1b, the skin is increasing in thickness on the left side of the stringer. The stringer is increasing in thickness with a width of 2,231mm or 99,2% at the bottom and 2,384 mm at the top or 106,0%. The width difference is 0,153 in this case. The reason for these differences within the same stringer could be that that the lateral movement also involved a slight rotation in the xy-plane. This would give rise to the possibility that the stringer cavity is larger at the top, explaining the width difference in the stringer. Other explanations would be that the core changes shape to a small extent in the autoclave due to temperature or pressure or that the shape of the core is not precise. This was previously referred to as the W-effect in test panel 4. In order for the last explanations to be true, a precise measurement of the core and its behaviour in the autoclave needs to be done.

Summary and conclusions

In this part, the production alteration that was introduced was the lateral movement of the cores in the autoclave by placing an expansion block between the outer core and the edge bar. This alteration simulates the shifting of the edge bar in the autoclave due to the autoclave pressure and the slope the edge bar rests on.
The only defect that was found with the visual inspection is in-plane waviness in the skin in the corner sections of the stringer. By looking at the cross sections, resin rich areas are observed. These are similar to the ones that are caused by rotating cores. Where the resin rich areas are present, the thickness in the skin is larger. The shape of the resin rich area is indented in the layers below it. In addition to the resin rich areas, the filler material has shifted sideways. The core is pushing the material sideways together with the complete stringer, instead of pushing the stringer over the filler material. This wedges the filler material between the stringer web and the skin laminate on the other side.

6.4 Panels with laminate alterations

The final panels will have the alterations present that the laminate is changed. In the actual production, the stringers are cut by hand as soon as the preform cores are removed. This leads to too height stringers for the stringer cavity that is present on the sides of the autoclave cores, simulated in panel 12 in section 6.4.1, and too short in panels 13.1 and 13.2 in sections 6.4.2 and 6.4.3. In panel 13.1, an error occurred in compressing the pack. For that reason, panel 13.2 was constructed to perfectly simulate the effects of having too short stringers. Finally, the filler shape and size is altered in panel 14 in section 6.4.4

6.4.1 Test panel 12: Higher stringer than the stringer cavity

The seventh test panel that is manufactured will have the process variation that the stringer will be pushed down by the top of the cores. In chapter 3, it was explained that the carbon fibre cores have a stringer cavity that encloses and gives shape to the stringer from the left and right side as well as from the top. The top of the carbon fibre core is thicker to close off the stringer of the flap from above and thinner where the stringer cavity is present. When the uncured stringers do not have the same height as the height of the cavity of the cores, the quality of the panel could be affected. The effect of when the stringers are too short can be found in test panel 1 and 2 in section 6.1.1and section 6.1.2.When they are too long, the core will be hanging on the stringer and create a downward force on the stringer. That process variation is simulated in this test part.

Manufacturing

In this part, the stringer will be made higher than the cores themselves. In the actual production, the cores close off the stringer cavities on the top side. So if the stringer is too long it will be pushed down by the cores and the autoclave pressure. This will be simulated with the height differences of stringer 1 of 1 mm and for stringer 3 of 2 mm. Stringer 2 will have a combination of the two, where one half of the stringer is 1 mm and the other half 2 mm. The reason that these height differences were used is because the resin rich areas in the corner sections in the actual panels have indentation sizes in the order of 1-2 mm. The setup for the manufacture of the panel is shown in figure 6.151.

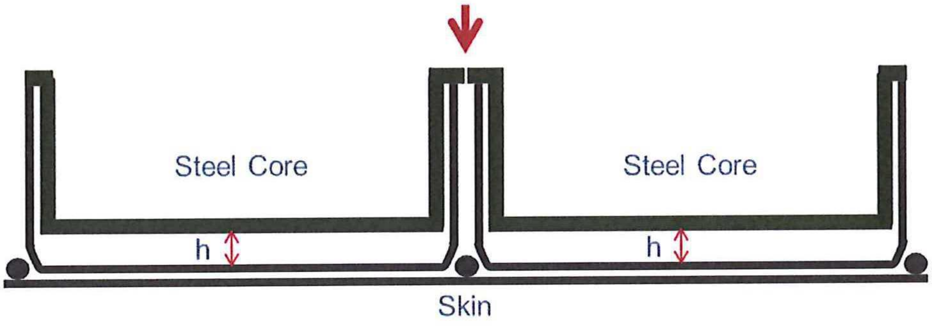


Figure 6.151: Setup of the process alteration for the higher stringer than the stringer cavity

The stringer laminate needs to be higher than the steel core in order to simulate the pushing down of the stringer. As a first set, the laminates of the stringer need to be preformed on higher cores than the original steel cores in order for the stringers to be higher. The steel cores are therefore modified by placing cork strips under the tops of both of the flanges of the cores, see figure 6.152. The larger laminates are placed on the cores as normal and are placed in the preform station. The cores with the height modification and the preformed laminate are shown in figure 6.152.

When the skin is placed on the core pack and turned on the steel ground plate, the cores and cork are removed. The height differences are then simulated by placing prepreg material (thickness 1 mm) under core 1 and 2 and cork (thickness 2 mm) under core 3 and core 4. The placement of the prepreg and cork is shown in figure 6.153 and figure 6.154.

Tape is placed over the top of the core and stringer, pushing the stringer downwards as soon as the support prepreg and cork material is removed from between the core and laminate. The end result is that the cores are hanging from the top with help of the tape as can be seen in

Figure 6.152: Increasing the height of the cores with cork for the preforming

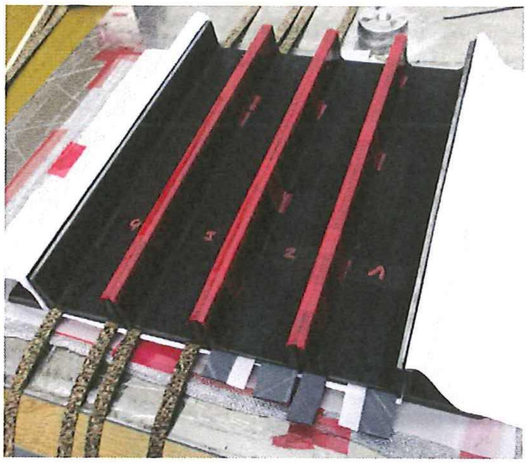


Figure 6.153: Creating the height differences of 1mm and 2 mm

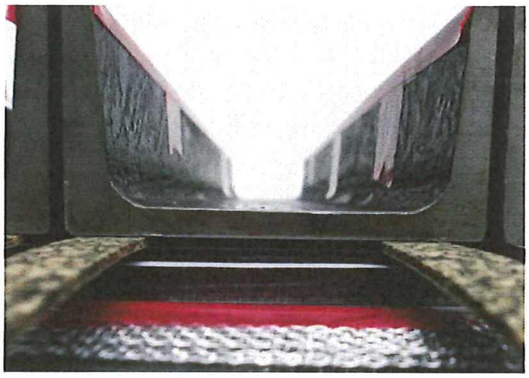


Figure 6.154: Height difference in core 3 with a height of 2 mm

figure 6.155. The tape has sufficient adhesive strength to keep the cores hanging until they enter the autoclave.

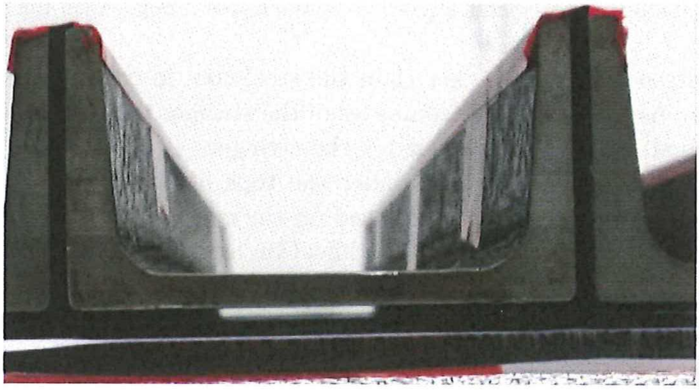


Figure 6.155: Height difference with the cork support removed under core 3

The height of the core above the laminate is measured and corresponds to the intentional 1 and 2 mm. The release is still on the inside of the U-profiles in order to remove the cork and prepreg support material; without the release film it would stick to the laminate.

The overview of the front and back of the panel after curing is shown in figure 6.156 and figure 6.157.

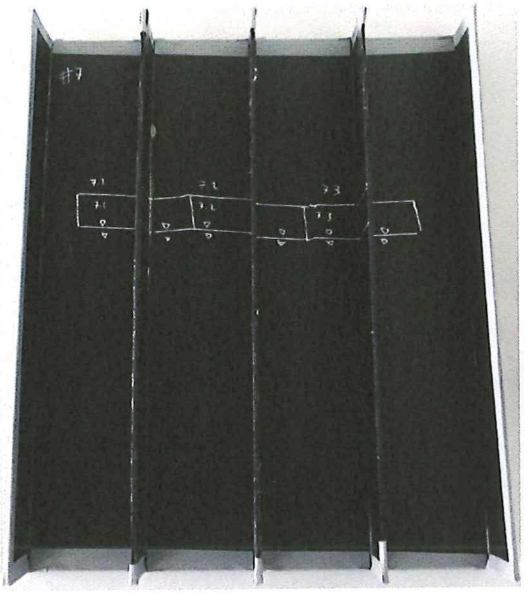


Figure 6.156: Panel 12: finished panel front view

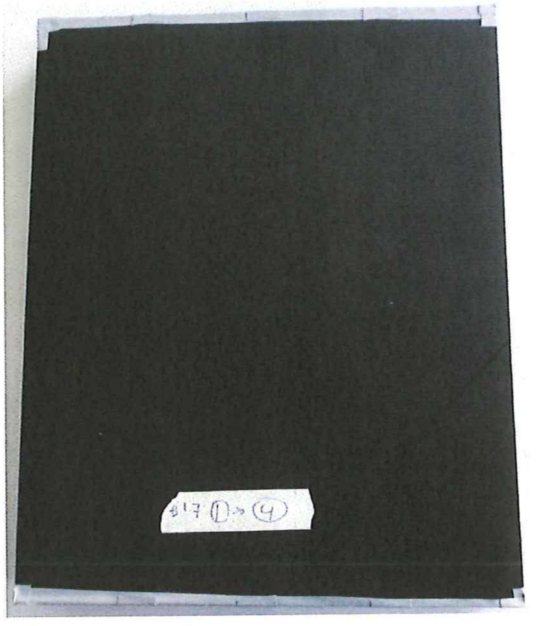


Figure 6.157: Panel 12: finished panel back view

Visual Inspection of the part

By visual inspection, the following defects are observed:

- In-plane waviness
- Enclosed release film

Release film was present on the laminate to allow for easy removal of the prepreg and cork support material. The foil was enclosed in the corner sections of all stringers, but could be removed from the cores 1 and 2. At cores 3 and 4, the foil is still enclosed and could not be removed. This indicates that the stringer with the largest height is pushed down more than the stringer with the smaller height. The pushing down of the stringer results in an open space in the corner section, which will fill with resin and encloses the release film. The enclosed release film is shown in figure 6.158.

Originating from the corner sections, small in-plane undulations can be observed. These undulations cover a larger area for the stringers with a larger height difference than for the stringer with a smaller height difference. That could indicate that there are resin rich areas present in the corner sections where the fibres start forming waviness.
In addition to the in-plane waviness in the corner sections of the stringers and skin, there is also in-plane waviness in the whole of the stringer surfaces. The stringer is pushed down from the top, so it is compressed and waviness starts to form. This waviness is stronger in the stringers where the height difference was 2 mm compared to the stringers with the height difference of 1 mm, where it was almost not present. The in-plane waviness in stringer 3 is shown in figure 6.159.

The horizontal line in the middle is the line where the release film above the line was removed for the adhesion of the laminate to the Tooltec during preforming. Below, the line, the release

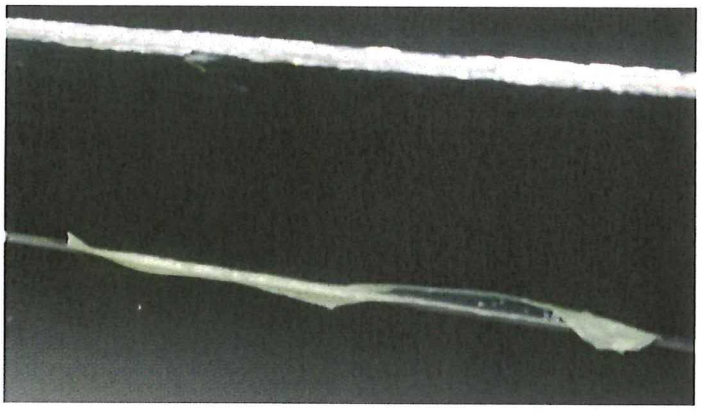


Figure 6.158: Enclosed release film in the corner section of stringer 3

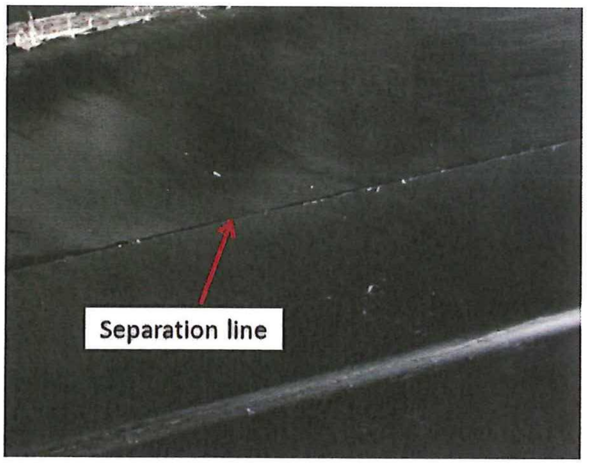


Figure 6.159: In-plane waviness in stringer 3

film was still present during the autoclave cycle as mentioned earlier. The line is just a visual line and is not a defect in the panel.

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.156. The cross sections were taken in one plane across all the stiffeners to have an equal comparison of the corner section, see figure 6.156. When looking at the cross section where the height difference is 1 mm, no defects are observed when looking at both the intersection in the corner as well as the stringer. For stringer 3, where the height difference is 2 mm, resin rich areas are present in the corner sections. The intersection with the resin rich area is shown in figure 6.160.

The enclosure of the release film in the corner section is also present in the figure. Similar to enclosed release film in the other test panels, it is also now the case that the release film is only enclosed by the resin and not the fibres. The top layer in the right corner section in figure 6.160 shows an increased thickness due to the pushing down of the stringer and is similar to the resin rich areas that are found in the actual panels.
In-plane undulations are also clearly present in the same corner and then especially in the second layer with the orientation of 90 degrees. The colour of the layer turns from light grey in the skin and stringer to an almost identical grey as the top layer in the corner section. That means that the orientation of the 90 degree layer changed. This indication is based on experience in examining the cross sections. The filler did not move and is still located in the centre of the stringer.

Figure 6.160: Resin rich areas in the corner sections as well as enclosed release film on the right side of the corner section in stringer 3

In the stringer, the in-plane undulations are present on the same side where also the release film was enclosed in figure 6.161. The outer layer changes from a 45 degree orientation to almost a 90 degree orientation, by looking at the change of grey scale of the outer layer. This indication is based on experience in examining the cross sections.

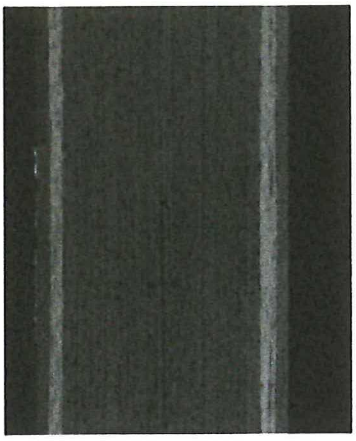


Figure 6.161: In-plane waviness in stringer 3

Thickness measurement

The thicknesses of the skin and stringers are displayed below in figure 6.162 and figure 6.163.

The thickness measurements can be seen in appendix D and the deviations from the tolerances in appendix E.
In this panel the cores 1 and 2 were hanging 1 mm above the skin of the laminate and core 3 and 4 2 mm. This results in that stringer 1 is 1 mm too high for the cavity, stringer two a combination of 1 and 2 mm and stringer 3 2 mm too high. The thicknesses of the skin section are almost similar for all the three stringers. In core 3, the W-effect can be seen, since on the right side of the skin of stringer 2 and on the left side of stringer 3 are pressing in the corner section more and less in the middle of the skin. Of main interest for this process alteration are

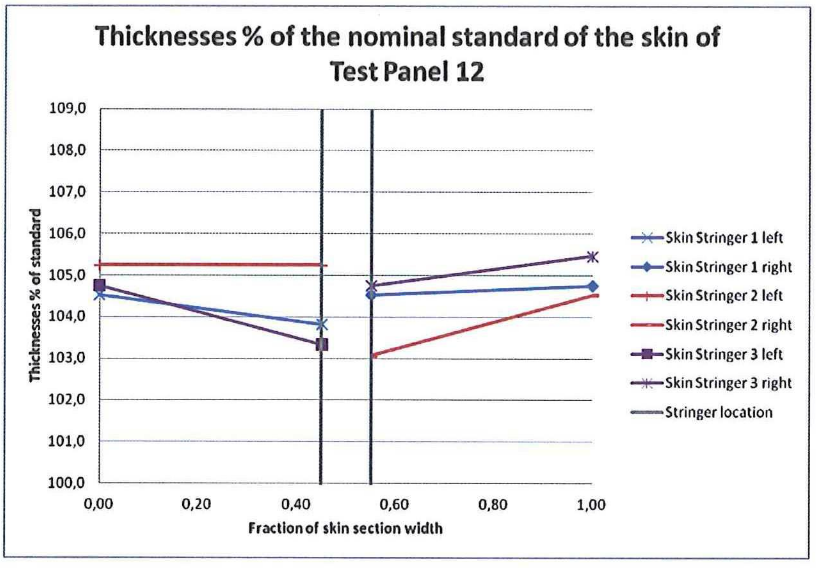


Figure 6.162: Panel 12: Thickness percentage of the nominal of the skin

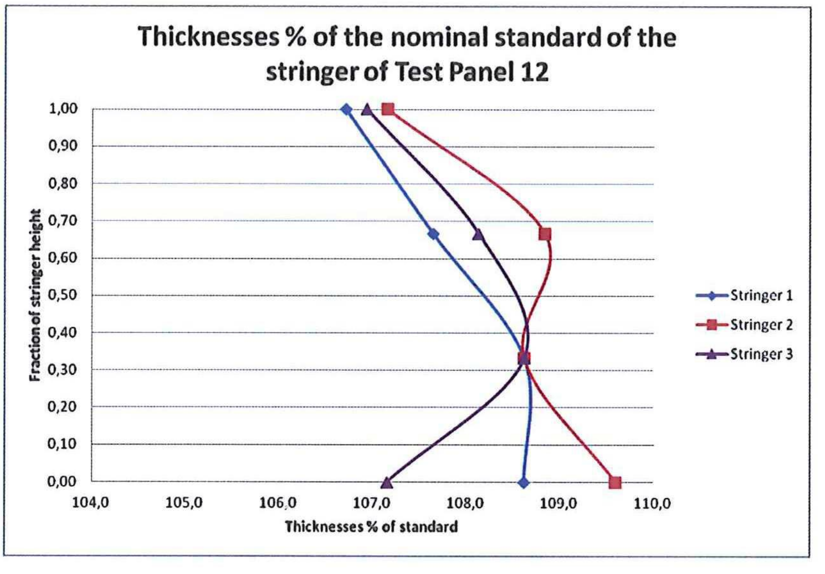


Figure 6.163: Panel 12: Thickness percentage of the nominal of the stringers

the stringer thicknesses in specific stringer 1 and 3. Stringer 1 is slightly thicker at the bottom of the stringer with a thickness of 2,444 mm or 108,6% compared to the top with a thickness of 2,401 or 107,1%. This is a difference of 0,043 mm. At stringer 3, there is only a 0,005 mm difference. However, the stringer is a bit thicker in the centre where the stringer is 0,036 mm thicker compared to the bottom. The assumption is that the stringer is compressed from the top, due to the higher stringers than the height of the cavity, resulting in the compaction of the stringer in the centre. This results in the undulations in the stringer that were observed as well as the increase in thickness in the centre for a larger stringer height difference.

Summary and conclusions

In this test part, the stringer is pushed down to simulate the effect when the stringer laminate is higher than the height of the cavity in the actual carbon fibre cores used in production. The cores in production are closed off at the top and when there is a mismatch in size, the top of

the core and the core will be hanging on the stringer laminate. As can be seen from the inner and visual inspection, the stringer is compressed and forced down. This creates, resin rich areas in the corner section radius for a height difference of 2 mm, from which the presence can also be assumed by the enclosed release film and the small in-plane undulation in the corner section radius, which are visible from the outside.
Next to the defects in the corner section, in-plane waviness is also present in the stringer. By compressing the stringer downwards, waves start to form which can both clearly be observed at the inner and visual inspection. From the thickness measurements can be concluded that the higher the stringer height difference, the more the effect is present that the stringer is thicker at the centre of the stringer compared to the top and bottom.

As a final conclusion, the pushing down of the stringer is successfully simulated and it can be concluded that the resin rich areas in the corner sections in the actual production that are described in 4 are caused by this pushing down. When the height difference is minimal, e.g. 1 mm, there is almost no effect on the panel quality and is even improving the compression of the intersection from the top.

6.4.2 Test panel 13 number 1: Stringer height - Shorter stringers

For the manufacturing of this part, the process alteration is that the flanges of the preformed stringers are smaller than the height of the cores. This alteration simulates the manufacturing defect in the actual production where the stringers do not have the right length. Too high stringers were simulated in test panel 12. When the stringers are shorter than the cavity height it results in the presence of a cavity above the stringer and below the top of the core stringer cover. In theory, this cavity should be filled with the material from the stringer and skin. Three different stringer heights will be simulated to show the relation between the stringer height difference and some defects.

Manufacturing

In this part, the stringers will be preformed as normal, but are cut of at different heights to simulate the mismatch between stringer height and stringer cavity of the carbon fibre cores. The stringers will be made shorter than the core height.
Between core one and two in stringer 1, the height is cut off 1 mm below the top of the core, for stringer 2, 2 mm and for stringer 3 at 4 mm below the top. The rest of the production progresses as normal. The rest of the manufacturing is done in the same way as for the other panels.

The cut off stringers with the cores, with stringer 1 on the left and stringer 3 on the right, are shown in figure 6.164.
The overview of the front and back of the panel after curing is shown in figure 6.165 - 6.166.

Visual Inspection of the part

By visual inspection, the following defects are observed:

- Slipped stringer plies
- Filler indentations on the back

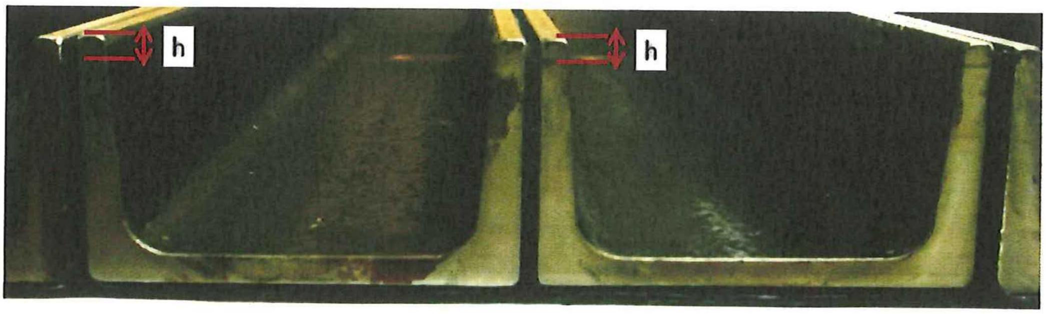


Figure 6.164: Lower stringers than the cores, with stringer 1 on the left

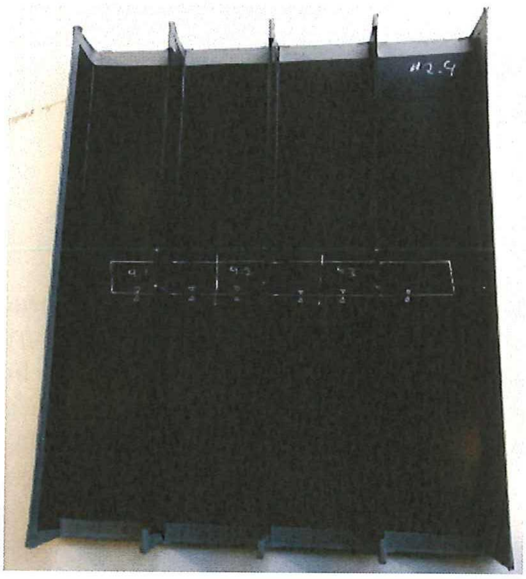


Figure 6.165: Panel 13.1: finished panel front view

Figure 6.166: Panel 13.1: finished panel back view

First of all, when unbagging the part, it is observed that the resin stains at the top of the stringers in the airweave differ in size for the different stringers. The shortest stain is at stringer 1 on the left and the longest at stringer 3 on the right. These stains are shown in figure 6.167.

The length of the stain could be an indication of the amount of resin present in the top panel of the stringer compared to the amount of fibres. Logically, stringer 3 is shorter before the autoclave than stringer 1 and 2, so if the cavity fills completely with material it will have more resin since the amount of fibres does not change. So shorter stringers lead to longer resin stains. When the airweave and the release film were removed, it was indeed observed that the final length of all the stringers was equal, namely the length of the steel core flange.

In addition to the resin stains, the same effect as slipped outer stringer plies is found in the stringers. The difference with slipped stringer plies is that the plies are not being dragged down by the cores, but their movement upwards to fill the cavity above the stringer is constrained. The constraining of movement is caused by the friction between the laminate and the core as well as the orientation of the fibres of the outer layer that does not allow for easy expansion upwards. The inner plies, mostly by 0 degree plies, did fill the cavity. The "slippage" height of the stringer plies corresponds directly to the height at which the stringers were cut off. The slipped stringer plies are shown in figure 6.168.

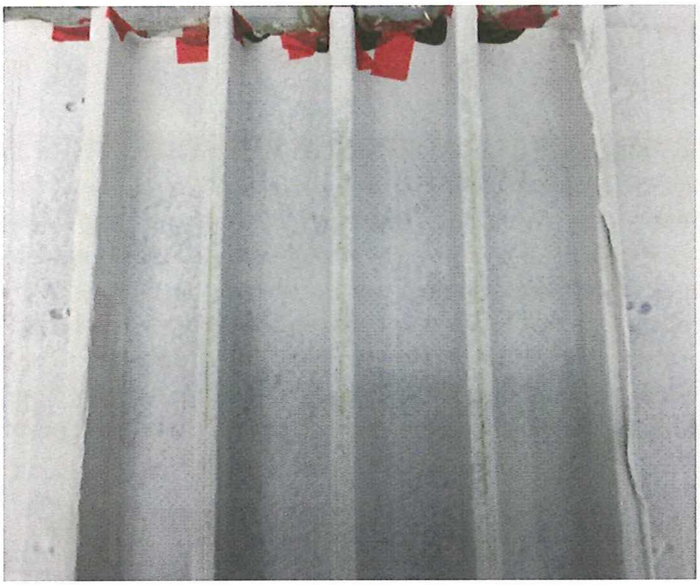


Figure 6.167: Brown stains in the airweave on top of the stringers after curing

Figure 6.168: Slipped stringer plies in the stringers, with stringer 3 in the front

In addition to the slipped stringer plies, filler indentations are observed on the back of the panel on the skin. This could be an indication that the filler material has shifted upwards. The filler indentations on the back are shown in figure 6.169 with core 1 on the left.

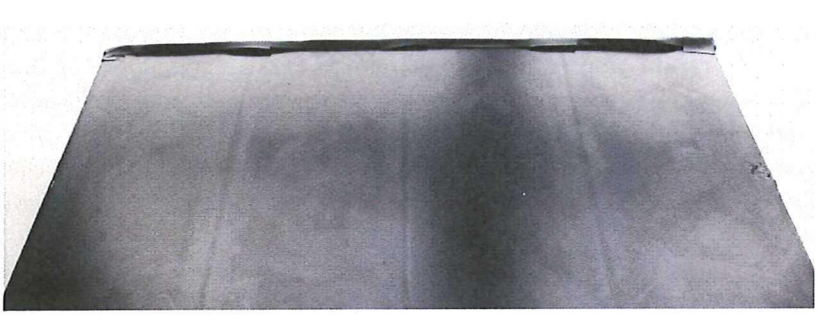


Figure 6.169: Filler indentations on the back on the outer mould line with core 1 on the left

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.165. When looking at the cross sections, there are several noticeable defects to observe. The main one is that the filler material shifted upwards for every core over a large distance. The main driving force of the vertical filler movement is that a cavity is present above the stringers that is filled with resin and fibres from the rest of the stringer. The resin also comes from the skin and drags along the filler material with it. Furthermore, there is no correlation between the stringer height difference with respect to the core and the distance that the filler material shifted upwards. For stringer 1 the filler material shifted upwards about 6 mm for stringer 1, 6 mm for stringer 2 and about 10 mm for stringer 3. As an example, the cross section of stringer 3 is shown in figure 6.170.

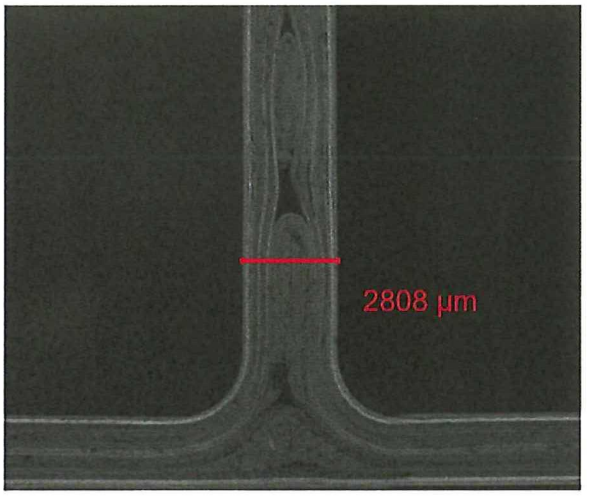


Figure 6.170: Vertical filler movement in stringer 3

The shifting of the filler material explains the filler indentations that were observed with the visual inspection on the skin of the part. By also looking at the thicknesses, which are further explained in the next section, it is concluded that the stringer pack was insufficiently compressed after preforming and turning. The thicknesses are far outside of the tolerances. This also explains the shifting of the filler material, since there was space available on both the top and sides for the filler material and stringer material to fill in the stringer section. Therefore, this panel is not considered to be representable for simulating the defects that correspond to different stringer heights. A new panel is constructed and explained in section 6.4.3. However, an important observation is that the material shifts upwards when the pack is under pressurized. This is a different situation than when the preform core is bigger than the autoclave core in test panel 8 (section 6.2.5). In the production of that part, there is also a cavity present between core and stringer, but the whole pack is compressed properly afterwards. It does however also lead to the shifting of the filler material upwards, but to a smaller extend, because of the missing cavity on the top and no cavity between stringer and core. In this panel the shifting of the filler material happens mostly during the autoclave cycle and for panel 8 in section 6.2.5 before the autoclave cycle.

In addition to the manufacturing defects, the slipped stringer plies can be observed clearly and are directly linked to the stringer height. These slipped stringer plies are seen as a defect, resulting from the stringer height difference. As an example, the top of stringer 3 with the slipped stringer plies is shown in figure 6.171.

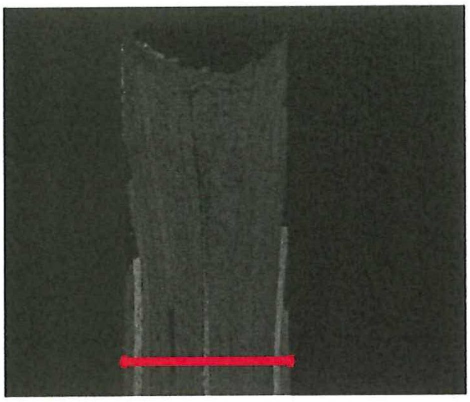


Figure 6.171: Slipped stringer plies on the top of stringer 3

Thickness measurement

In addition to the defects in the cross sectional images, the thicknesses measurements show indeed that the stringer and skin thicknesses are out of tolerances. Because there is no relation between the height of the stringer and the thickness and shifting of the filler material, the conclusion is made that the panel was under pressurized and the material was free to fill the corresponding cavity. The resin that is needed to fill the stringer cavity comes from the skin. This leads to a thin skin and a thick stringer as is explained below. The thicknesses of the skin and stringers are displayed below in figure 6.172 and figure 6.173. The explanation on how the graphs are constructed is explained section 6.1.1.

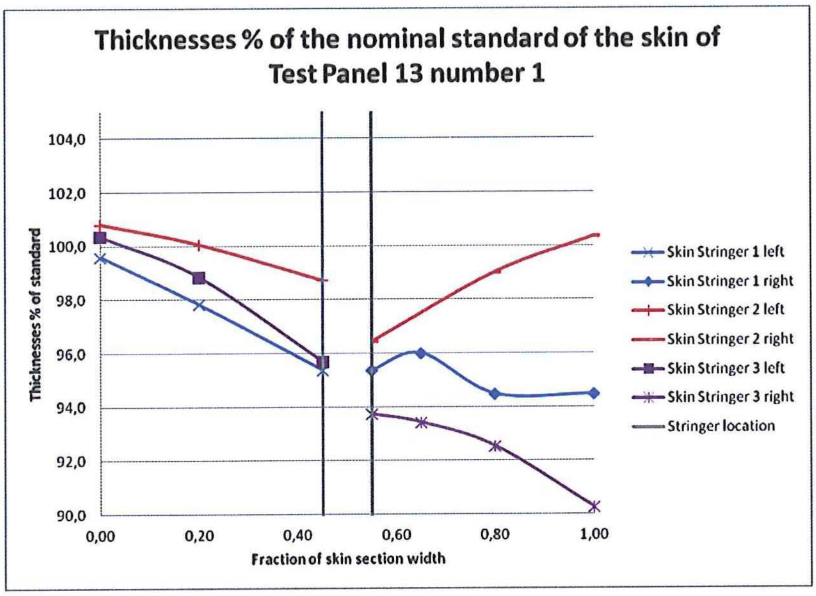


Figure 6.172: Panel 13.1: Thickness percentage of the nominal of the skin

The skins next to the stringers are all very thin compared to the nominal with at the right of stringer 3 a thickness of 2,031 mm or 90,3%. Comparing the thickness of the skin to the thickness of the stringer, it is concluded that the resin from the skin is pushed out into the stringers. The reason that the resin is pressed out of the skin is that the resin was free to move into the stringer, since it was needed to fill the cavity. The stringers are out of tolerances with stringer 1, being the thickest with a thickness at the bottom of 2,865 mm or 127,3%. All the stringers are thinner at the top, which is logical due to the presence of the cavity above the

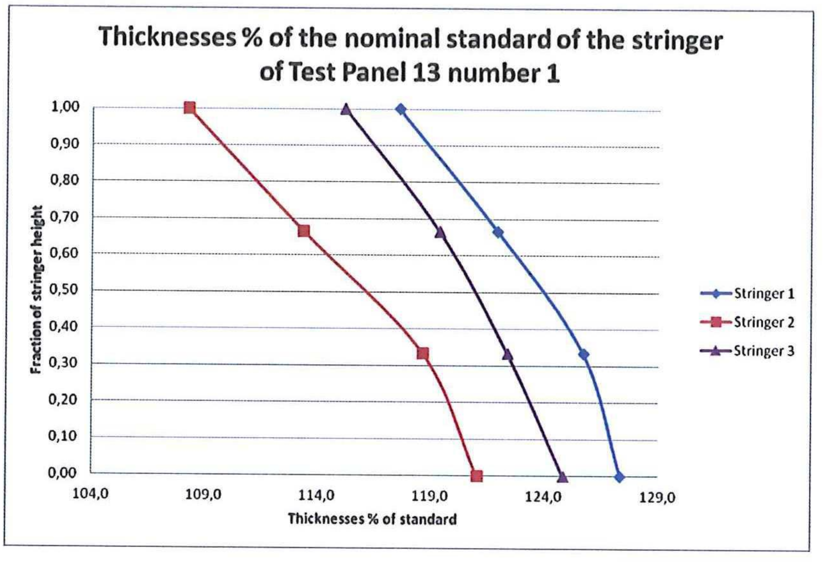


Figure 6.173: Panel 13.1: Thickness percentage of the nominal of the stringers

stringers, with for example for stringer 1 with a thickness of 2,645 mm or 117,6% This is a difference with the bottom of 0,220 mm. Even at the top of the stringer, the thickness is still very large and close to the maximal allowed value. Also, the W-effect, which was explained in panel 4, is slightly present when looking at core 2 between stringer 1 and 2. The thickness is lower at the stringer on the right side of stringer 1 and on the left side of stringer 2 and larger in the middle.

Summary and conclusions

In this test part, the production alteration was made to cut the flanges of the preformed stringers shorter than the flange of the steel cores. With this alteration, the production error is simulated that if the stringers are cut too short in actual production, that a cavity will be present between the top of the stringer and the top of the core stringer. The defects that were found with the visual inspection were slipped stringer plies and filler indentations on the back. The slipped stringer plies result from the shorter stringers, where the friction and the orientation of the plies ensure that the outer layers do not fill the cavity. On the other hand the inner, and to the largest extend the 0 degree plies, fill the cavity on top. This also leads to a thicker stringer at the bottom and thinner at the top.
However, this panel is not fully representable for the recreation of the shorter stringers, because the stringer pack was not sufficiently compressed during the production. This is concluded from the non-coherent vertical filler movement with the cavity height and the too small thickness of the skin and the too large thickness of the stringers. The conclusion that can be drawn from this is that a too wide cavity, because of under pressurization, leads to a vertical filler movement.
A new panel is constructed (section 6.4.3) which is properly compressed, to better simulate the effect of the stringer length before the autoclave cycle on the panel quality.

6.4.3 Test panel 13 number 2: Stringer height - Shorter stringers

For the manufacturing of this part, the process alteration is that the preformed stringers are cut off lower than the height of the cores. This is the same alteration as in panel 13.1 in section 6.4.2. However, in that part, the manufacturing defect occurred that the stringer pack

had insufficient pressure, causing the vertical movement of the filler material and the out-of-tolerance thicknesses. In addition, the expected defects due to the shorter stringers occurred in the form of slipped stringer plies.
As a recap, the alteration of having shorter stringers than the core flange height simulates the manufacturing defect in the actual production where the stringers are not cut off at the right length. This results in the presence of a cavity above the stringer and below the top of the core flange. In theory and according to panel 13.1, this cavity should be filled with the material from the stringer and skin. Three different stringer heights will be simulated to show the dependence of the stringer height difference compared to the defects.

Manufacturing

In this part, the manufacturing will be done the same way as in panel 13.1. The exception is that special attention is paid to the correct pressurizing of the stringers after the preforming and compressing. The pack is checked for cavities between laminate and cores just before the vacuum build up to ensure that there are also no cavities present during the autoclave cycle. The stringers are again cut off at different heights to simulate the mismatch between stringer height and stringer cavity of the carbon fibre cores.
Between core one and two in stringer 1, it is cut of 1 mm below the top of the core, for stringer 2, 2 mm and for stringer 3 at 4 mm below the top. The rest of the manufacturing is done in the same way as for the other panels.
The cut off stringers with the cores for this part, with stringer 1 on the left and stringer 3 on the right, are shown in figure 6.174.
The overview of the front and back of the panel after curing is shown in figure 6.175 - 6.176.

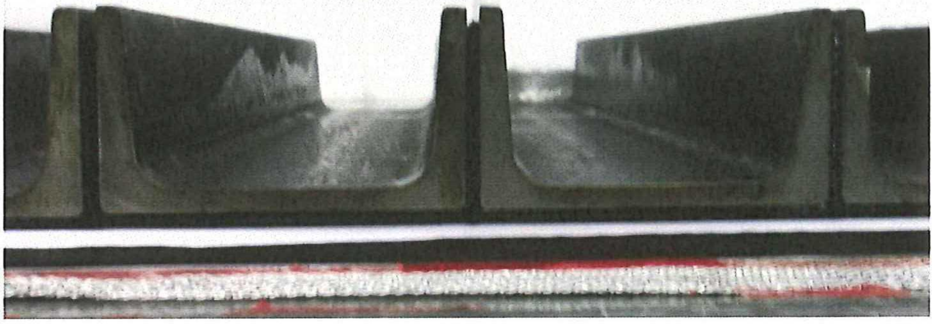


Figure 6.174: Shorter stringers than the cores with stringer 1 on the left

Visual Inspection of the part

By visual inspection, the following defect is observed:

- Slipped stringer plies
- Filler indentations (to a small extent)

Similarly to panel 13.1, when unbagging the part, it is observed that the resin stains at the top of the stringers in the airweave differ in size for the different stringers. The shortest stain is at

Figure 6.175: Panel 13.2: finished panel front view

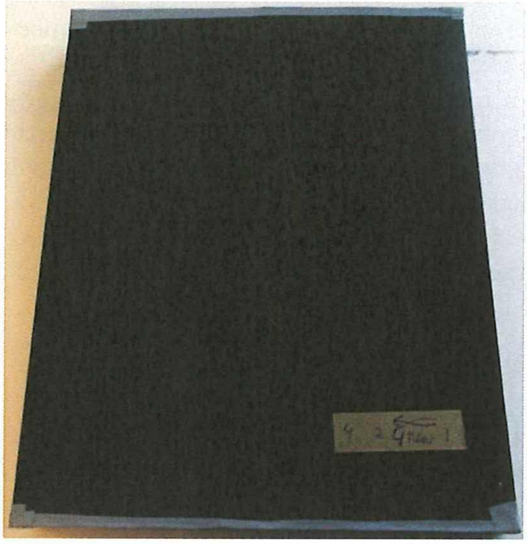


Figure 6.176: Panel 13.2: finished panel back view

Figure 6.177: Brown stains in the airweave on top of the stringers after curing

stringer 1 on the left and the longest at stringer 3 on the right. However, the stains are present to a smaller extent than for panel 13.1. The stains are shown in figure 6.177.

In addition to the resin stains, the same effect of the slipped stringer plies is found in the stringers as in panel 13.1. The height of the slipped stringer plies again directly corresponds to the size of the cavity above the stringer and the top of the core. The slipped stringer plies are shown in figure 6.178.
The corresponding explanations for the different sizes of resin stains and slipped stringer plies are given in section 6.4.2. This time, the filler indentations are also present on the back, but to a smaller extent than for 13.1. This could indicate that the filler movement is less than in panel 13.1 or not even be present at all. The filler indentations are shown in figure 6.179.

Figure 6.178: Slipped stringer plies with stringer 3 in the front

Figure 6.179: Filler indentations on the outer mould line

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.175. The views are also indicated in that picture. The complete images can be seen in appendix D which include all the thickness measurements of the cross sections.
The first observation is that the filler material in all the stringers has moved up slightly. However, the distance that the filler material moved upwards is almost the same for all stringers ranging from 1,5 - 2,0 mm for the all three stringers. As explained in the thickness section, the panel was not under pressurized before the autoclave. The assumption is that as soon as the resin is moving upwards to fill the cavity, the stringer is stuck between the two halves of the stringer laminate flanges. The filler is firmly wedged between the two halves and cannot move up further, because the space within the stringer for the filler material to move upwards is smaller due to proper pressure. As an example, the intersection with the filler material of stringer 3 is shown in figure 6.180.

In addition to the filler material, the slippage of the stringer plies is observed clearly. The outer plies show the least movement upwards, followed by the $\pm$ 45 degree plies. The, darker, 0 degree plies fill the most panel of the cavity. As an example, the top of panel of the slipped stringer plies of stringer 2 are shown in figure 6.181.

Thickness measurement

Contrary to the thickness measurements from panel 13.1, the thicknesses of this panel are all within tolerances and an expected relation is present between the size of the cavity and the thickness of the stringers. The thicknesses of the skin and stringers are displayed below in figure 6.182 and figure 6.183.

The skins thicknesses are all very close to the nominal of what the thickness should be. The two outer cores are rotated away from the stringer with core 1 rotating counter clockwise and

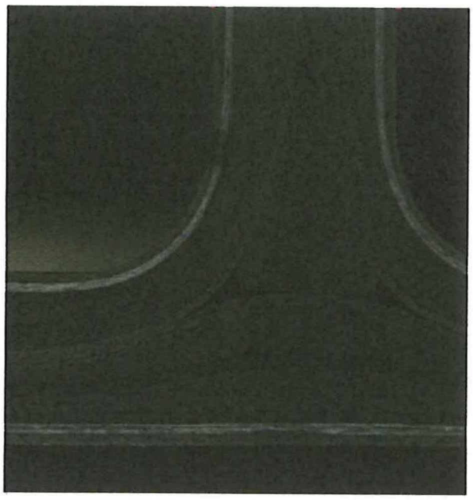


Figure 6.180: Wedging of the filler material between the two stringers halves in stringer 3

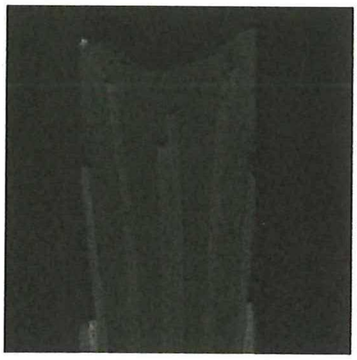


Figure 6.181: Slipped stringer plies in stringer 2

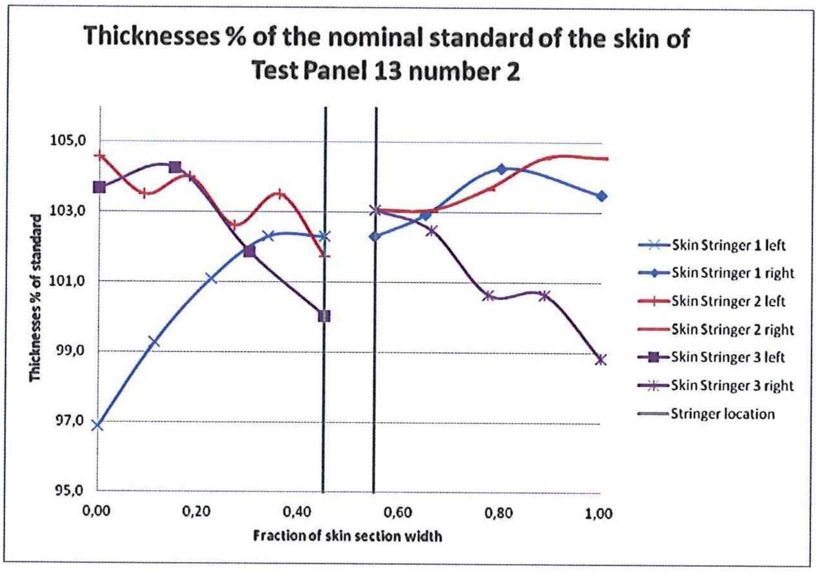


Figure 6.182: Panel 13.2: Thickness percentage of the nominal of the skin

core 4 rotating clockwise. However, the thickness differences are close to each other, so this is not clearly proven.

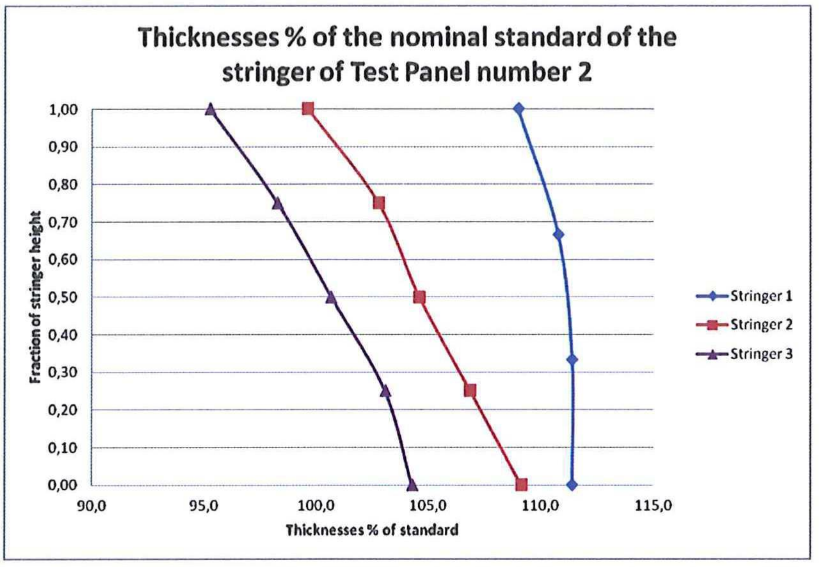


Figure 6.183: Panel 13.2: Thickness percentage of the nominal of the stringers

Table 6.4: Stringer values for panel 13.2

Height difference (mm)	Calculated area to nominal before curing (mm^2)	Actual area after curing (mm^2)	Thickness bottom of nominal (mm)	Thickness top of nominal (mm)
0	101,25	-	-	-
1	99,00	111,56	111,4 %	109,0 %
2	96,75	105,66	109,1 %	99,6 %
4	92,25	101,00	104,3 %	95,2 %

Core 2 and 3 are both pressing down in the corners and exert less pressure in the middle. This is explained by the W-effect, which was explained in panel 4.
All the stringers are thicker at the bottom than at the top. This is logical since the cavity above the stringers needed to be filled with extra material and due to the W-effect. The average thicknesses of the stringers also decrease with an increasing cavity height. In order to see if there is a relation between the areas of the stringer before and after the autoclave cycle and the difference between the thicknesses, the following tables are created:

The goal from these two tables is to see how the cavity above the stringer is filled up. In other words, by checking the area of the stringer before the autoclave cycle and after, it can be determined if the material comes from the skin or from the stringer. Also, it can then be seen

Table 6.5: Stringer differences in percentages

Difference between	Calculated area to nominal before curing differences	Actual area after curing difference	Thickness difference of bottom	Thickness difference of top
1-2	97,7 %	94,7%	97,9%	91,4%
2-4	95,3%	95,6%	95,6%	95,6%

how the areas and thicknesses of the stringers change with an increasing cavity size.
The main conclusion that is drawn from these tables is that the areas and thicknesses after curing decreases for an increasing cavity size and corresponds to the decrease in area before curing. The area after curing of the stringer has however increased compared to before curing per stringer. This is a trend that was also seen in the other panels and has to do with the pressurization of the skin and pushing the resin upwards. In this panel it also has the additional reason that the filler material is pushed up and is partially located in the stringer. The thickness differences at the bottom of a height difference of 2 mm and 4 mm compared to the height difference of 1 mm are almost identical to the differences of the calculated areas to the nominal before curing. However, the thickness at the top of the height difference of 1 mm is almost just as thick as the bottom. This means that the additional resin for that stringer comes from the skin. This explains also why the skin on the left side of the stringer is much thinner than the other skin sections.
The difference between the 2 mm and the 4 mm shorter stringer is on the other hand identical between the calculated area, actual area and the bottom of the stringer and the top of the stringer. This is also observed from figure 6.183 where the stringers 2 and 3 have an almost identical shape, with the difference that stringer 3 is shifted to the left. The difference in calculated area to nominal before curing and the actual area after curing difference between stringer 1 and 2 is therefore only due to the higher thickness of stringer 1 at the top.

Summary and conclusions

In this test part, the production change was made to cut the preformed stringers shorter than the flange of the steel cores. With this alteration, the production error is simulated that if the stringers are cut too short in actual production, that a cavity will be present between the top of the stringer and the top of the core stringer. This is the same as for panel 13.1, but special attention was paid that the stringer pack was pressurized properly.

The defects that were found with the visual inspection were slipped stringer plies and very small filler indentations on the back. The filler material moved up slightly, but is wedged between the two stringer halves and is thus independent of the cavity height. The slipped stringer plies result from the shorter stringers, where the friction and the orientation of the plies ensure that the outer layers do not fill the cavity. On the other hand the inner, and to the largest extend the 0 degree plies, fill the cavity on top. The measured cross sectional stringer areas after curing correlate to the calculated areas before the curing. Since the stringer becomes higher due to the cavity, the stringer also has a more triangular shape where it is thicker at the bottom and thinner at the top. As main conclusions, the stringer thickness becomes smaller with an increasing cavity height and the height of the outer slipped stringer plies is close to identical to the cavity height.

6.4.4 Test panel 14: Filler material size and shape

The process alteration for this test panel is to examine the influence of different filler shapes and sizes. During the manufacturing of the test panels, the same filler material is used as for the actual production. However, the cavity in the intersection is bigger as will be explained in the manufacturing section below. Also with respect to the actual part, there is less filler material used than would be expected based on the cavity it is supposed to fill. In this test part, a stringer is made with 50% of the filer material as well as 100% and a triangular shaped is filler is used with the correct filler amount. This triangular shaped filler material is currently also used in the production of the A350 wing covers.

Manufacturing

The production of this panel is as normal, with the exception that different filler material sizes and shapes are used. In order to calculate the cavity of the intersection between the skin and the two stringer halves, the following geometry is used as displayed in figure 6.184.

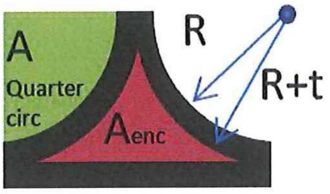


Figure 6.184: Definitions of the geometry

With these definitions defined, the area of the intersection is calculated as follows:

$$A_{tot} = 2(R+t)(R+t) \tag{6.4}$$

$$A_{circ} = \frac{1}{4}\pi(R+t) \tag{6.5}$$

$$A_{int} = A_{tot} - 2A_{circ} \tag{6.6}$$

The cavity that needs to be filled in the actual panel in the intersection of stringer and skin is 3,19 mm^2. Of the test panel that is 4,19 mm^2.
In other words, the cavity of the test panel is 31% larger than that of the actual part. However the same filler material amount is used. Currently, a carbon fibre strip of 20 mm is twisted to become the filler material. For the actual part, this corresponds to an area of 0,125x20= 2,50 mm^2 which leads to a percentage of the intersection covered by the filler material of 78,4%. For the test panel this is 59,7%. So in the actual panel and the test panels, the intersection area is filled with resin from the panel to compensate for the remaining fibre free area.
In this panel a filler size of 50% of the nominal filler size is used in stringer 1. This corresponds to a carbon fibre strip of 10 mm. In stringer 2, the filler size is 50% larger than the nominal size, which corresponds to a filler material strip of 30 mm. For stringer 3, a special triangular shape is constructed from a strip of the same carbon fibre material with an equivalent width of 36 mm. This strip is formed into the triangular shape, using a special machine, the resulting filler material strip is shown in figure 6.181. An overview of the different filler materials and their relation to both the test panel and actual flap are given in table 6.6:

The overview of the different filler materials that are placed in the intersections are shown in figure 6.186 for the 50% and 150% filler material and for the triangular filler material in figure 6.187. The overview of the front and back of the panel after curing is shown in figure 6.188 - 6.189.

Visual Inspection of the part

By visual inspection, the following defects are observed:

- In-plane waviness

Table 6.6: Different filler material values

Intersection type	Radius (mm)	Intersection area (mm^2)	Filler strip width used (mm)	Percentage covered	Ideal filler strip width for 100% coverage (mm)
Actual flap	1,6	3,19	20	78,4%	25,5
Test part	2,0	4,19	20	59,7%	33,5
Actual part: 50% cross sectional filler area	1,6	3,19	10	39,2%	25,5
Actual part: 150% cross sectional filler area	1,6	3,19	30	117,6%	25,5
Test part: 50% cross sectional filler area	2,0	4,19	10	29,8%	33,5
Test part: 150% cross sectional filler area	2,0	4,19	30	89,5%	33,5
Test part: Triangular filler	2,0	4,19	36	107,4%	33,5

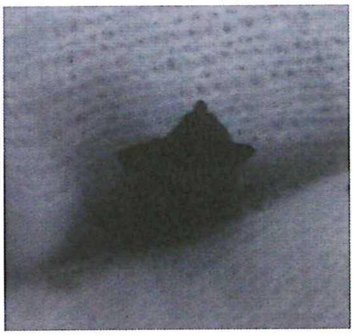


Figure 6.185: Triangular filler material

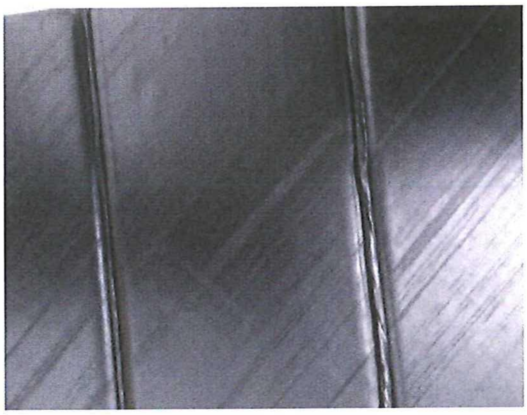


Figure 6.186: 50% and 150% filler material place in the intersection

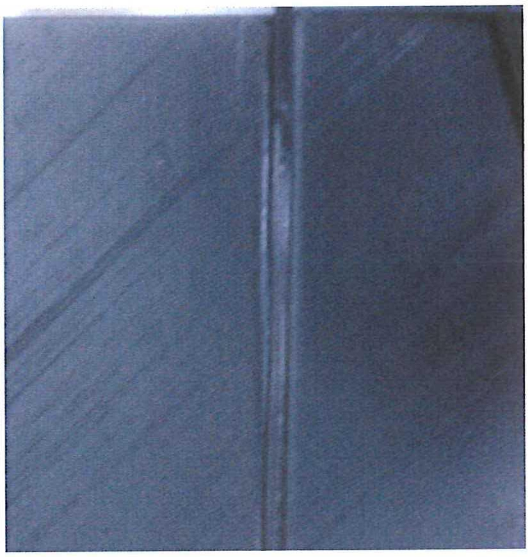


Figure 6.187: Triangular filler material placed in the intersection

- Out-of-plane waviness
- Filler indentations on the back

On the back of the panel on the skin, filler indentations with out of plane waviness in the form of a wrinkle are present below stringer 1. This is the stringer with the 50% filler material. This indicates that either the filler material, due to an insufficient cross section, was not able to fill the intersection properly or that it moved upwards or that the resin flow from the material to the intersection was insufficient, so that the skin leaves an out-of-plane wave. The filler indentations on the back of stringer 1 are shown in figure 6.190.

The origin of the undulations is explained in the evaluation of the cross sections section and they are caused by the W-effect and can be seen in the stringers in figure 6.191.

Evaluation of the cross sections

The locations of the cross sections are indicated in figure 6.188.
The cross sectional images of the three different filler materials are shown in the figure 6.193 - figure 6.194.

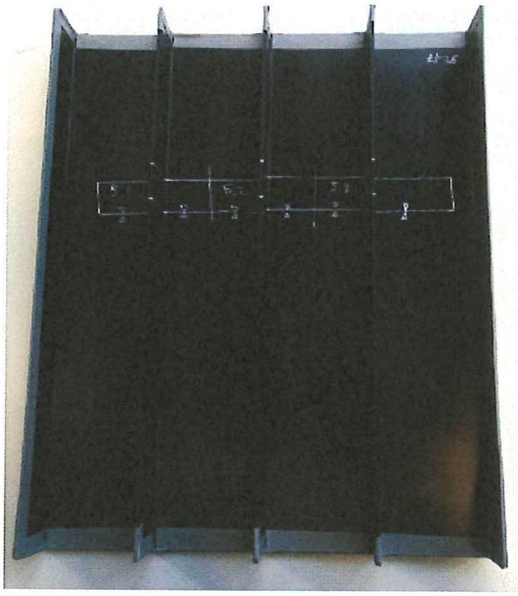


Figure 6.188: Panel 14: finished panel front view

Figure 6.189: Panel 14: finished panel back view

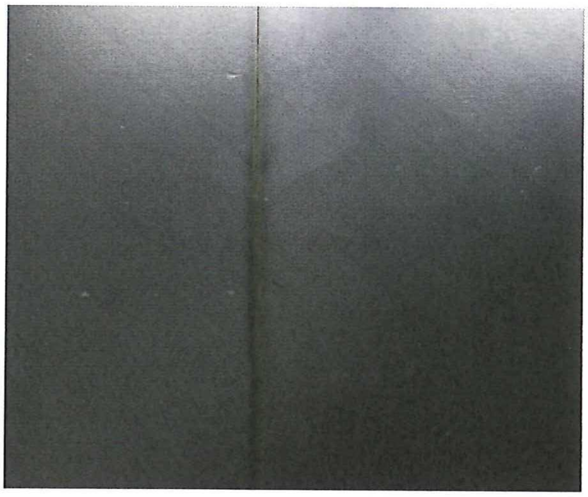


Figure 6.190: Filler indentation for stringer 1 on the outer mould line

From these images, the influence of the different filler sizes and material is seen clearly. The 50% filler in stringer 1 moved completely up the stringer with a distance of 2 mm, due to its insufficient size. As a result, the fibres in the skin filled the intersection, creating a large wave in the skin. This consequently leads to the wrinkles at the bottom surface of the skin. For the 150% filler material in stringer 2, the laminate in the stringer is completely compressed. This can be seen from comparing the thickness of the laminate of the stringer halves next to the filler material with that of stringer 1. The filler material also moved up slightly with a distance of 0,7 mm. In stringer 3, the filler material also moved upwards, in this case with a distance of 0,5 mm Comparing stringer 2 and 3, it is seen that the triangular filler material fills the intersection better with fibres with almost no pure resin spots. Also the triangular filler material has more material than the 150% filler.

Additional, the in-plane waves are also seen in the cross sectional images in the outer surface. Next to the in-plane waves, also out-of planes are observed in both stringer 1 and stringer 2. By looking at the thicknesses, it is assumed that the tooling deforms in the autoclave, clamping

Figure 6.191: In-plane undulations in the stringers

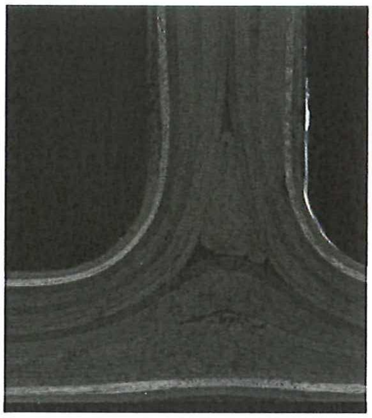


Figure 6.192: 50% filler material in the intersection of stringer 1

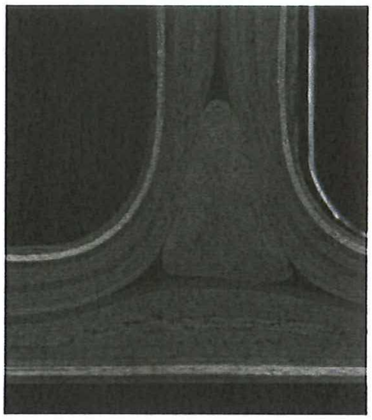


Figure 6.193: 150% filler material in the intersection of stringer 2

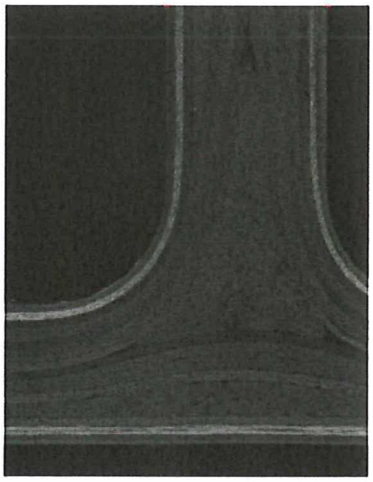


Figure 6.194: Triangular filler material in the intersection of stringer 3

the bottom of the stringer by the so-called W-effect. The top of the stringer is then compressed from the top by the autoclave pressure and because the stringer is pushed upwards, resulting in the compression of the stringer in axial direction. When examining the top of the stringer, it can indeed be concluded that the stringer was compressed on the top, due to the deflection of the layers to the left. This is the result from an axial compression. As an example, the out- and in-plane undulations of stringer 1 are shown in figure 6.195 as well as the top of the stringer in figure 6.196. More on the axial compression of the stringer is explained in the thickness measurement section.

Thickness measurement

The thicknesses of the skin and stringers are displayed below in figure 6.197 and figure 6.198.

The skins thicknesses are all close to the nominal of what the thickness should be. Interesting to see is that the skins have globally the same shape for all the skins on the right side and all

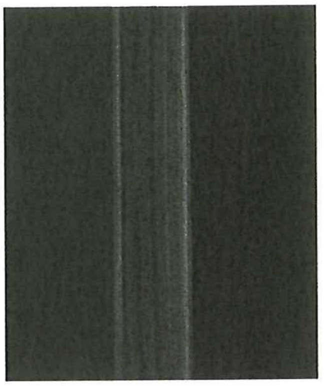


Figure 6.195: In-plane undulation in stringer 1

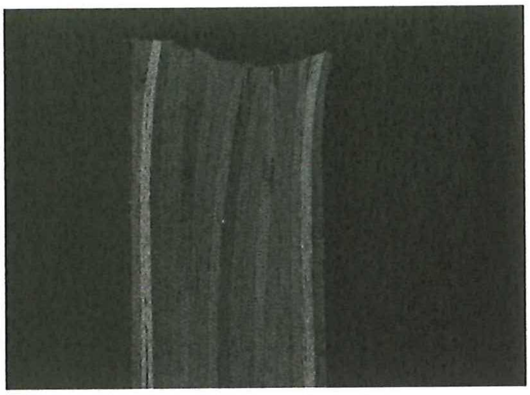


Figure 6.196: Top of stringer 1

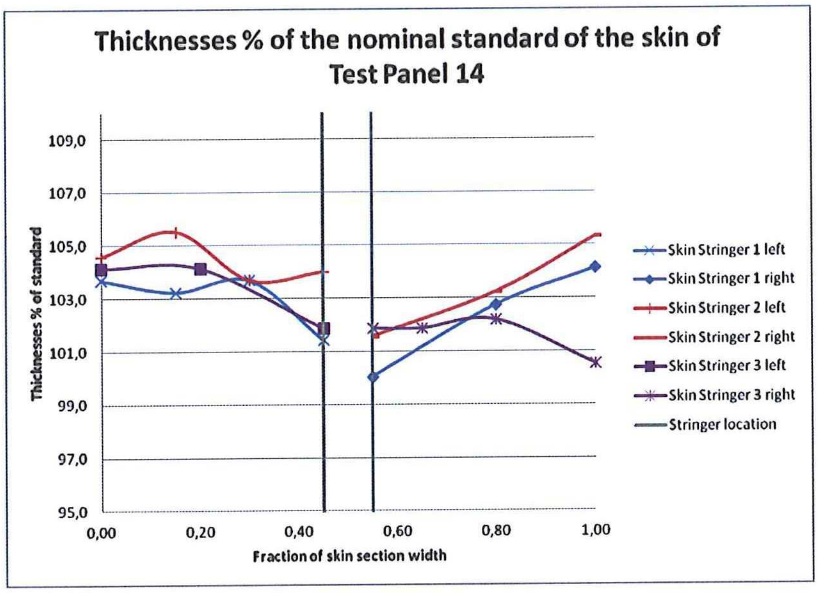


Figure 6.197: Panel 14: Thickness percentage of the nominal of the skin

the skins on the left side. The panel has the same contour as the outer contour of the core, so with a core with a perfect straight web, these results would not be possible. Core 2 for example is pressing down on the right side of stringer 1 and the pressure decreases, closer to the centre of the core. After that, the core again exerts more pressure near the corner of stringer 2, resulting in a thinner skin. By looking at the stringer thicknesses, they are all thicker at the bottom than at the top. The conclusion from this is that the steel cores deform slightly due to the autoclave pressure in the way as described in test panel 4 as the W-effect. The fact that the undulations occur is due to the autoclave pressure that is exerted in the top, the bottom of the stringer is pushed upwards by the filler and the clamping on the bottom due to the filler in figure 6.199.

This deformation would explain the thickness differences as well as the shifting of the filler material upwards for all three stringers. As soon as the stringer gets stuck between the cores, the laminate becomes clamped between the filler and the cores. On the top of the stringers, there is a layer of release film, the airweave and the vacuum bag. These layers are pressed onto the stringers and create a flat surface. As soon as the core flanges are pressed inwards, the ancillary material at the top of the core will move with it. This leads to that the release film for

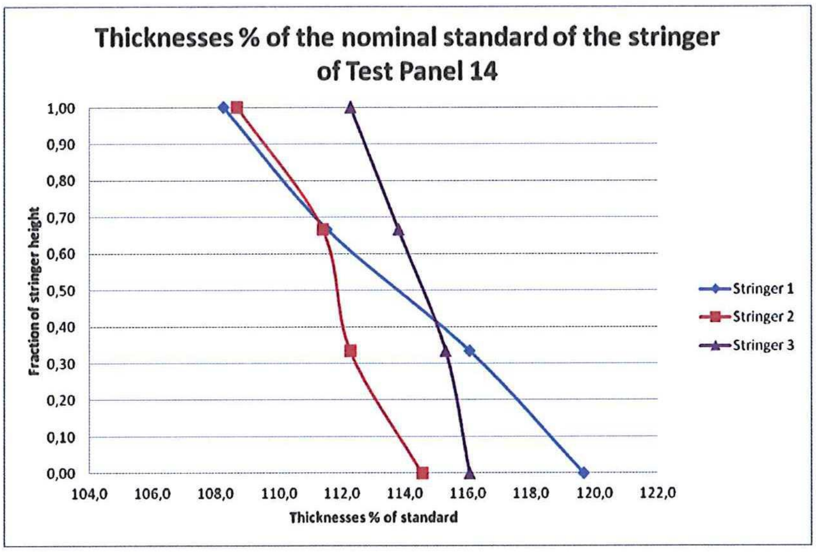


Figure 6.198: Panel 14: Thickness percentage of the nominal of the stringers

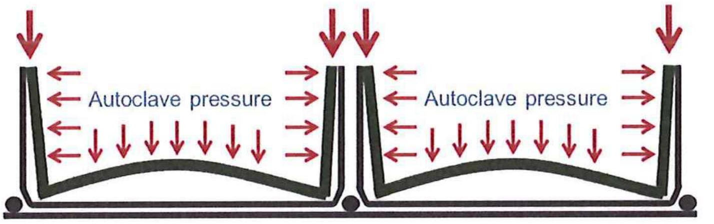


Figure 6.199: Cause of in-plane waviness in the stringers

instance is not completely straight in tension above the top, but that it is slacking due to the pressurization. This gives the option for the autoclave pressure to push directly on the top of the stringer laminate instead of that the pressure it taken up mostly by the tension in the release film above it. With the pressure exerted on the laminate from the top and the laminate clamped below, the fibres start to deform into undulations. This last panel is in the real production not possible, since the cores are closed off at the top, so the pressure cannot be exerted directly onto the laminate. However, the carbon fibre core can deform due to the pressure, so the thickness variations can occur.

By looking at the thickness differences of the individual stringers with respect to each other, it is seen that stringer 1 is the thickest at the bottom with a thickness of 2,692 mm or 119,6% with respect to the nominal. The filler material of 50% cross section is pushed all the way up the stringer, due smaller size of the filler. This leads to the local thickness increase at the bottom and also to a large thickness difference with the top of 0,257 mm. Stringer 2 has the smallest thickness at the bottom of 2,577 mm or 114,5%. In figure 6.193 it can be seen that the laminate is pressurized a lot between the filler material and the core and it also leads to a smaller total stringer thickness. More fibre material in the bottom suggests that the deformation of the core is less, which also corresponds to a smaller width difference compared to the top of 0,132 mm. The same is true for stringer 3.

Summary and conclusions

In this part, different filler materials and sizes were used to examine the effects on the quality. Currently, not enough filler material is used in the production of the flaps in order to have 100%

coverage of the intersection area. To study the effect of adding a different size of filler material or a different shape of filler material, three different fillers are used in different stringers in the same part. A filler with 50% of the cross sectional area of the currently used filler, a filler with 150% and a triangular shaped filler material are used in the construction of this test part. The defects that were found with the outer quality visual inspection were in-plane waviness in the stringers and out-of-plane waviness and filler indentations on the back of the skin along the length of the stringer with the 50% filler material. Inspecting the cross sections for the inner quality shows that the 50% filler material is too small for the intersection and moved upwards into the stringer. The triangular filler material fills the intersection the best with almost no pure resin spots. The laminate of the stringer with 150% filler material between the filler and the core is over pressurized by the autoclave pressure. Examining the thicknesses of the panel has led to the conclusion that the cores have elastically deformed in the autoclave. This causes a thicker laminate in the skin in the centre between the stringers and a thinner laminate in the skin near the corners. Another result of the core flange bending as well as the shifting of the filler material upwards is that the stringers are all wider at the bottom than at the top. Different compared to the actual panels is that in this test panel out-of-plane and in-plane undulations are present in the stringer. The reason for this is that the stringer laminates are clamped between the filler and core. Also, the autoclave pressure is exerting force on the top of the stringer due to the deformation of the tooling. In the actual panels, the tool is closing of the top of the stringer, so no force is directly exerted on the stringer. As a main conclusion, the filler amount is used currently in the production of the flaps, but the filler amount in the test panel should be increased. If the shape is changed to a triangle, the intersection will be filled more compared to the twisted round filler material.

6.5 Summary and comparison of the results

In order to find the causes of the defects which occur in the flaps, test panels were made which incorporated variations on the manufacturing process. By introducing the production process variations and examining the panel quality after processing, the causes were determined. Key in producing test panels that represent the actual flaps from serial production is to use tooling, materials and a manufacturing process that is as similar as possible to the actual panels.
As a result of the test panel manufacturing, a defect map was constructed that shows images of the defects per category and its respective cause. The defect map is based on the conclusions from the trials which are given in this chapter. Additionally, the results from the trials serve as the basis for setting the requirements for a new tooling concept which are given in chapter 8. The defect map can be used to identify defects in the actual process and the matching causes easily. This defect map will also serve as a basis for setting the requirements for the new tooling concept. The complete defect map is shown in figure 6.200 and the comparisons and summaries below will be done according to the detectibility of the defects by visual inspection, evaluations of the cross sections and thickness measurements. Also a short overview is given on which steps should be taken in order to localise the individual cause of a defect, when the global cause is determined by observing the defects.

Defects detectable by visual inspection

Undulations
Undulations (or waves) are defects in cured carbon fibre panels whereby the fibres show waviness in either the in-plane or out-of-plane direction of the fibre. They are assumed to originate when an external force is applied to the fibres or if movement is constrained. In-plane undulations are a form of fibre waviness that occurs in the longitudinal direction of the fibres in the plane

of the ply. In other words the orientation of the fibres within the carbon fibre layer changes. Out-of-plane undulations are a defect where the carbon fibre layers themselves show waviness. Out-of-plane waviness is, unlike in-plane waviness, independent on the fibre orientation.
The in-plane waviness is most seen clearly on the outside of the part, because it concerns the waviness of individual fibres in the plane of the laminate and is observed by a difference in a reflection of light. Additionally it can be observed from an evaluation of the cross sections by checking the shape of the individual fibres or by checking the grey scale colour of the fibres. The grey scale changes when the orientation changes within a ply.
Out-of plane waviness can be seen by visual inspection as lines in the laminates surface that are independent of the fibres orientation. For both types of undulations, only waviness in the outer layer can be observed by visual inspection. Presence of undulations on the outside could give an indication that undulations are present through the thickness of the laminate as well.
In the test panels there is in-plane waviness present already in the rolls of prepreg material and is also seen in the cured laminate. This defect is therefore not being considered as a manufacturing defect. Since it has a negligible effect on the final part quality, no action is being taken by Airbus to change the prepreg
In test panels 8 and 12, when the preform core is wider than the autoclave core and if the stringer is higher than the stringer cavity, the presence of the in-plane undulations in the stringer indicates that there is an axial compressive force acting on it. This is also the case when a too large filler material is used as in panel 14, where the laminate is clamped at the bottom and the autoclave pressure acts directly on the stringer top. In-plane undulations are also present in the corner section of the skin where resin rich areas are present, like in panels 10, 11 and 12.
In test panel 6 and 7, the core was hanging and undulations are present in the in- and out-of-plane direction in both the skin and the web of the U-profile. The degree and distance of slipped stringer plies directly correspond to the degree and presence of undulations. The undulations in the web are caused by a combination of the slipped stringer plies and the constraining of the whole pack.
Undulations are also present if the preform core is smaller than the autoclave core like in panels 4 and 5. In panel 9, where the cores are shifted in x-direction with ramps present in the laminate, in-plane waves were indicated with the visual inspection in the panel close to the dry spots of the skin with the core with the largest shifting of the core.
When undulations are present in other layers than the top layers, they can only be observed by evaluating the cross sections. Examples of this are panels 9 and 7. In panel 9, out-of-plane undulations are observed where the web of the stringer is squeezed to one side due to an uneven pressure. In panel 7, severe undulations and wrinkles are observed by evaluation of the cross sections and caused the skin to be up to 25% thicker than the nominal value, because of the build up of fibres in the skin. Therefore a higher thickness could indicate that severe undulations are present on the inside of the part.

Slipped stringer plies
The defect of slipped stringer plies is that the outer ply or plies shifted with respect to the inner layers in the cured stringer even though they were at the same height before curing. The slipped stringer plies are seen clearly by visual inspection since it concerns the outer layers of the laminate. To obtain the effect of slipped stringer plies, two main different causes can be stated. One is that slipped stringer plies result from the shorter stringers, where the friction and the orientation of the plies ensure that the outer layers are squeezed and do not fill up the cavity. On the other hand the inner, and to the largest extend the 0 degree plies, fill up the cavity on top. This was demonstrated in panel 13.1 and 13.2 where the slipped stringer ply height corresponds directly to the cavity height above the stringer.
The other cause of slipped stringer plies is that the individual layers are dragged down with a shear force when the resin becomes liquid in the autoclave and was demonstrated in test panels

5, 6 and 7. In test panel 6 and 7 a hanging core was present where the presence of slipped stringer plies is more severe with an increased hanging height.
In panel 5 the preform core is smaller than the autoclave core. Here, the cores are resting on the fillers, creating a gap between the web of the steel core and the skin of the laminate, leading to slipped stringer plies.
Slipped stringer plies often cause other defects when the outer layers are dragged down, like undulations and wrinkles, since the movement of the extra carbon fibre material is constrained in the skin.
Slipped stringer plies can also always be observed clearly with the evaluation of the cross sections and the number of slipped layers is easy to count. Also by measuring the thickness, an indication for slipped stringer plies can be given. For part 13.2, the stringer thickness becomes linearly less with an increasing cavity height.

Dry Spots
Dry spots indicate that there is no contact between the tooling and the laminate. The dry spots are mainly caused by improper evacuation of entrapped air when the laminate is closed off too much or if the pressure is not enough so that there is not enough resin present to fill the cavity, e.g. the critical cavity dimension is reached. Dry spots are present in part 3, where the stringers were sealed off from the vacuum, leading to improper evacuation of the entrapped air. In test panel 9, the dry spots are present in the under pressurized section of the skin, indicate that the cavity is too large and that the critical cavity height was reached. The pressure in the autoclave itself is uniform during curing and the dry spots are caused by the distance between laminate and core.

Defects detectable by the evaluation of the cross sections

Wrinkles
A wrinkle is a special kind of waviness where the carbon fibre layer folds over itself, and could thereby entrap the release film in the surface layers. The same as for undulations, an external force or the constraining of movement is causing the formation of a wrinkle. The tooling is in contact with the outer ply of the laminate, so the most likely cause is that the tooling is pressing the outer layer downwards. A wrinkle is formed mostly in combination with slipped stringer plies, because the extra material from the stringer is pushed into the skin. Also a wrinkle is most often only present in one or a few of the outer layers.
This is for example the case in panels 6 and 7 where the core is hanging and pushing the outer layers into the skin, forming wrinkles in the corner sections. This is the same with part 5. The severity of the wrinkles increases with the distance of the slippage of the plies in the stringer. Wrinkles can only be observed by evaluation of the cross sections, but inclusion of the release film could give an indication that a wrinkle is present in a corner section.

Resin rich areas
Resin rich areas occur in the corner section between the laminate and the stringer. The outer layer is over saturated with resin, which causes the carbon fibre layer to expand in thickness. This defect is almost the same as the wrinkles, with the difference that the whole stringer seems to be pushed down without the outer layer moving separately from the other layers. In this case, no fold of only the outer layer of the laminate will occur. In panel 12, resin rich areas in the corner sections are present from pushing the stringer downwards since the stringer is higher than the height of the stringer cavity. The resin rich areas in the corner sections are also caused by the core movement in y-direction, by both lateral movement in panel 10 and rotation in the xy-plane in panel 11. Where the resin rich areas are present, the thickness in the skin is

larger on average than if the resin rich areas are not present. The shape of the resin rich area is determined by the pushed down layers below it.
Where resin rich areas are present, the thickness in the skin is also larger on average than if the resin rich areas are not present.

Filler misalignment
One of the defects that is clearly noticeable from the cross sectional images is the misalignment of the filler material. The defect of misaligned filler is that the filler material is not in the centre of the intersection of the two stringer halves and the skin. The filler material has then either shifted upwards and is located between the two stringer halves or sideways when it is located between the skin laminate and the web of the U-profile laminate.
For upward filler misalignment, there is space in the stringer available for the filler to move upwards, e.g. the stringer cavity is too wide, the filler too small or there is space above the stringer that needs to be filled. For sideways misalignment, there needs to be a sideward movement or force acting in the translational direction of the stringer. The resulting force seems to shift the complete stringer away from its original location or constrains the movement of the stringer in relation to the movement of the filler and skin. The conclusion is therefore that either there is a force pushing the stringer sideways or that the skin and filler material have moved sideways.
The bad preforming and compressing of the pack in test panels 1 and 2 resulted in the vertical movement of the filler up the stringer. The preformed material was not attached to the web of the steel core when the pack was compressed, causing the filler to move upwards in the autoclave. Also, if the cavity of the stringer is too wide, the filler material also had space to shift upwards as was demonstrated in panels 13.1 and 8. In panel 13.1, there was also a cavity present between the stringer and the top of the core, which further assisted in the vertical filler movement (also in panel 13.2. In panel 14, where the filler material is at 50% of its size, the filler material shifts upwards.
Sideways filler misalignment was demonstrated in panels 4 and 5, where the preform core is smaller than the autoclave core. In panel 11, the filler is also misaligned sideways due to the sideways movement of the core. The core is pushing the material sideways together with the complete stringer, instead of pushing the stringer over the filler material like in panel 5. This wedges the filler material between the stringer web and the skin laminate on the other side.
The presence of upward filler misalignment can also be indicated by visual inspection. In- and out-of-plane undulations can be present on the outside of the skin as well as indentations on the skin is across the entire length of the filler location. The sideways misalignment of the filler can only be proven by checking the inner quality.

Defects detectable by thickness measurements

Mismatch between tooling ramp and ply step location
Differently from all the other panels, panel 9 was made with the manufacturing alteration that the cores are shifted in x-direction with ramps present in the laminate. The mismatch in ply steps and tooling ramps is concluded from thickness measurements, but also from evaluation of the cross sections.
The main conclusion from the thickness measurements is that the outer surface and contour of the panel are formed by the tooling. In addition, the actual thickness of the laminate and the ramps are determined by the number of plies when in compression and by the tooling shape when there is a cavity present.

W-effect
Examining the thicknesses of some panels (6, 11, 13.2, etc) has led to the conclusion that the

cores have elastically deformed in the autoclave. This causes a thicker laminate in the skin in the centre between the stringers and a thinner laminate in the skin near the corners. Another result of the deforming core is that the stringers are all wider at the bottom than at the top. This effect is significant enough to influence the part quality, so a stiffer tooling is advised for further tests or the w-effect needs to be examined more in the actual parts to see the compliance with the test tooling.

Steps to be taken to localise the specific defects cause

If the cause of the defect is determined to be that the preform core is wider or less wide than the autoclave core, the caul plate and preform core width as well as the cured panel width need to be measured and compared to their nominal values. The deviating values are causing the defects. Additionally if the cause is that the preform core is less wide the placement and alignment of the edge bars and of the caul plate cores needs to be checked for the presence of cavities, e.g. no cavity between edge bar and Femi and laminate or between core and laminate. Finally, the presence of hanging core defects needs to be checked.

If the cause of the defect is determined to be that the laminate stringers are longer or shorter than the stringer cavity of the caul plate core, the caul plate core stringer cavity, the preformed laminate stringer height and the cured panel stringer height need to be measured and compared to their nominal values. The deviating values are causing the defects.

If the cause of the defect is determined to be that the caul plate core is hanging, the caul plate core stringer pack width including the stringer laminate, the individual caul plate core widths, the cavity space for the complete stringer pack width and the cured panel width needs to be measured and compared to their nominal values. Also, the placement and alignment of the edge bars and the caul plates needs to be checked, e.g. no cavity between the edge bar and Femi/laminate and between the core and laminate.

If the cause of the defect is determined to be that the caul plate core moved sideways in the autoclave, either the caul plate(s) moved in y-direction if the defects are linear along the entire core length, or the caul plates rotated when the defects are locally present. The causes of the sideways movement originate from, misalignment and misplacement of the edge bars and/or the cores. To identify the specific cause of the defects the placement and alignment of the edge bars and caul plate cores needs to be checked, e.g. no cavity between edge bar and Femi/laminate or between core and laminate.

If the cause of the defect is determined to be that the caul plate core in x-direction is misaligned with the laminate, the placement and alignment of the laminate and caul plate cores needs to be checked. Also the position and dimensions of the ramps and the alignment of the tooling ramp locations with the ply drop locations needs to be checked.

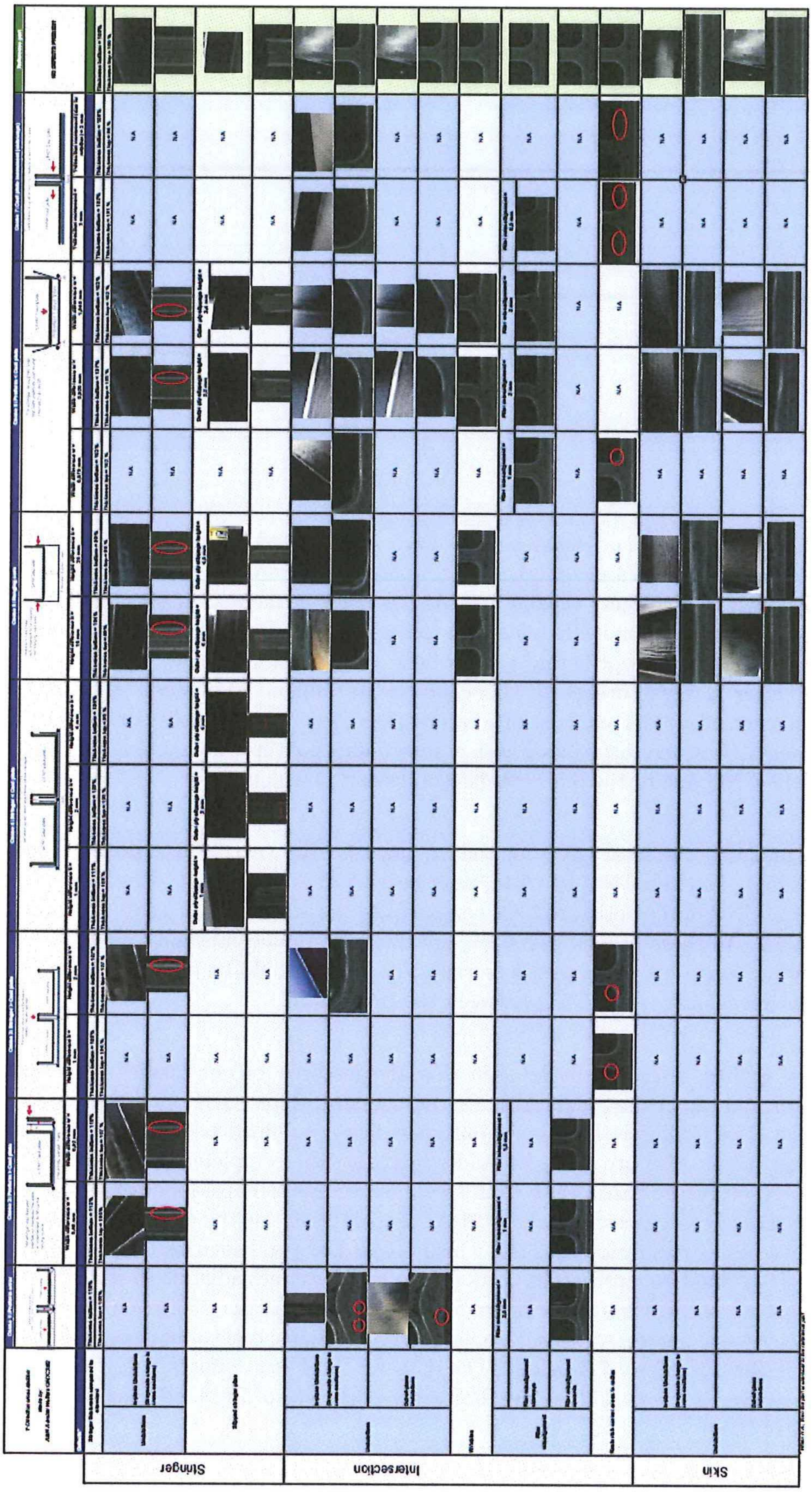


Figure 6.200: Defect map of the defects which result from the process alteration causes (details in appendix F)

Chapter 7

Economical analysis

Currently, most panels are of insufficient quality to be shipped directly after manufacture. The panels need to be repaired and reworked first, in order to remove all the defects that are present due to manufacturing. These repairs cost Airbus a lot of money. If these defects cannot be repaired, or it is not economically beneficial to repair them, they are scrapped completely. The idea of a new tooling concept is that there will be fewer repairs needed, since fewer defects will be present after manufacturing. In this chapter, an economical analysis is performed on the costs of the current repairs and cost of scrap panels (Cost of Non-Quality or CNQ). The idea is that the more defects can be avoided with a new tooling concept, the more money can be saved. For that, the CNQ due to the different defects needs to be examined.

As a first analysis, the total CNQ for the SA flaps for the year 2013 is done, as measured in December 2013, and the CNQ for 2014, as measured in August 2014. The two corresponding graphs of the CNQ of the outboard flaps compared to the other SA panels are shown in figure 7.1 and figure 7.2. In these graphs, the CNQ are divided in nonconforming products/concessions (conc), rework (rew) and scrap panels (scrap). Attention should be paid to the deviation of the meaning of the colours of the CNQ between the two graphs.

From these graphs, it can easily be seen that the majority of non-quality costs for the total SA program come from the Single Aisle (SA) OutBoard Flaps (OBF), followed by the InBoard Flaps (IBF). The CNQ for the in- and outboard flaps combined is almost just as much as for all the other panels that are made in Stade, including the complete vertical tail plane (VTP). Most of the cost for the flaps comes from scrapping complete flaps, followed by the rework and to a small extend the concessions. For 2013, the total CNQ for the outboard flaps equalled 2.2 million euros. The expectation for 2014, which is based on extrapolating the data from figure 7.2 till August, is 1.8 million euros. The costs are slightly lower already due to several improvement projects that decreased the rework hours for thickness deviations, bulges and glass ply defects. The average rework per aircraft (AC), so for 2 outboard flaps, due to the several different defects for 2013 is shown in figure 7.3 below. The data for 2014 was unfortunately not available yet, so the economical analysis will be based on the defect data of 2013, combined with the overall CNQ data of 2014.

The total production costs are around 16 million euros. Taking into account the 2.2 millions of CNQ comes down to that the CNQ is 13% of the total production costs. Looking at figure 7.3, the rework hours due to slipped stringer plies is 7,9 and for the undulations 7,7 hours. The

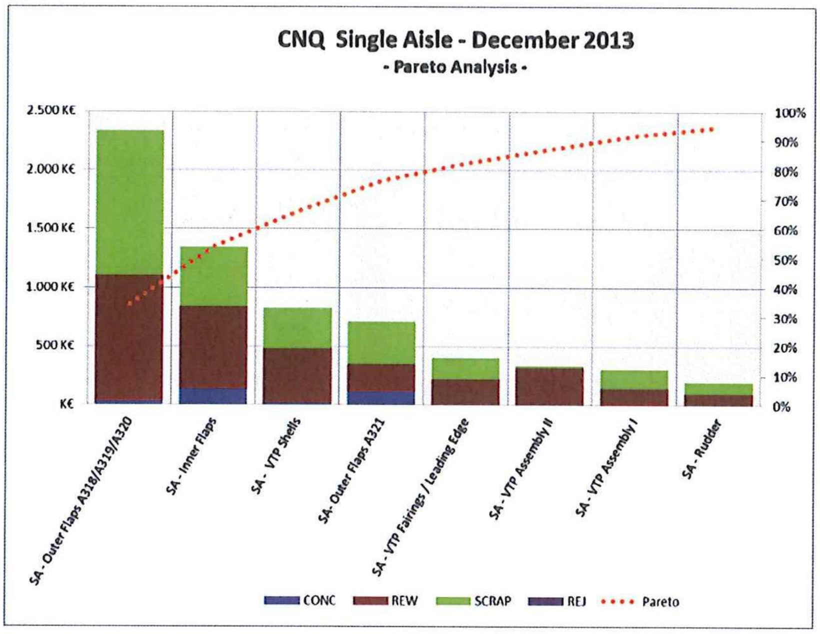


Figure 7.1: Cost of Non-Quality for SA panels 2013 till December

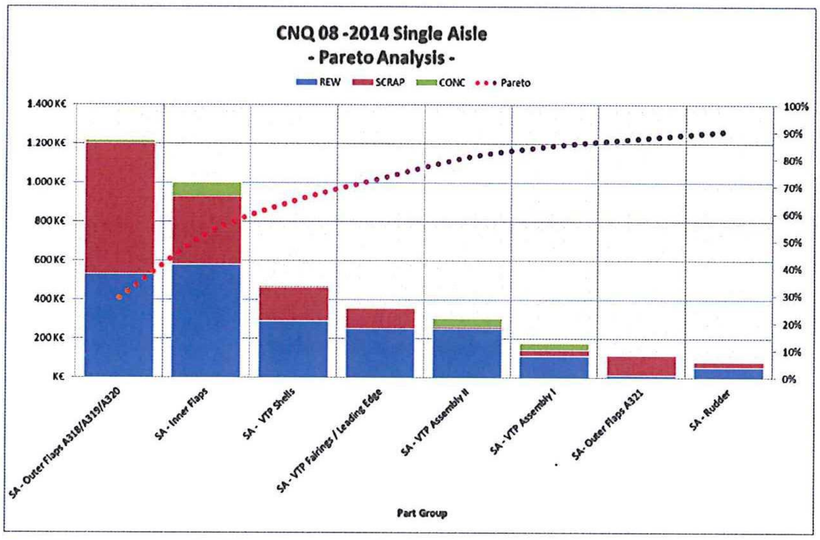


Figure 7.2: Cost of Non-Quality for SA panels 2014 till August

total rework hours per AC are 22,2, so the slipped stringer plies and the undulations combined take up 71% of the time of the rework. So as a rough estimation, the slipped stringer plies and undulations combined cost 1.562.000 Euros in rework per year by extrapolating the data. Ideally, the new tooling concept removes all the causes of these two defects completely, leading to production cost savings of 1.562.000 Euros. These savings should pay for the investments that need to be done in order to remove the causes of the defects in a maximum given time, called the maximum payback time. The time in which the investments are paid back with the savings is called the Return of Investments (ROI). This ROI needs to be below the maximum payback time set by Airbus before an investment is considered. At the moment this ROI time is set to 1,8 years.

Airbus uses a business case template where you can fill in the savings and costs and the Excel macro will, among other results, calculate the RIO. The macro takes into account all the variables for the upcoming years, like the expected production rate and the discount rate. Both the

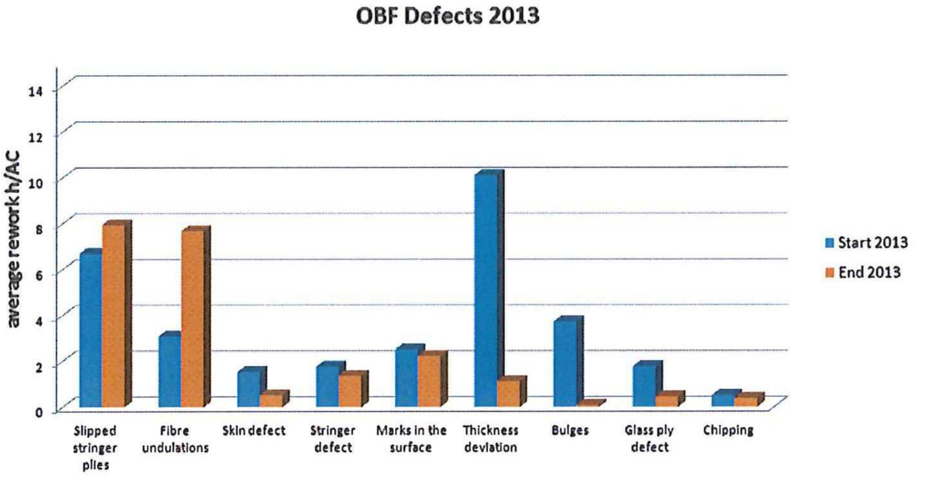


Figure 7.3: The average rework for the OBF per AC, due to different defects for 2013

costs and the investments can be divided over the next years in a lot of different ways, changing the ROI with every alteration. Attention should be paid on finding the optimal distribution to have the lowest ROI possible.
In addition to only paying the investments back with the savings, it is also known how much the recurring savings will be after the implementation and pay back of the investments. These savings will permanently lower the manufacturing costs of the outboard flaps. In this project however, a simple business case is setup, because it concerns an indication of the budget of the tooling only.

If the slipped stringer ply and undulations defects would be removed completely, Airbus would save in 1,8 years:

$$1,8 \cdot 1,1562 = 2,8 million \tag{7.1}$$

However, these defects cannot be removed 100% with a new tooling concept. So as a reasonable assumption it will be assumed that it is possible to reduce the slipped stringer plies and undulations to 20% of the current defects and thus 20% of the repair costs of these defects. This would result in a saving in 1,8 years of:

$$2,8 \cdot 0,8 = 2,2 million \tag{7.2}$$

As a conclusion, 2,2 million Euros is the money that is available for a new tooling concept that would reduce the slipped stringer ply and undulation defects to 20% of the original rework amount.

Chapter 8

Requirements for tooling design

In this chapter the requirements are listed for the new tooling design, which includes the results from the reproduction of the defects in the test panels and the causes of the defects that were determined. In addition to the requirements and suggestions that are set from the defect causes, also the general requirements with respect to the tooling are stated. When all these requirements are implemented, panels of acceptable quality should be able to be produced.

Tooling general

- Ideally, there is one set of tooling for both preforming and the autoclave cycle. That way, the following causes of in- and out-of-plane undulations in the skin and stringers, slipped stringer plies, wrinkles, resin rich areas and horizontal filler movement defects are removed, since both toolings have the same dimensions and the following situations are eliminated:
  - Preform core cavity is smaller than the autoclave core
  - Preform core cavity is larger than the autoclave core
- If one set of tooling is used for the preform and autoclave step, the tooling is ideally not removed from the panel (for instance for the removal of release film or cutting the stringers) between the performing and the autoclave build-up. That way, the following additional cause of defects is removed:
  - Hanging core
- If it is not possible to have one set of tooling, the autoclave caul plate cores are preferably slightly smaller than the preform cores, since the least defects will be present in the finished part.
- Ideally, the stringers need to be cut to the exact length, by ensuring that the cutting template has the exact dimensions as the stringer cavity and that the template is always placed correctly or that the stringer is cut on the tooling itself. Preferable, the stringer laminate is cut to size already before the performing, but it needs to be ensured that the performing does not shift the laminate sideways so that the two stringer halves are of equal length, not that one is shorter than the cavity and one is longer. By ensuring the equal length of the stringer laminate as the stringer cavity, the following additional causes of in-plane waviness in the stringer, slipped stringer plies and resin rich areas defects are removed:

  - Stringer cavity is larger than the stringer of the laminate
  - Stringer cavity is smaller than the stringer of the laminate

Preforming

- During performing, the laminate needs to be secured properly in order to avoid the shifting of the laminate (e.g. by clamping, vacuum, pressure etc). Also after the preforming, the stringer laminate should still be attached to the preform core so that the corner section stays in place around the preform tool. The shifting and non attachment of the laminate to the preform tool can cause stringers of unequal heights but also the following cause of defect is removed:
  - Wrong preforming

Tooling placement and positioning

- Marks or constraints of the tooling need to be present for both the preform and the autoclave build-up step. Essential is that the tooling lines up perfectly with each other. Since the tooling is conical, shifting in the x-direction will result in a preform core cavity that is smaller than the autoclave caul plate core if the core is shifted in the narrower direction and larger if it is shifted in the wider direction. This problem can also be avoided by having one set of tooling that is not removed from the stringer pack. The marks and constraints between the tooling cores will eliminate the following cause of defect:
  - Caul plate movement in x-direction
- The stringer pack needs to be placed perfectly with respect to the edge bars. Marks or constraints need to be used for this so that the caul plates are not on a slope of the edge bar supports. That way the tooling cannot shift in the autoclave due to the pressure and the liquidity of the resin. The following additional causes of defects are then removed:
  - Caul plate movement in y-direction
  - Caul plate rotation around the z-axis
- Preferably, the dimensions of the width of the core stringer pack is slightly smaller than the cavity on the Femi mould between the two edge bars. That way the stringer pack will always fit if it is aligned properly.

Lifting and Handling

- Tooling must be capable of being handled safely
- Where the weight, size or shape of the tooling prevents them from being moved by hand, the tooling or each component panel must either be fitted with attachments for lifting gear or be designed so that it can be fitted with such attachments (e.g. threaded holes) or be shaped in such a way that standard lifting gear can easily be attached.
- Where the tooling is to be moved by hand (for instance the carbon fibre caul plate cores), it must either be easily movable or be equipped for picking up (e.g. hand-grips etc) and moving in complete safety.

Materials/Finish

- All surfaces are to be protected against surface corrosion
- The corrosion protection must be suitable for the environment in which the tool will be used(e.g. the autoclave)
- The tool must be resistant to:
  - resin used for the panel (epoxy resin)
  - solvents used by Airbus
  - lubricant
  - environmental influences
- The tooling materials need to be certified by Airbus or must have been certified in the past by Airbus
- The following characteristics shall be taken into account during the mould design:
  - Moulds have to be stiff enough to produce panels within the required dimensional tolerances, taking into account the maximum pressure difference between the cavity and the ambient atmosphere.
  - The thermal capacity of the mould has to be in compliance with the required heating/cooling rates for the impregnation and the curing cycle.
  - The moulding surface which is in contact with the panel has to meet the requirements of the part.
- Favorably, the tooling material should:
  - Be of a low density, for easy handling.
  - Be wear resistance due to handling and usage
  - Have a higher thermal expansion coefficient than the laminate for easy placement and removal as well as supplying pressure in the corner sections of the laminate and ensure satisfactory compaction.
  - Be reusable for the manufacture of multiple panels.
  - Be easy to clean.

Operating conditions

- The tooling should be usable in the following conditions without any loss in structural integrity and laminate compaction capabilities:
  - The tooling should be usable in the autoclave and withstand 170 degrees Celsius with a margin of +10 degrees and 6 bars of pressure + 1 bar margin
  - The tooling should be usable at room temperature conditions of 20 degrees Celsius with a -4 degree margin
  - The tooling should be usable with a maximum humidity of 70 % (shopfloor conditions)

Costs

- For every 10% that the amount of rework due to the slipped stringer ply and undulation defects is reduced by the new tooling concept, roughly 280.000 Euros is available to cover the costs of the tooling. As an estimate the amount of rework on the slipped stringer plies and the undulations can be reduced to 20% when all the requirements are taken into account. This means that a total of 2,2 million Euros is available for a new tooling concept that reduces the rework of these defects by 80%

Chapter 9

Conclusions

In this chapter the final conclusions are stated that are derived from this master thesis. In the introduction chapter 1 the main research question was stated which needed to be answered in this master thesis:

What are the requirements of a new tooling concept in order to eliminate the causes of the manufacturing defects that occur in the production of the CFRP T-stiffened co-cured SA flaps skin panels?

In order to answer this question, the question was divided into several different sub questions. The answers to these sub questions together will give a well-argued answer to the main research question. The three sub research questions are:

1. Which defects are currently present in the panels and what could be the possible causes?
2. How can the possible causes be related to the anticipated defects that are currently present in the part?
3. What are the requirements for a tooling concept in order to produce a perfect part?

For sub-question one, actual panels from the production were examined for defects and the description is given in chapter 4. The defects can be observed by either visual inspection, the evaluation of cross sections or both. By checking the quality, the defects can be determined and categorized. As a first conclusion, the defects that are present in the actual flaps are in- and out-of-plane undulations, slipped stringer plies, wrinkles, resin rich areas, and filler material misalignment in horizontal direction. Furthermore, the possible causes of these defects were determined by inspecting the current production process, the tooling and by referring to literature. The next step to answer question two was to simulate the possible causes in the manufacturing of test panels. The goal was to try and recreate the defects in test panels by changing process parameters. For this, test panels were manufactured that represent a section of the out board flaps. By changing the process parameters, the causes of the defects were simulated successfully by means of altering the process. Additionally to the defects that are present in the actual flaps, also dry spots and vertical filler movement defects were simulated. However, these defects were not planned. Nevertheless, their causes were determined and described. As a main conclusion

to what the main causes can be for the defects in the actual flaps is the mismatch and removal and insertion back in of preform cores and the autoclave caul plate cores. Additionally, when the tooling is not placed in correctly, this will cause shifting and rotation of the tooling in the autoclave. To a small extend, the length of the stringer laminates with respect to the height of the stringer cavity influences the quality of the stringers. The shifting of the cores in x-direction is of a lesser importance, but the expansion of the laminate under the autoclave pressure and the ramps have an influence on the panel quality.
As an answer to sub-question 3 and also the main research question, the requirements are set-up in chapter 8 which need to be followed, in order to produce perfect panels. It could be that not all requirements can be achieved simultaneously. As a result, a trade-off needs to be made on which requirements to fulfil depending on the requirements and constraints that are set by Airbus. There is a potential for big savings that followed from the economical analysis if the number of defects is reduced. For every 10% that the amount of rework due to the slipped stringer ply and undulation defects is reduced by a new tooling concept, roughly 280.000 Euros is available to cover the costs of the tooling.

In addition to these conclusions and answers to the research questions, more specific conclusions and causes of defects are given in section 6.5

Chapter 10

Recommendations and further studies

In this chapter, the recommendations are stated on subjects that could be improved for future similar studies to obtain more accurate and/or more conclusive results. Also the future possibilities for further studies are given. For this thesis, test panels have been constructed in order to find the causes of the defects that are currently present in the SA outboard flaps. The fact that test panels were made indicates that not the actual production process was used for making these test panels, but that the production process was simulated using a representative production process that resemble the actual process as accurately as possible. In chapter 6, the production process of the test panels and its deviations of the actual process are described. In order to simulate the production process better, the test panel production and its material usage could be done more similarly. Some deviations from the actual production process have a negligible effect on the results that are derived from the test panels. Examples are the dimensions of the tooling, the number of cores used, manual ply layup, placing the skin on the stringer pack followed by turning and the vacuum channel and vacuum build-up.
However some alterations in the production have more effect on the panel quality and can influence the cause of defects to some extent. This is also shown in the 15 test panels that were made for this thesis. These differences are the tooling material, one set of tooling that is used for preforming and autoclave, flat skin, filler size.
As a recommendation for future and similar research, the five deviations from the current production mentioned above should be changed to more accurately copy the actual production process. That means that the test panel autoclave caul plate cores should be made from carbon fibre with the same lay-up as the actual cores, that different preform cores should be used that are made from aluminium, that the skin should have the same curvature as of the flaps and that the amount of filler material is scaled for the radius of the corner sections of the material. The best solution would be to produce the test panels, but with all the original materials and cores that are also used in the actual production. This is however impossible, because of logistical and monetary reasons. Additionally, the alterations mentioned earlier that are assumed to have a negligible effect on the panel quality can also be incorporated in equalizing the production of the test panels to the actual panels to ensure an identical process.

As a future step as a follow up for this project is of course to design a new tooling concept that fulfils all the requirements that were stated as a result from the defects that were found. In addition to the possibility to do more tests on test panels, tests can be done on the actual panels to verify the finding from this thesis and from there on either modify the current tooling and process accordingly. An other option would be to develop a completely new concept with for instance one set of tooling instead of a preform tool set and an autoclave caul plate core set, or for instance soft tooling or hybrid tooling as was mentioned as a successful alternative from literature. Having one set of tooling will most likely reduce the number of defects significantly, because most of the defect causes originate from either a mismatch in dimensions of the two toolings or the placement of the autoclave cores after preforming.

Another recommendation is that further studies have to be performed to examine the effects of the cores in the autoclave and which parameters have an influence to what degree. During the production of the test panels, the W-effect was observed which greatly influenced the panel quality and thickness of the laminate. The effect is also observed to a certain degree in the actual panels, but since a different material (different stiffness, thermal expansion coefficient, etc) is used for the cores, different effects and severity of the deformation will occur.

In order to perfectly isolate the causes of the defects, more tests have to be performed. Currently, most process alterations have been simulated once, so the chance could exist that the defects that were observed were not due to the intended process alterations, but to an external factor that was unaccounted for during the production. An example of this is for instance test panel 1 and 2 where the cause for the shifting of the filler material is derived from wrong preforming. However, the possibility could also be that the stringer pack was not sufficiently clamped like in test panel 13.1 in order to get the same defects. In order to know for sure what the exact cause is, more tests have to be done and the production process has to be monitored even more accurately.
Related to this is that the severity of the defects with relation to the process alteration should be monitored and simulated for more test panels. The severity of the defects has been simulated with for instance two different heights of hanging cores. Here, observations were made that the severity of the defects increases with an increasing hanging core. Similar simulations have been done with for example the shifting of the cores in x-direction and the shorter stringers than the cavity height. However for the shifting and rotating of the cores, only one test panel has been created, so in order to see the dependence of the shifting of the cores, more tests have to be done.

Additionally, for the rotation and shifting of the cores in y-direction it was unclear how much the core shifted in the autoclave itself and how much they were just pushed with the whole pack to the other side. Defects have been observed and the cores did move, but it is unclear to which size of shifting and rotation they belong. In order to better simulate this, a new set-up of the tooling needs to be made where both of the edge bars can move from side to side while still compacting the pack sufficiently.
Similarly for the hanging core, as soon as the autoclave pressure is applied, the cores are pushed down already by some distance when the resin is not liquid yet. Therefore it is difficult to measure the height that the cores are hanging and if the height directly corresponds to the slipped stringer ply height. This is however very difficult to measure. One option would be to apply the pressure of 6 bars, take the panel of the autoclave and measure how much the cores moved down. After the autoclave cycle, the relation can be checked with the height of the hanging core after applying the autoclave pressure with relation to the height slipped stringer plies.

As another subject, the cross sectional images were made after the production of several panels instead of after every part. That way, the inner quality of a panel was not known, only till after several other panels had been made. There were no practical or available methods to monitor precisely what happens with the individual plies that are not on the surface of the laminate. Therefore, some defects were not known till after the cross sectional images were made. Better would have been to check the inner quality after the manufacture of every panel so that the findings can be used for the following part. An example of the downside of evaluating the cross sections after a batch of panels is that it was assumed that panel 1 and 2 had a good quality and the decision was made to proceed with the other trials. However, when evaluating the cross sections after the manufacturing of panel 6, the filler material shifted upwards, which had as a cause that the preforming was not done correctly. It would have however been better to know the quality immediately after the manufacture of a test part, to take into account the defects for the panels after.

From a planning point of view it took a long time to arrange everything for setting up the trials. For future research it is advised to start with this as early as possible, because of the complexity of arranging the workplace, materials and autoclave time slots.

Another alternative future step that serves as a follow up is that the results from this thesis can be used as a basis in finding causes of similar defects that are present in similar T-stiffened panels in for instance the A350 and A380 program and the inboard A320 flaps. Since the production process is similar to the A320 outboard flaps and similar defects are present, there can be correlations with the causes of these defects. The idea would then be to correlate the defect map with the panels of other programs and expand the defects map where necessary to have a complete overview. That way, the defect map can be used to locate defects an easily determine the causes without testing all the possible causes for every program individually. Money and time can be saved by having a homogenised defects map, which for instance also can be used by suppliers and subcontractors. The extension and applicability of the defects map is in this case a recommendation for Airbus to get the maximum use of the research done for this thesis.

Finally, further research can be done on detecting most or all of the occurring defects from an outer quality inspection or at least with non destructive testing of the parts. Now, there is only a basic understanding of detecting inner defects from visual inspection and thickness measurements. Still, the parts needed to be cut to evaluate the cross sections, but better would of course be to detect the defects with for example ultra sonic testing. That way, the defects that are present on the inside of the part can also be detected in the actual flaps without destroying them. Probably not all defects that are present in the inside of the part can be quantified in detail, but should be detectable at least.

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Appendix A

FPQ Meassurement Locations

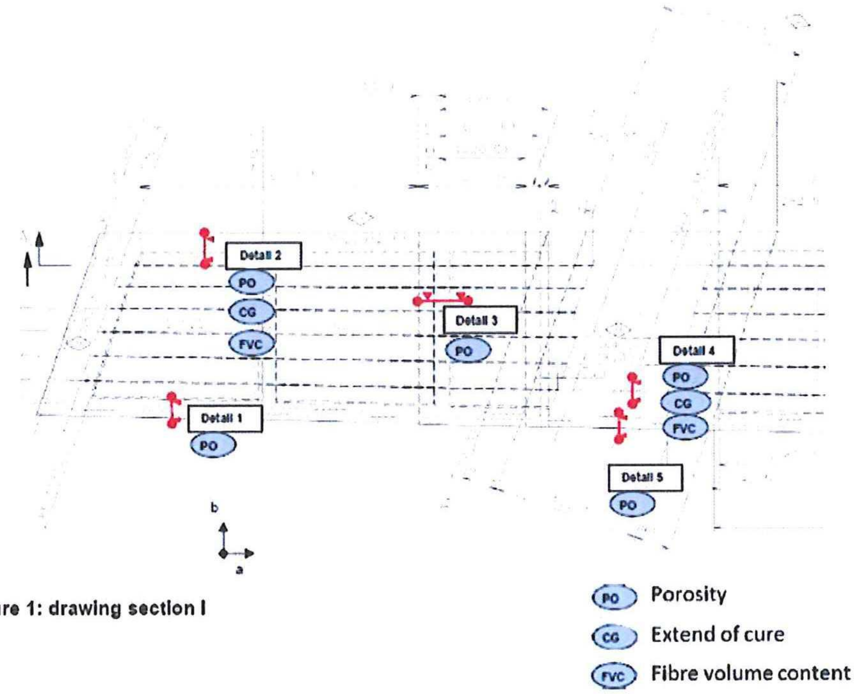


Figure 1: drawing section I

Detail 1:	a: mid between Rib17 and 18;
	b: total length of joggle
Detail 2:	a: mid between Rib17 and 18;
	b: total length of change of thickness
Detail 3:	a: Rib16 total length of the ramp;
	b: mid between Stringer2 and Stringer3
Detail 4:	a: Track 4 (mid of);
	b: Stringer6
Detail 5:	a: Track 4 (mid of);
	b: total length of joggle

Figure A.1: FPQ meassurement location in section 1 of the outboard flaps

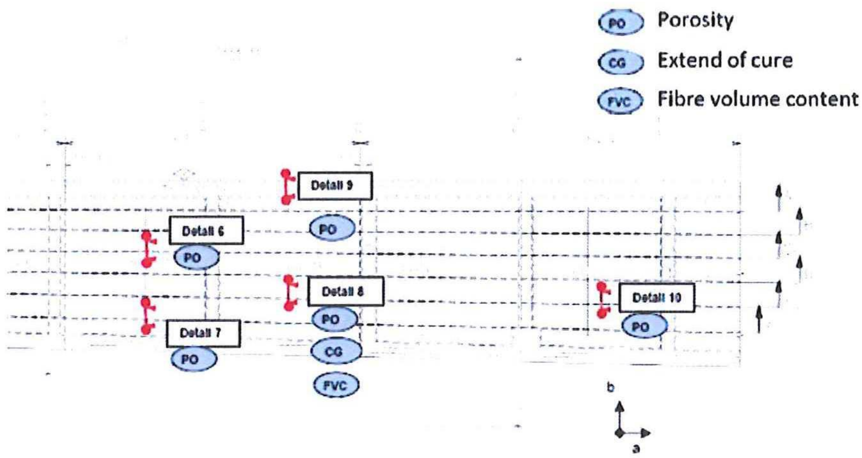


Figure 2: drawing section II

Details 6:	a: mid between Rib12 and 13; b: Stringer3 (document whole height and the stringer foot (+/- 20mm of mid stringer)
Details 7:	a: mid between Rib12 and 13; b: Stringer6 (document whole height and the stringer foot (+/- 20mm of mid stringer)
Details 8:	a: mid between Rib11 and 12; b: Stringer5 (document whole height and the stringer foot (+/- 20mm of mid stringer)
Details 9:	a: mid between Rib11 and 12; b: total length of the joggle
Details 10:	a: mid between Rib9 and 10; b: Stringer5 (document whole height and the stringer foot (+/- 20mm of mid stringer)

Figure A.2: FPQ meassurement location in section 2 of the outboard flaps

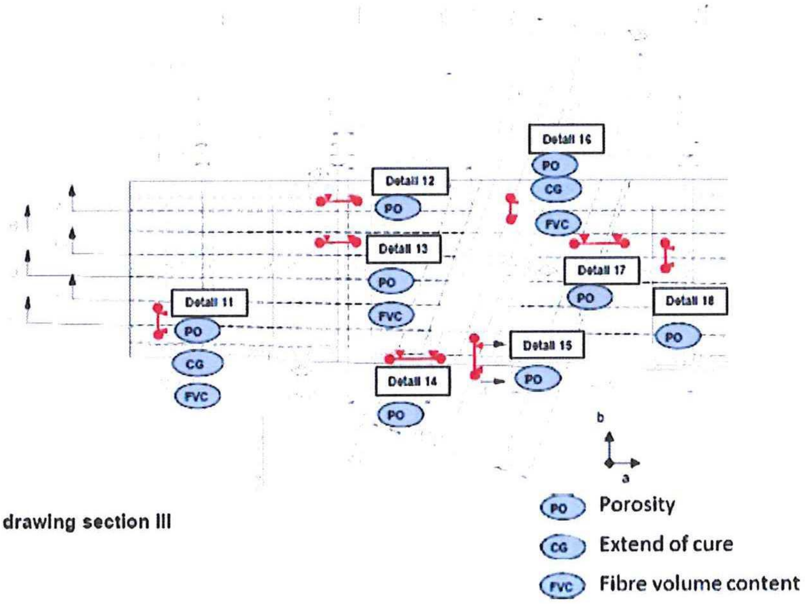


Figure 3: drawing section III

Details 11: a: mid between Rib8 and 9;
b: Stringer6 (document whole height and the stringer foot (+/- 20mm of mid stringer)

Details 12: a: Rib7 total length of the ramp
b: Stringer1

Details 13: a: Rib7 total length of the ramp
b: Stringer3

Details 14: a: track ramp, total length of the ramp
b: joggle thickness 2,7 mm

Details 15: a: between Rib5A and 5B
b: total length of the joggle

Details 16: a: between Rib5A and 5B
b: Stringer 1

Details 17: a: track ramp, total length of the ramp
b: between Stringer 2 and Stringer 3

Details 18: a: between Rib4 and beginning of ramp
b: Stringer3 (document whole height and the stringer foot (+/- 20mm of mid stringer)

Figure A.3: FPQ meassurement location in section31 of the outboard flaps

Appendix B

Width differences between the NEO outboard flap CFRP Cores and CAD models

In the tables, OL is "Oben Links" or upper left which indicates the cores that are used for the upper left flap. OR is "Oben Rechts" or upper right, which indicates the cores that are used for the upper right flap. Accourding to the CAD models, these core sets should have the same dimensions. In total the meassured dimsensions and the comparrison to the CAD is given for one set of five cores for the OL (cores 204, 206, 208, 210 and 212) and one set of 5 cores for the OR (cores 205, 207, 209, 211 and 213).

		204/205			delta	
	OL	CAD Model	delta	OR	CAD Model	delta
Rib 1	78,80	77,05		78,90	77,05	
2	75,75	75,22	0,53	75,65	75,22	0,43
3	73,62	73,19	0,43	73,70	73,19	0,51
4						
Track	72,60	69,50		72,70	69,50	
	71,70	70,30		71,80	70,30	
7	67,70	67,60	0,10	67,70	67,60	0,10
8	66,60	65,80	0,80	66,45	65,80	0,65
9	65,35	65,20	0,15	65,30	65,20	0,10
10	63,70	63,70	0,00	63,70	63,70	0,00
11	62,15	62,00	0,15	61,95	62,00	-0,05
12	60,55	59,90	0,65	60,65	59,90	0,75
13	58,35	58,30	0,05	58,40	58,30	0,10
Track	59,30	56,90		59,10	56,90	
	58,20	56,70		58,30	56,70	
16	54,98	54,80	0,17	55,05	54,80	0,25
17	53,75	53,50	0,25	53,65	53,50	0,15
Rib 18	53,60	53,00		53,70	53,00	

Figure B.1: Width differences between the NEO outboard flap CFRP Cores and CAD models number 1

		206/207			delta	
	OL	CAD Model	delta	OR	CAD Model	delta
Rib 1	82,52	80,80		82,60	80,80	
2	79,40	78,80	0,60	79,50	78,80	0,70
3	77,23	77,00	0,22	77,30	77,00	0,30
4	0,00					
Track	75,70	73,20		75,90	73,20	
	75,10	71,50		75,20	71,50	
7	70,60	70,20	0,40	70,85	70,20	0,65
8	69,61	69,10	0,50	69,65	69,10	0,55
9	68,25	67,70	0,55	68,25	67,70	0,55
10	66,46	66,10	0,36	66,75	66,10	0,65
11	64,73	64,30	0,42	64,85	64,30	0,55
12	63,28	62,80	0,48	63,45	62,80	0,65
13	60,85	60,40	0,45	61,25	60,40	0,85
Track	61,10	58,40		61,60	58,40	
	60,40	57,10		60,60	57,10	
16	57,23	56,70	0,52	57,50	56,70	0,80
17	55,43	55,30	0,13	56,15	55,30	0,85
Rib 18	55,70	54,00		56,10	54,00	

Figure B.2: Width differences between the NEO outboard flap CFRP Cores and CAD models number 2

		208/209				delta
	OL	CAD Model		OR	CAD Model	
Rib 1	85,30	83,20		85,80	83,20	
2	81,85	81,60	0,25	82,55	81,60	0,95
3	79,80	79,60	0,20	80,90	79,60	1,30
4						
Track	78,20	75,80		78,40	75,80	
	77,50	74,10		77,50	74,10	
7	73,40	72,90	0,50	73,85	72,90	0,95
8	72,60	71,70	0,90	72,35	71,70	0,65
9	70,65	70,30	0,35	70,95	70,30	0,65
10	69,05	68,70	0,35	69,35	68,70	0,65
11	67,20	66,80	0,40	67,40	66,80	0,60
12	66,10	65,10	1,00	65,80	65,10	0,70
13	65,65	65,30	0,35	63,65	65,30	-1,65
Track	63,70	59,50		63,90	59,50	
	62,70	59,40		63,00	59,40	
16	59,55	59,10	0,45	60,25	59,10	1,15
17	58,10	57,70	0,40	59,05	57,70	1,35
Rib 18	58,00	56,30		58,30	56,30	

Figure B.3: Width differences between the NEO outboard flap CFRP Cores and CAD models number 3

	210/211				delta	
	OL	CAD Model		OR	CAD Model	delta
Rib 1	87,10	85,40		87,50	85,40	
2	84,15	83,80	0,35	84,75	83,80	0,95
3	82,05	81,70	0,35	82,85	81,70	1,15
4						
Track	80,30	78,30		80,50	78,30	
	79,50	75,80		79,70	75,80	
7	75,35	75,00	0,35	75,95	75,00	0,95
8	74,30	73,80	0,50	74,85	73,80	1,05
9	72,95	72,40	0,55	73,25	72,40	0,85
10	71,25	70,90	0,35	71,55	70,90	0,65
11	69,35	69,10	0,25	69,65	69,10	0,55
12	67,90	67,40	0,50	68,30	67,40	0,90
13	65,70	65,10	0,60	66,05	65,10	0,95
Track	65,80	63,10		66,10	63,10	
	65,00	61,90		65,20	61,90	
16	61,95	61,40	0,55	62,40	61,40	1,00
17	60,45	60,00	0,45	60,85	60,00	0,85
Rib 18	60,25	58,50		60,40	58,50	

Figure B.4: Width differences between the NEO outboard flap CFRP Cores and CAD models number 4

		212/213				
	OL	CAD Model		OR	CAD Model	delta
Rib 1	89,90	87,90		90,50	87,90	
2	86,95	86,50	0,45	87,90	86,50	1,40
3	84,90	84,50	0,40	85,55	84,50	1,05
4						
Track	82,90	80,40		83,10	80,40	
	82,00	78,70		82,10	78,70	
7	78,55	77,70	0,85	79,15	77,70	1,45
8	76,83	76,40	0,42	77,75	76,40	1,35
9	75,50	74,90	0,60	75,75	74,90	0,85
10	73,80	73,30	0,50	74,15	73,30	0,85
11	71,85	71,40	0,45	72,15	71,40	0,75
12	70,45	69,80	0,65	70,60	69,80	0,80
13	68,15	68,10	0,05	68,45	68,10	0,35
Track	68,30	65,40		68,20	65,40	
	67,40	64,40		67,40	64,40	
16	64,50	63,70	0,80	64,80	63,70	1,10
17	63,00	62,20	0,80	63,25	62,20	1,05
Rib 18	62,70	60,70		62,60	60,70	
Average for all cores			0,43			0,70
Total average for left and right cores			0,56			

Figure B.5: Width differences between the NEO outboard flap CFRP Cores and CAD models number 5 and total average

Appendix C

Material properties of materials used in production

Art:	Carbon Prepreg - UD		
Bezeichnung:	**HexPly 6376C-HTS(12K)-5-35%**		
HTZ:	HEXPLY6376C-HTS(12K)5-35%-BREITE		
Vorschrift:	75-T-2-0123-1-1 / Issue 5 (November 2011)		
Hersteller:	Hexcel		
Lieferant:	Hexcel		
AVS/Buyside:	AVS		
ID-Nummer	92462404	89440270	89440904
Breiten: [mm]	1200	300	300 ATL
Dicke: [mm]	0,125 (CTP)		
ATL-Trägerpapier:	Mondi Packaging SBL130 white ; D1H/D8L		

Flugzeug-typ:	**Bau-gruppe:**	**Bauteil:**	**Breiten:**	**TPV:**	**AKL-Zyklus:**
A318-20	ÄLK	Holme	ATL: 300	TPV-SSE-04-72	10/26
A318-20	ILK	Oberschale/ Unterschale	300/ATL: 300	TPV-SSE-04-20	10
	ÄLK	Beplankungen, Verstärkungslagen	300 ; ATL: 150,300	TPV-SSE-04-112 TPV-SSE-04-81	10
A321	ÄLK	Holme	300	TPV-SSE-04-71	10/26
		Beplankungen, Verstärkungslagen	300, ATL: 150,300	TPV-SSE-04-63 TPV-SSE-04-78	10/26
A380	MLK/ÄLK	Ober- und Unterschale	1200/ATL: 300	TPV-SSE-04-16	160

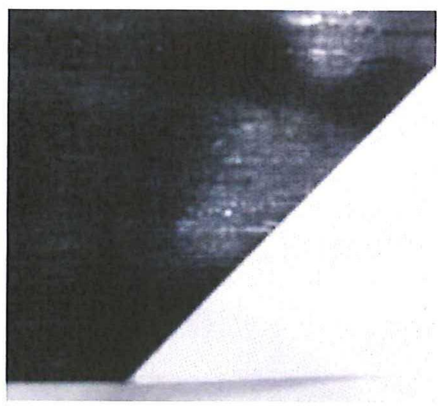


Figure C.1: Carbon fibre prepreg material properties

Art:	Trennfolie (Selbstklebend)
Bezeichnung:	Chemstick 203S (alt: 700 - 3S)
HTZ:	MBBN620-0,08-215
Vorschrift:	Qualifiziert nach 80-T-31-2910
	ABS 0777
	AIPI 03-02-019
Hersteller:	Saint-Gobain
Lieferant:	Saint-Gobain
AVS/Buyside:	AVS
ID-Nummer	69344151
Breiten: [mm]	1000
Dicke: [µm]	115 (base: 70 ; adhesive: 45)
Max. AKL-Temp.:	180 °C (80-T-31-2910)
Datenblätter:	D
Herstell- oder Ablaufdatum vorhanden? Wenn ja, wo?	In der Kernrolle

Figure C.2: Tooltec material properties

Appendix D

Cross sections of the micro sections of the test panels

Figure D.1: Cross section of panel 1 stringer 1 skin

Figure D.2: Cross section of panel 1 stringer 3 skin

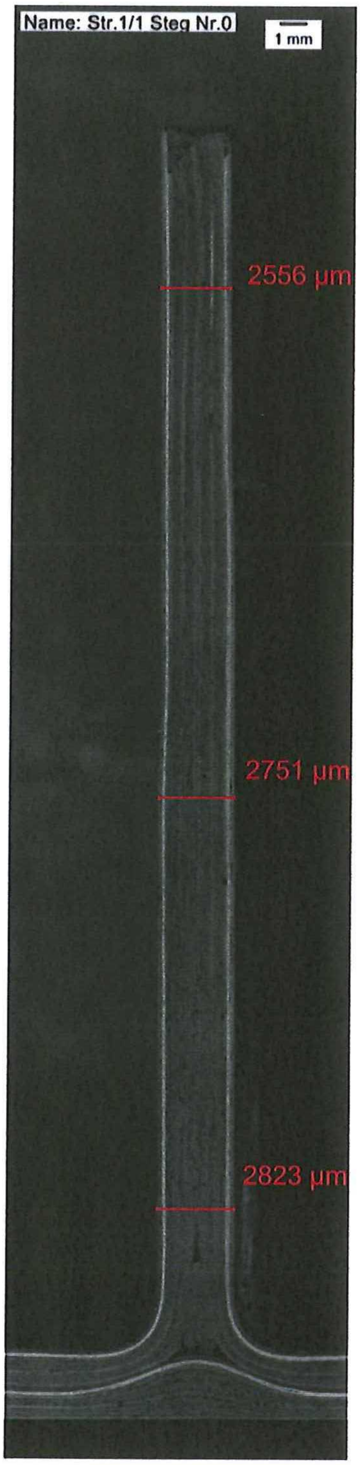


Figure D.3: Cross section of panel 1 stringer 1

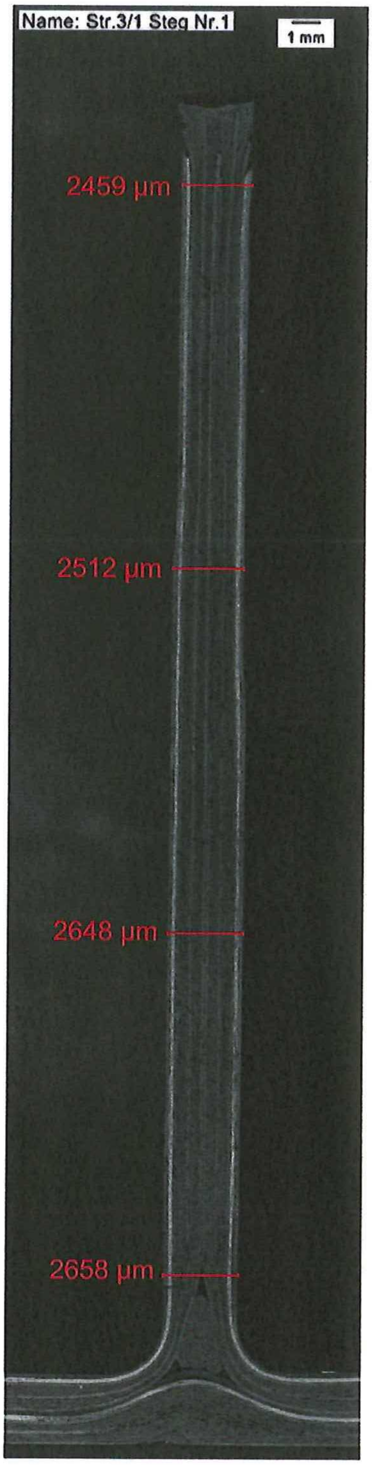


Figure D.4: Cross section of panel 1 stringer 3

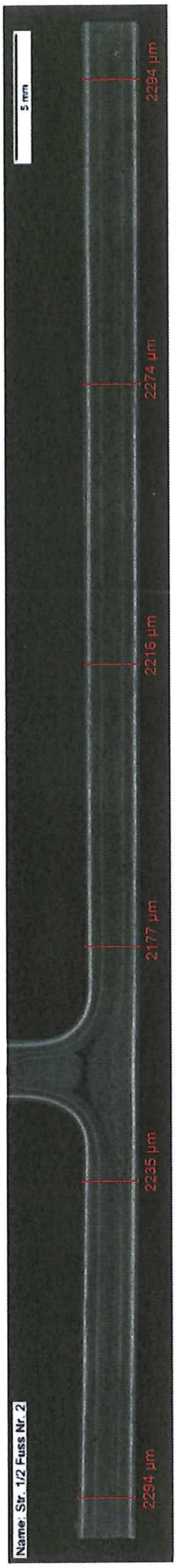


Figure D.5: Cross section of panel 2 stringer 1 skin

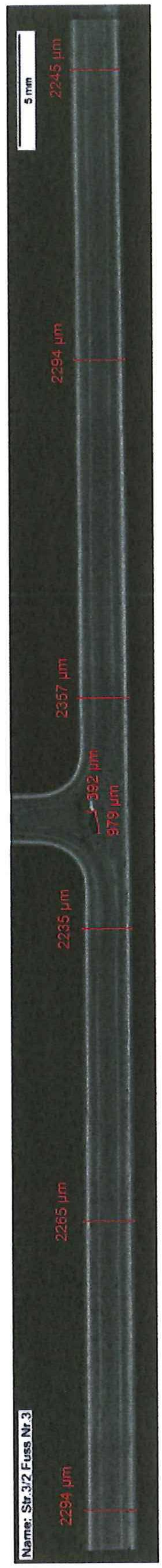


Figure D.6: Cross section of panel 2 stringer 3 skin

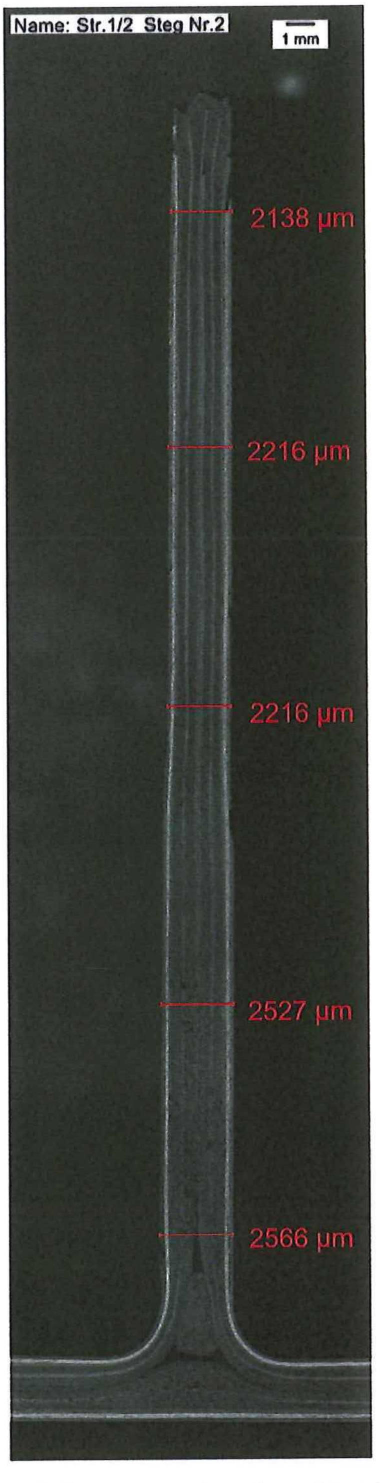


Figure D.7: Cross section of panel 2 stringer 1

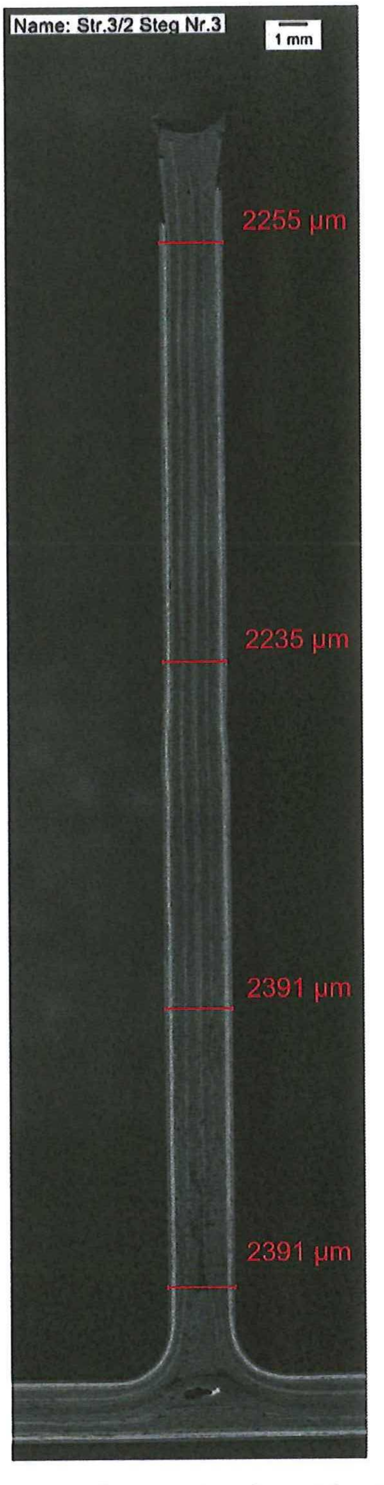


Figure D.8: Cross section of panel 2 stringer 3

Figure D.9: Cross section of panel 3 stringer 1 skin

Figure D.10: Cross section of panel 3 stringer 3 skin

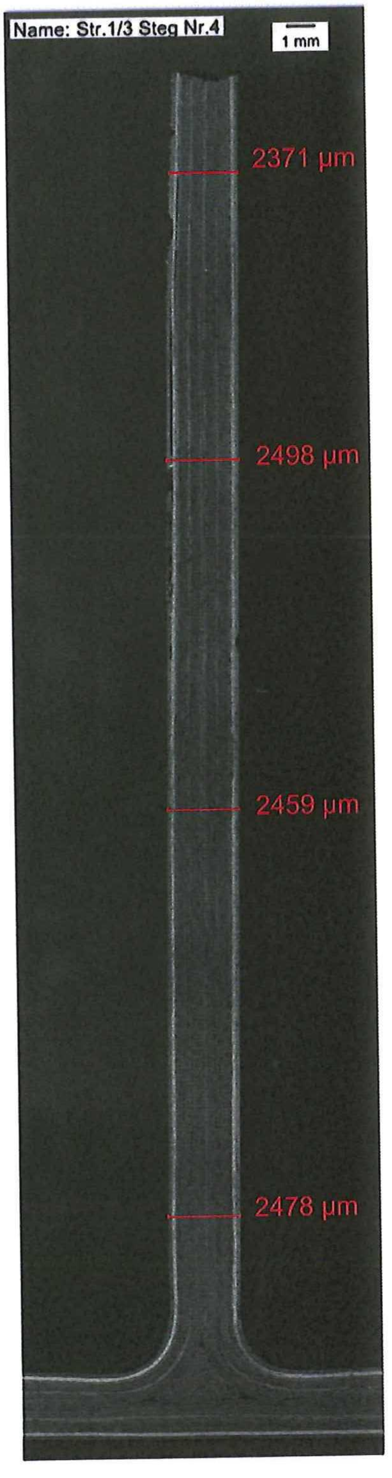


Figure D.11: Cross section of panel 3 stringer 1

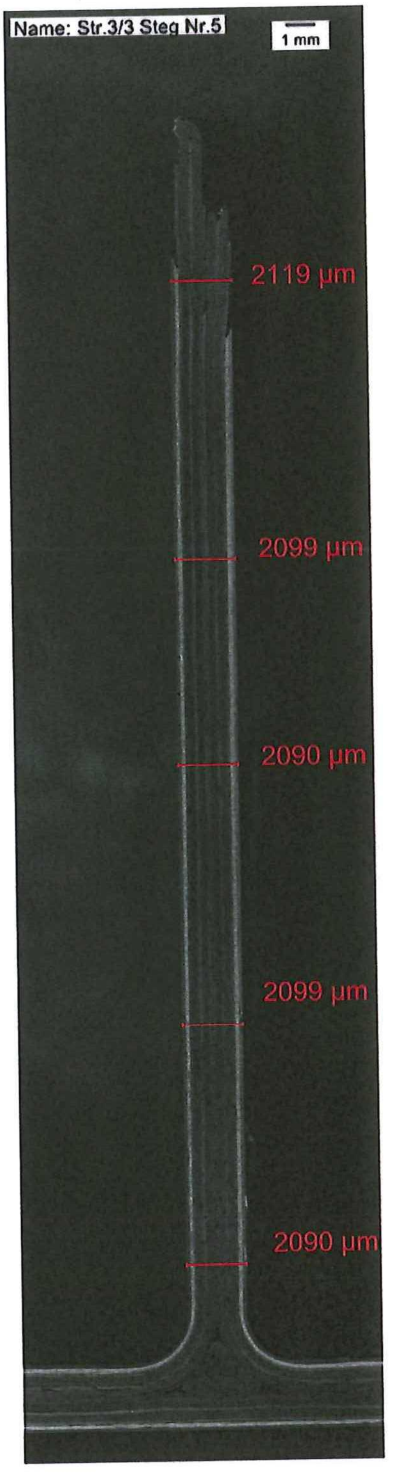


Figure D.12: Cross section of panel 3 stringer 3

Figure D.13: Cross section of panel 4 stringer 2 skin

Figure D.14: Cross section of panel 4 stringer 3 skin

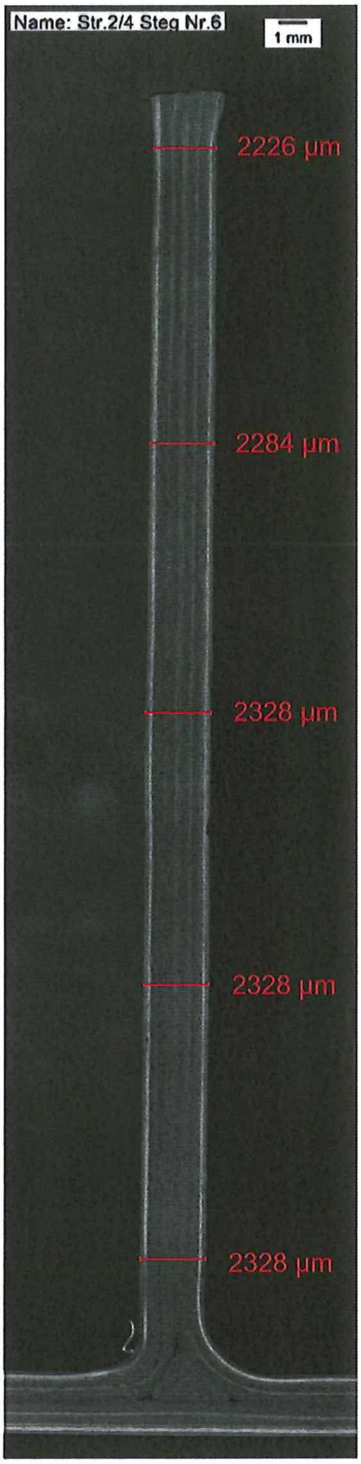


Figure D.15: Cross section of panel 4 stringer 2

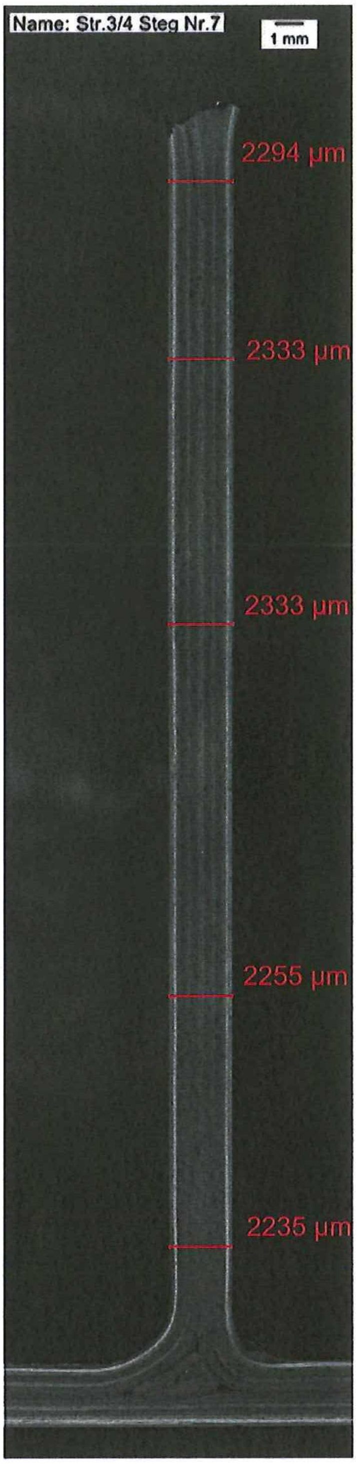


Figure D.16: Cross section of panel 4 stringer 3

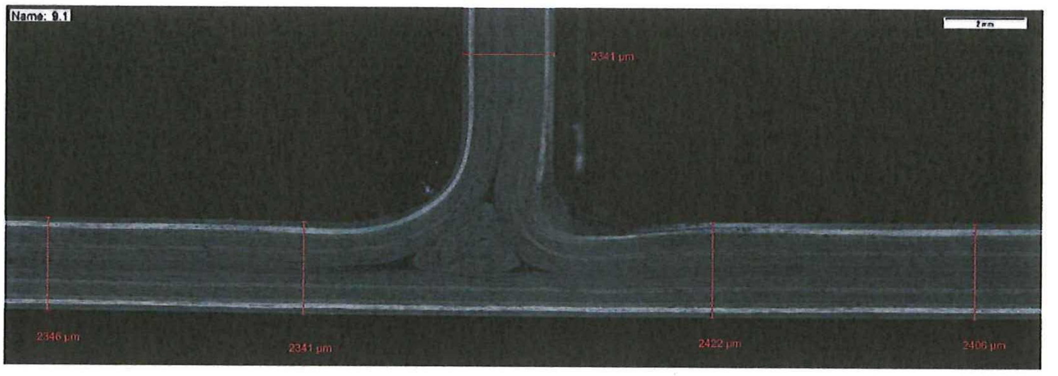


Figure D.17: Cross section of panel 5 stringer 1 skin

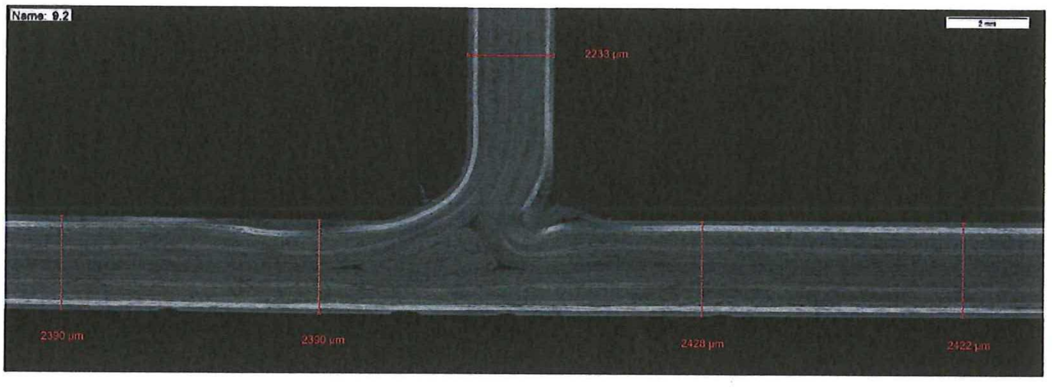


Figure D.18: Cross section of panel 5 stringer 2 skin

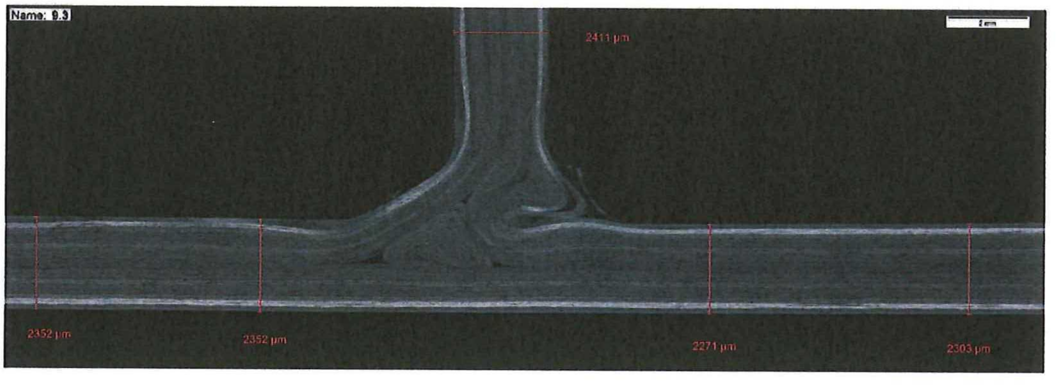


Figure D.19: Cross section of panel 5 stringer 3a skin

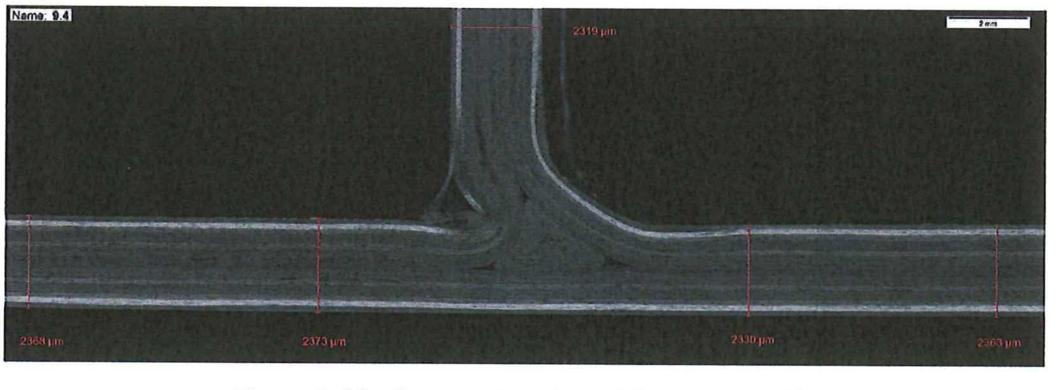


Figure D.20: Cross section of panel 5 stringer 3b skin

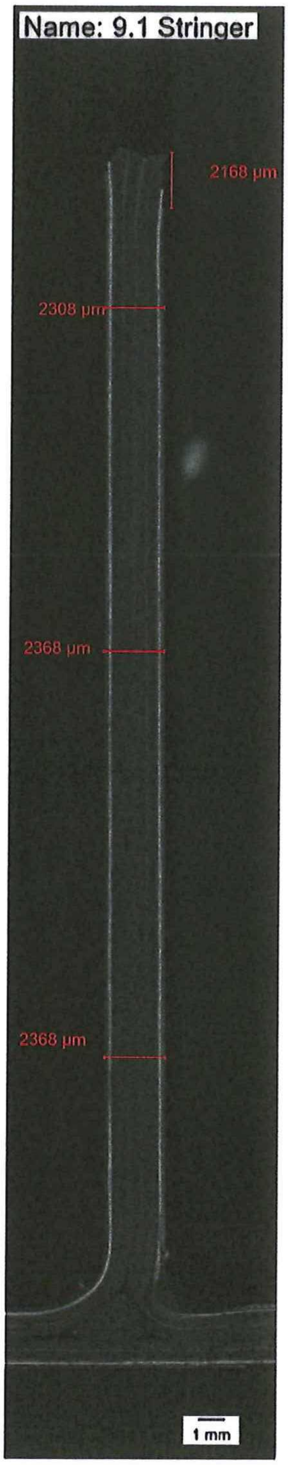


Figure D.21: Cross section of panel 5 stringer 1

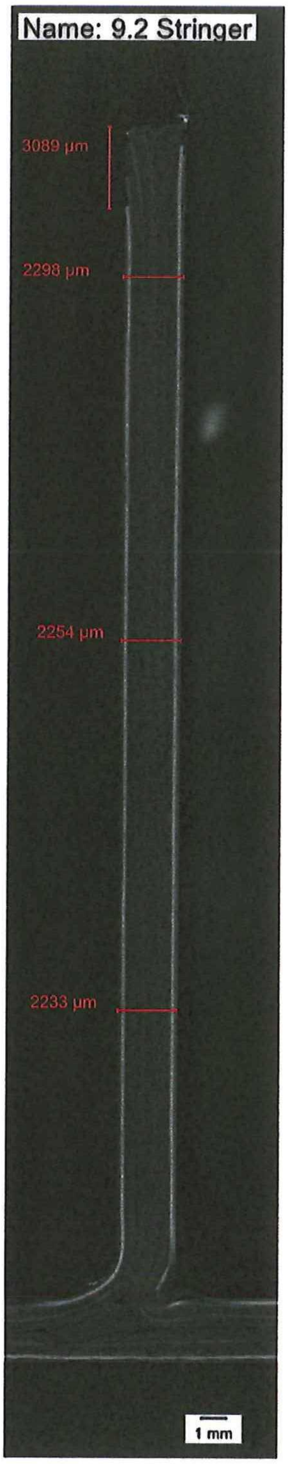


Figure D.22: Cross section of panel 5 stringer 2

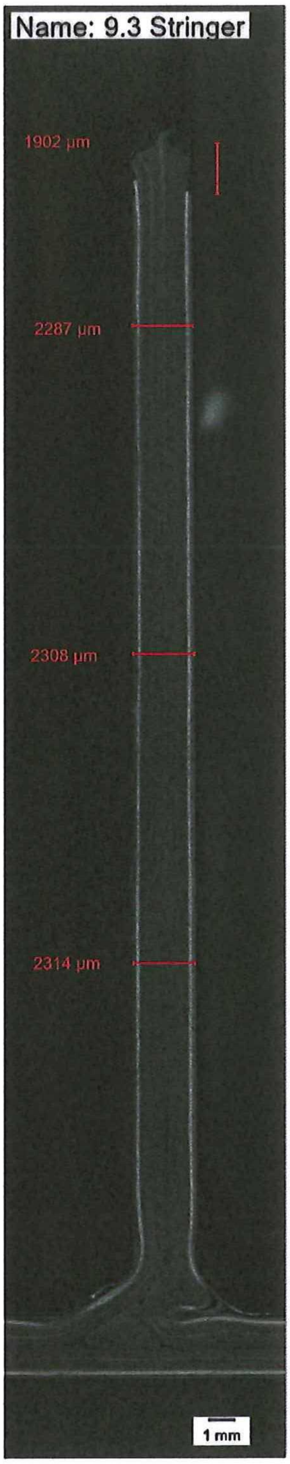


Figure D.23: Cross section of panel 5 stringer 3a

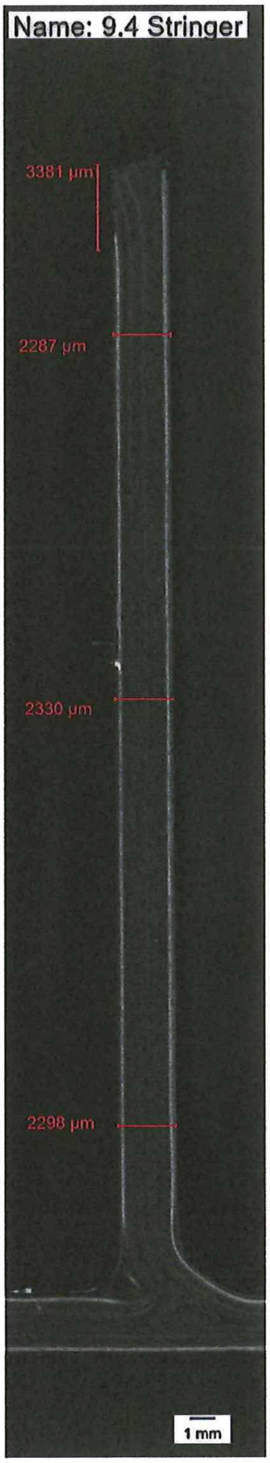


Figure D.24: Cross section of panel 5 stringer 3b

Figure D.25: Cross section of panel 6 stringer 1 skin

Figure D.26: Cross section of panel 6 stringer 2a skin

Figure D.27: Cross section of panel 6 stringer 3a skin

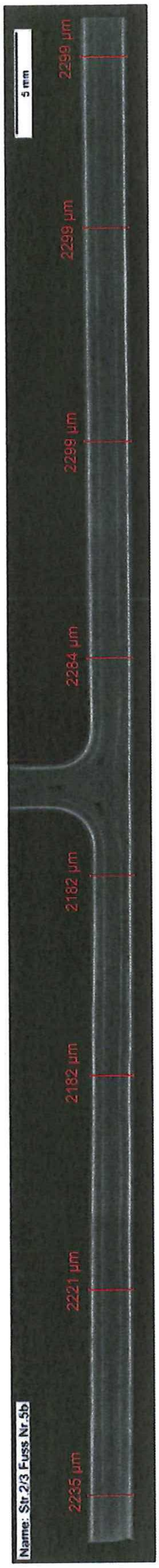


Figure D.28: Cross section of panel 6 stringer 2b skin

Figure D.29: Cross section of panel 6 stringer 3b skin

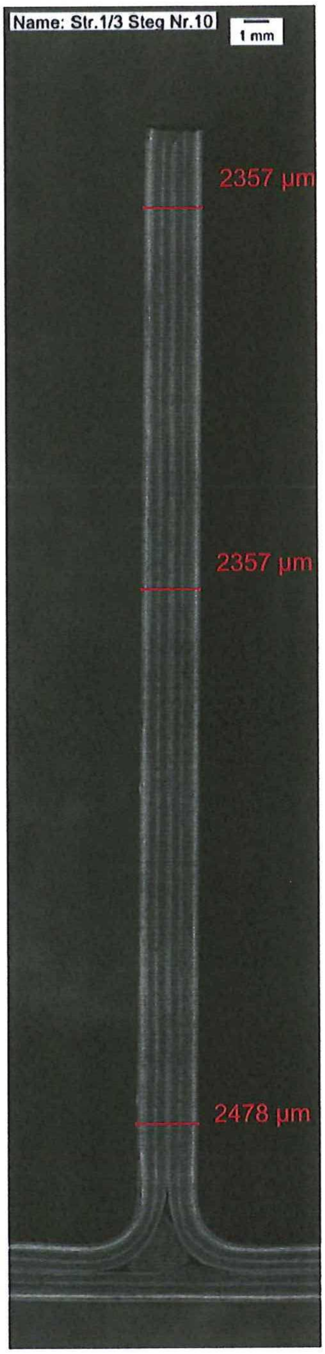


Figure D.30: Cross section of panel 6 stringer 1

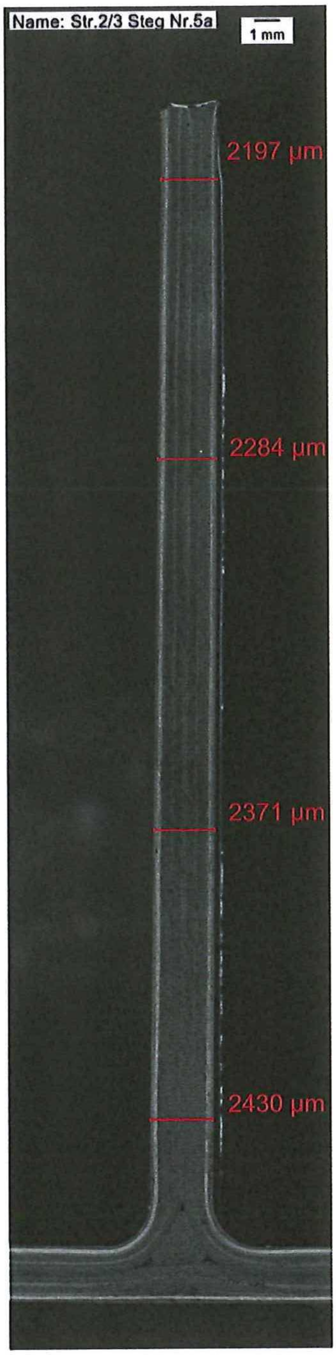


Figure D.31: Cross section of panel 6 stringer 2a

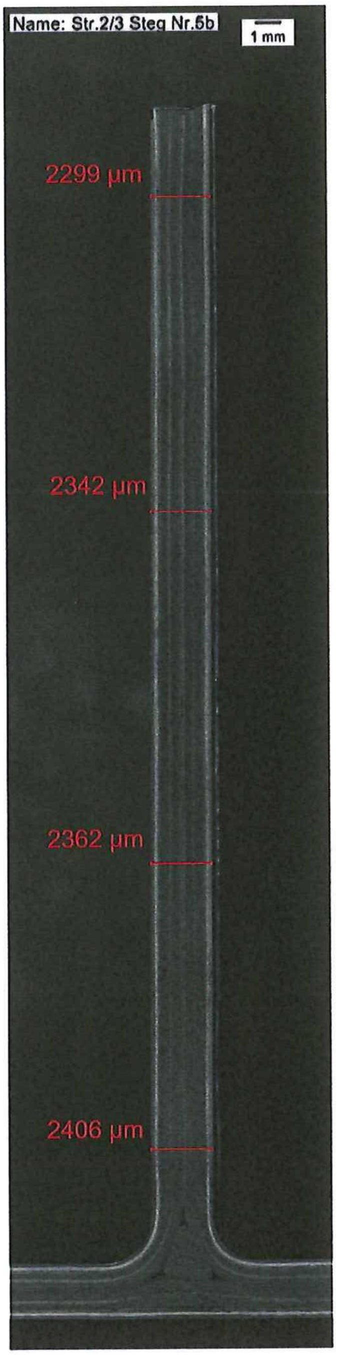


Figure D.32: Cross section of panel 6 stringer 3a

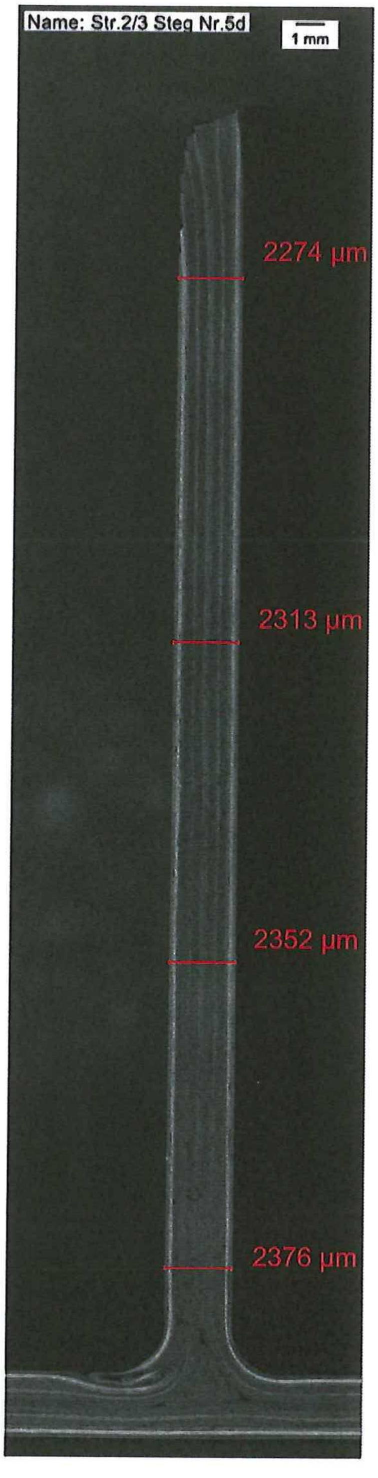


Figure D.33: Cross section of panel 6 stringer 2b

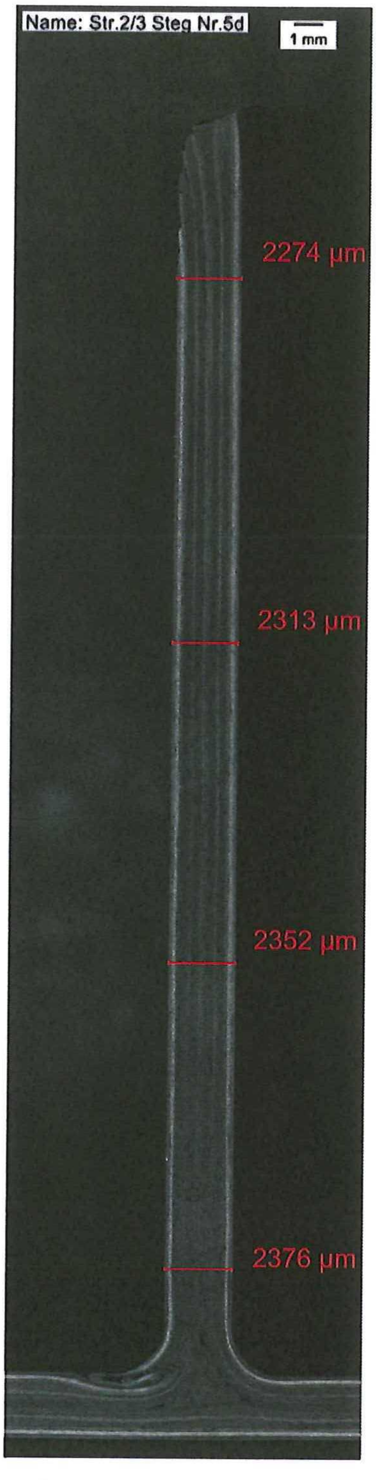


Figure D.34: Cross section of panel 6 stringer 3b

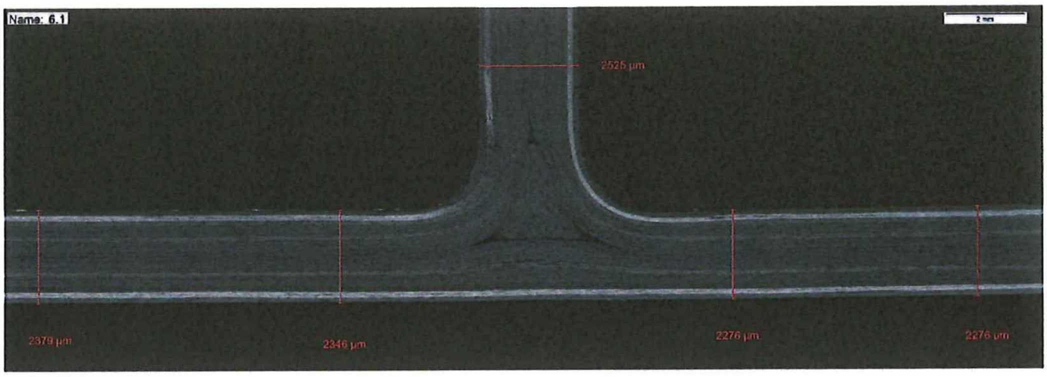


Figure D.35: Cross section of panel 7 stringer 1 skin

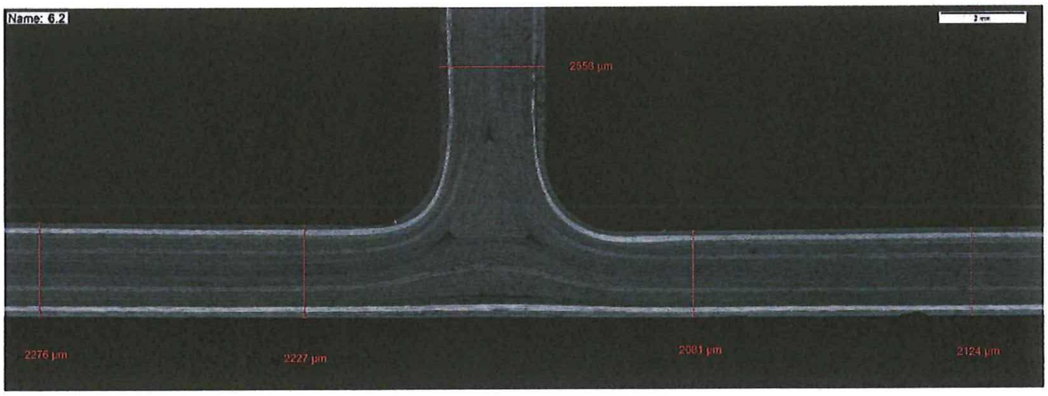


Figure D.36: Cross section of panel 7 stringer 2a skin

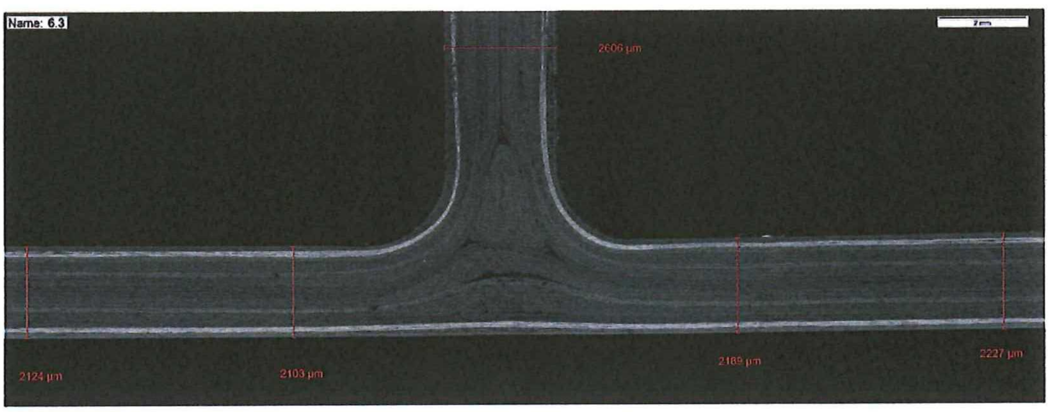


Figure D.37: Cross section of panel 7 stringer 3a skin

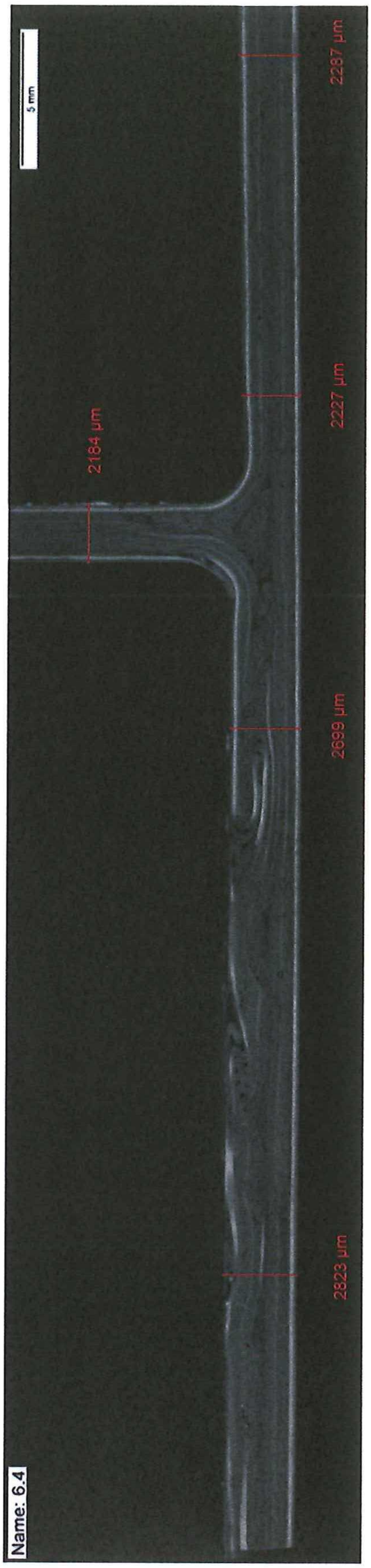


Figure D.38: Cross section of panel 7 stringer 2b skin

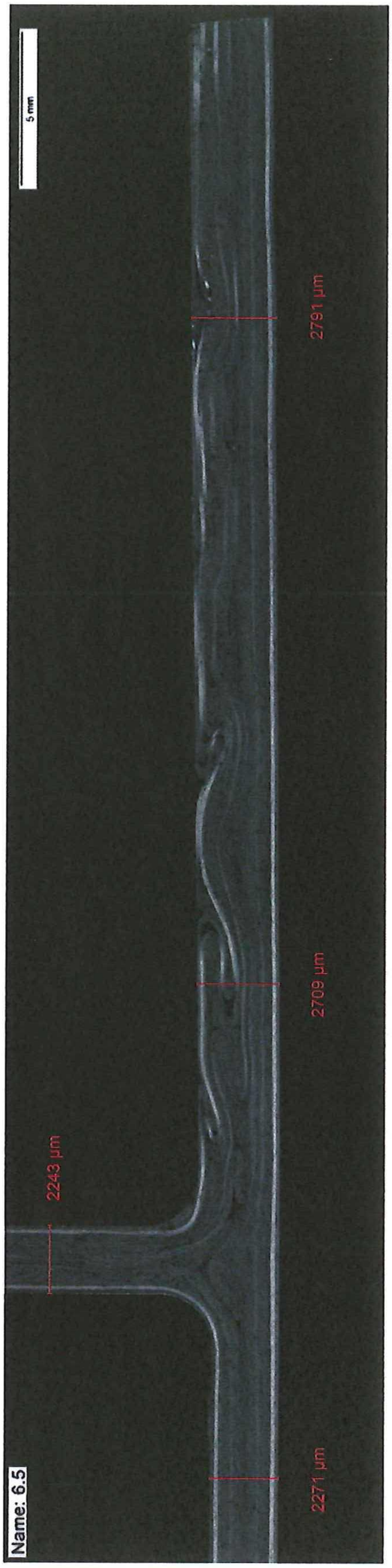


Figure D.39: Cross section of panel 7 stringer 3b skin

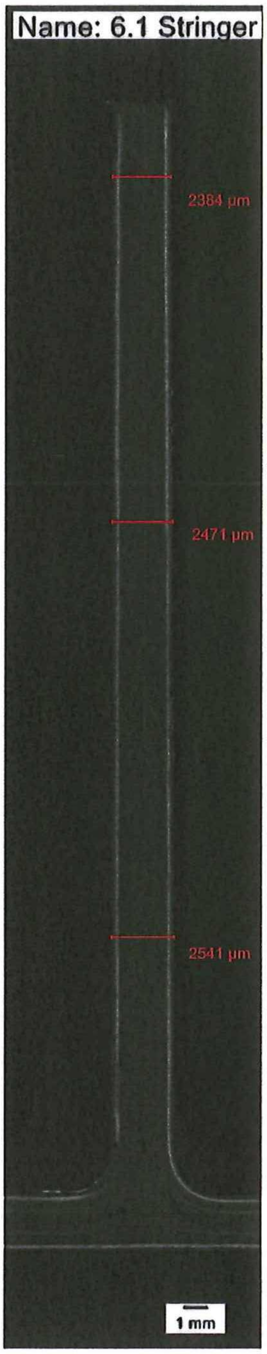


Figure D.40: Cross section of panel 7 stringer 1

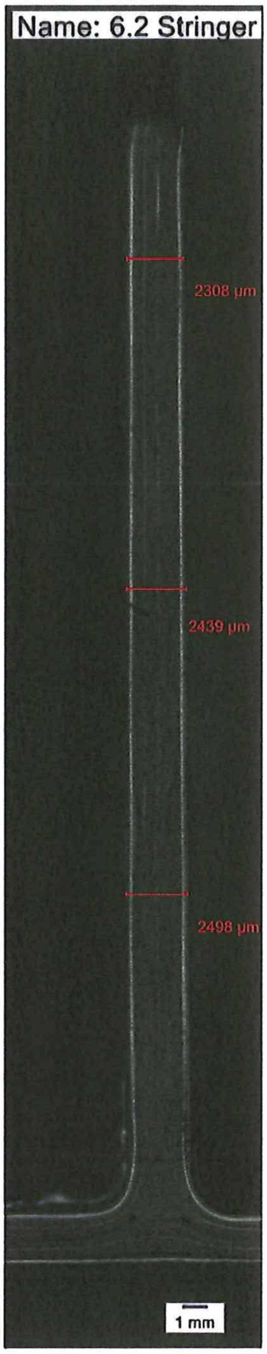


Figure D.41: Cross section of panel 7 stringer 2a

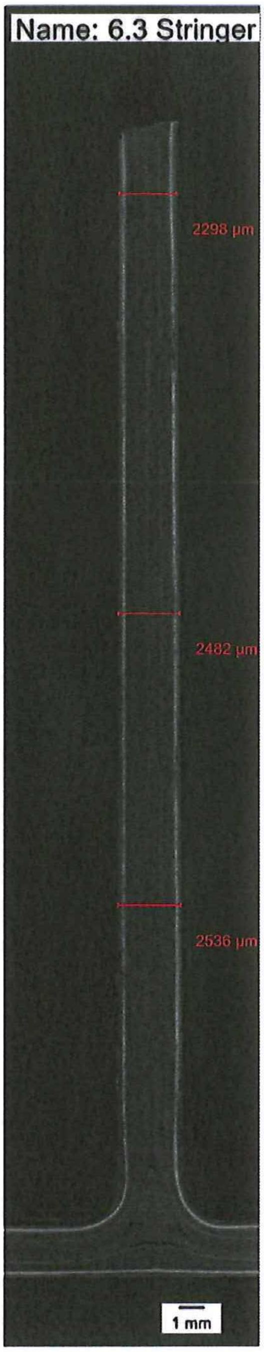


Figure D.42: Cross section of panel 7 stringer 3a

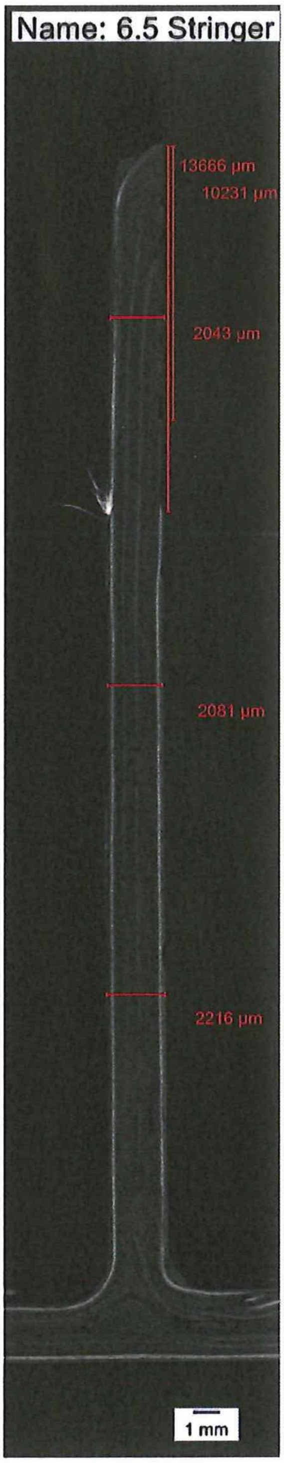


Figure D.43: Cross section of panel 7 stringer 2b

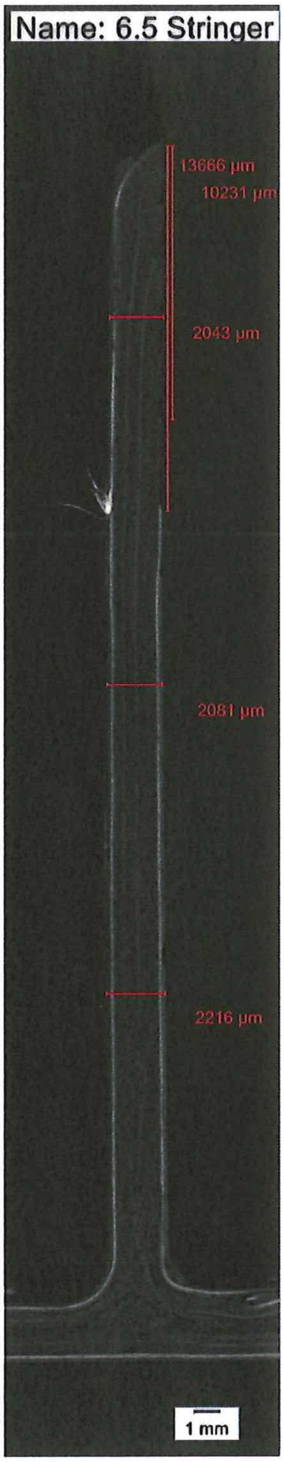


Figure D.44: Cross section of panel 7 stringer 3b

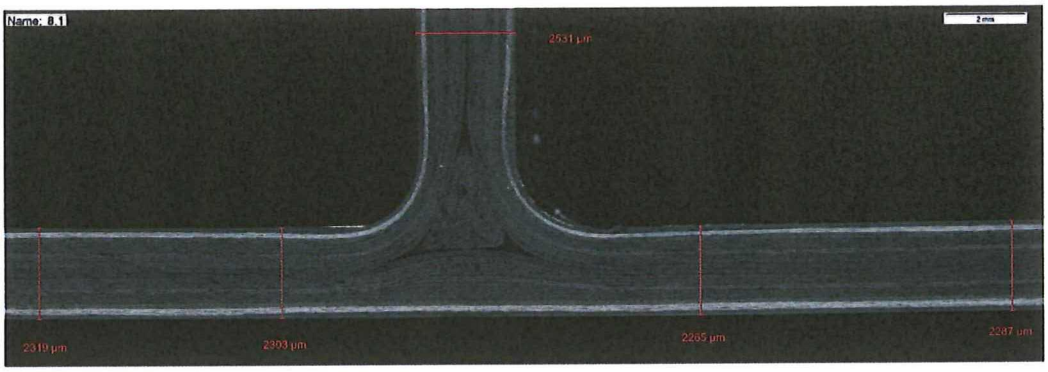


Figure D.45: Cross section of panel 8 stringer 1 skin

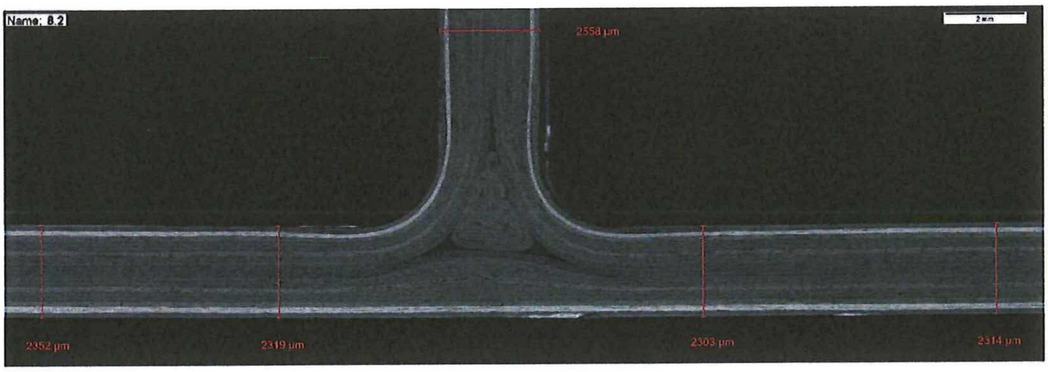


Figure D.46: Cross section of panel 8 stringer 2 skin

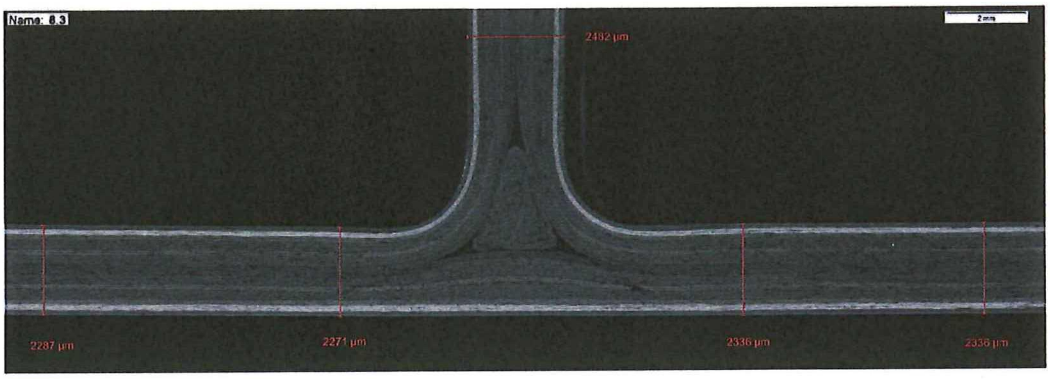


Figure D.47: Cross section of panel 8 stringer 3 skin

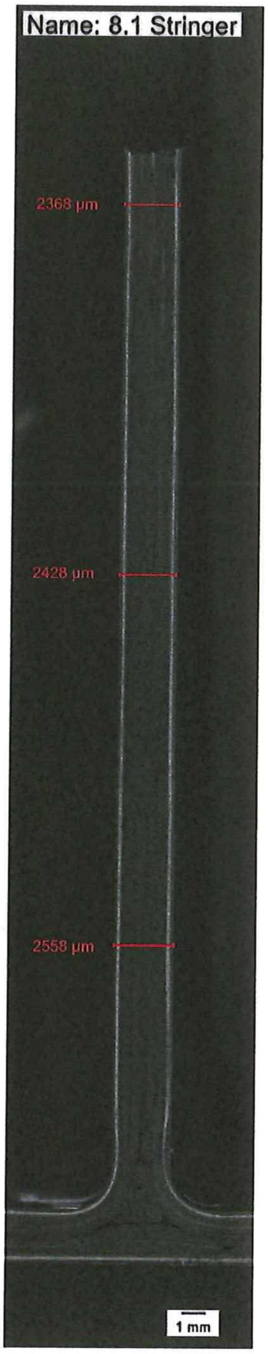


Figure D.48: Cross section of panel 8 stringer 1

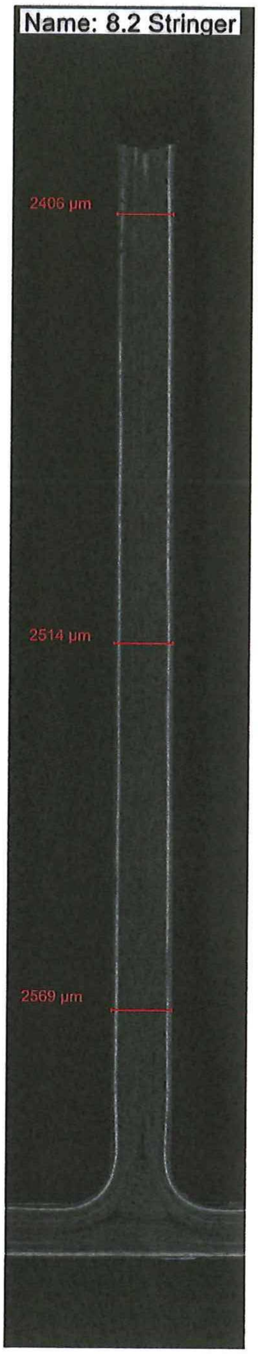


Figure D.49: Cross section of panel 8 stringer 2

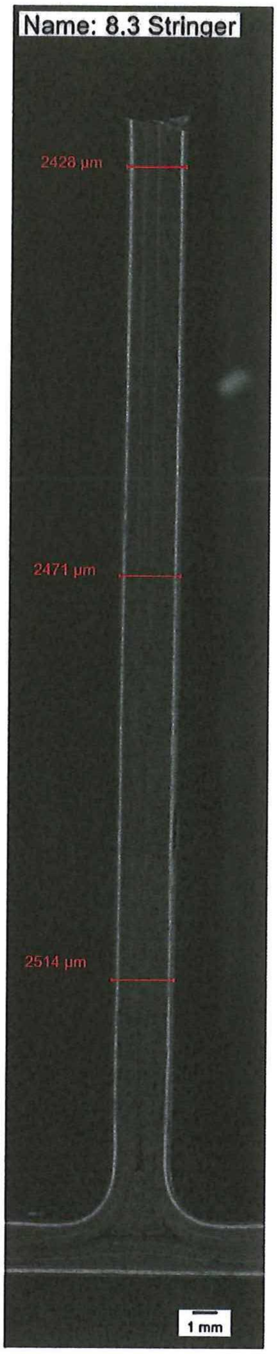


Figure D.50: Cross section of panel 8 stringer 3

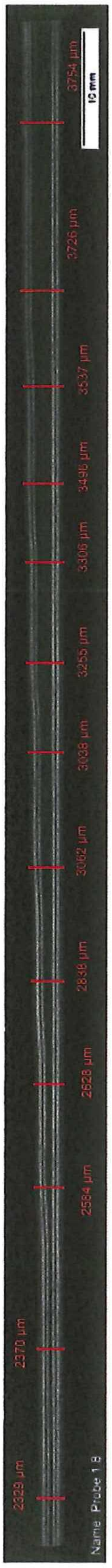


Figure D.51: Panel 9 core 1 left

Figure D.52: Panel 9 core 1 right

Figure D.53: Panel 9 core 2 left

Figure D.54: Panel 9 core 2 right

Figure D.55: Panel 9 core 3 left

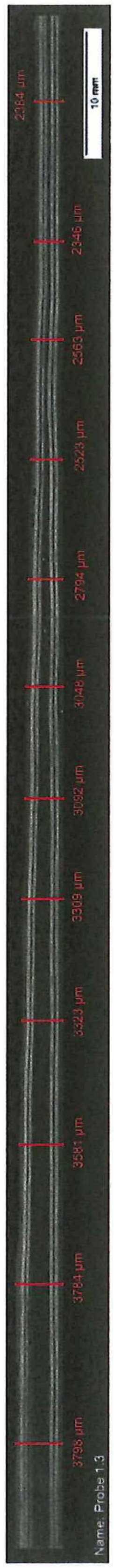


Figure D.56: Panel 9 core 3 right

Figure D.57: Panel 9 core 4 left

Figure D.58: Panel 9 core 4 right

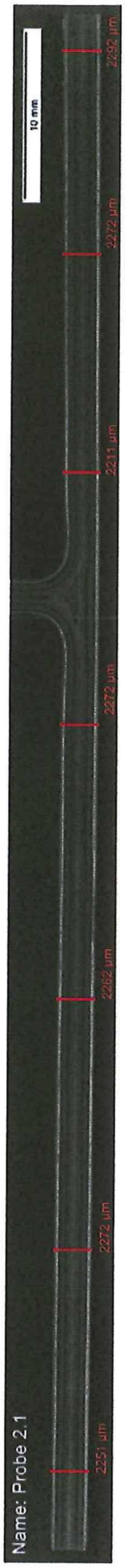


Figure D.59: Panel 10 stringer 1a skin

Figure D.60: Panel 10 stringer 2a skin

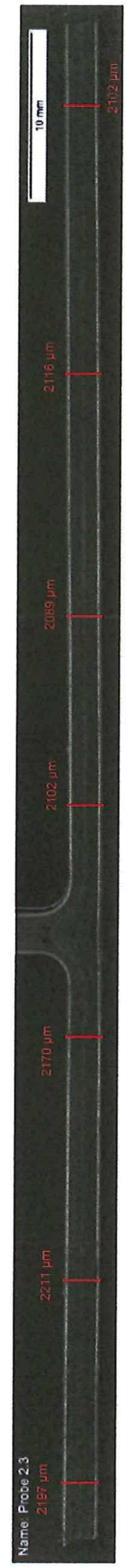


Figure D.61: Panel 10 stringer 1b skin

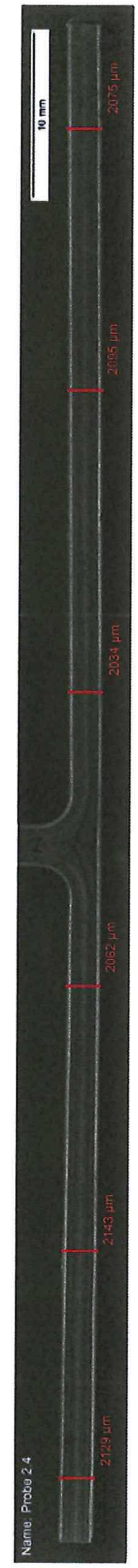


Figure D.62: Panel 10 stringer 2b skin

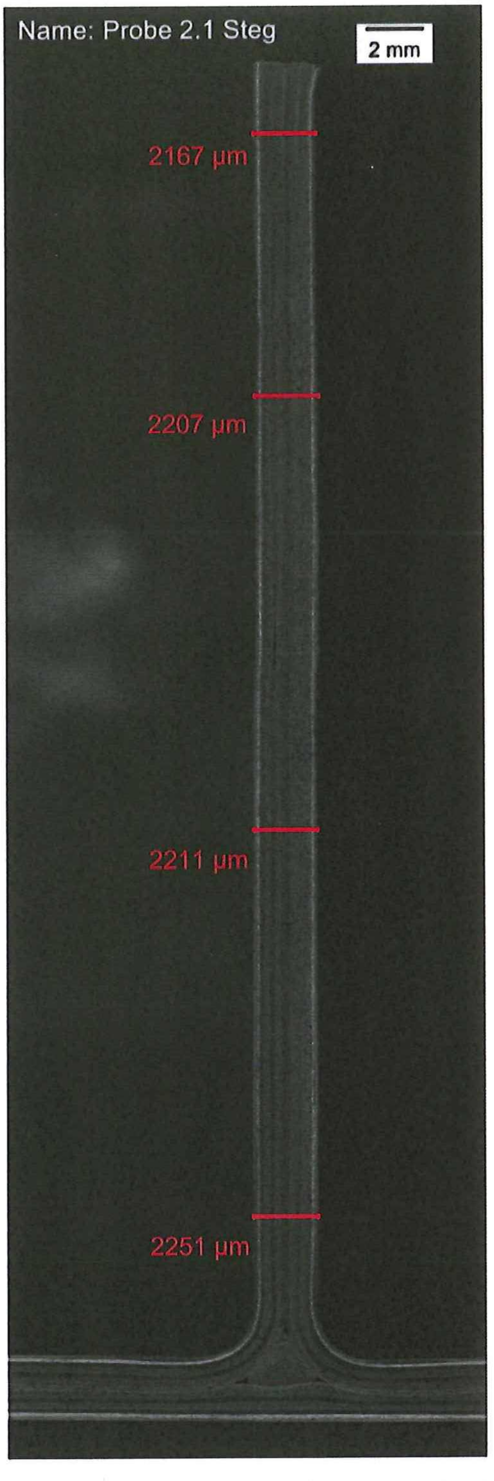


Figure D.63: Cross section of panel 10 stringer 1a

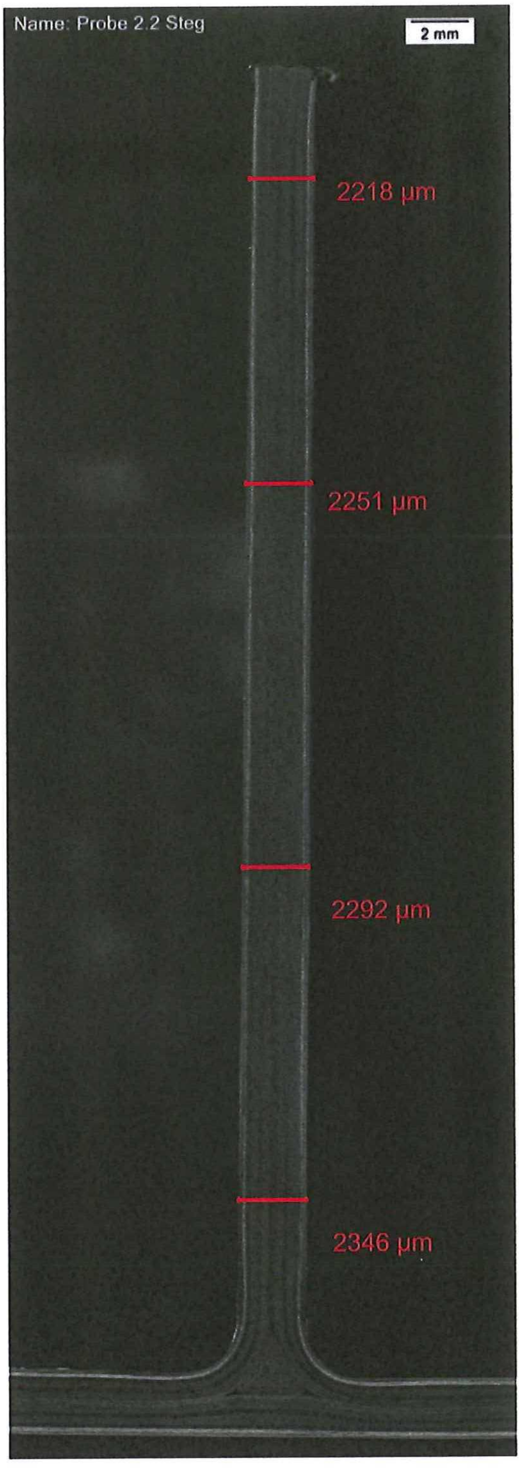


Figure D.64: Cross section of panel 10 stringer 2a

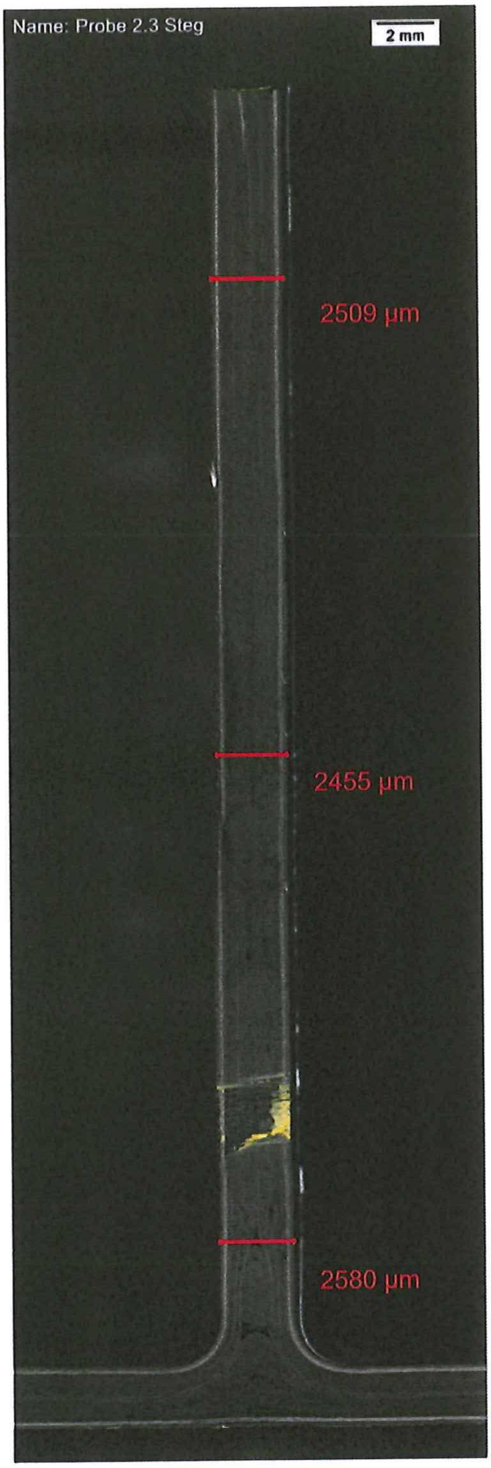


Figure D.65: Cross section of panel 10 stringer 1b

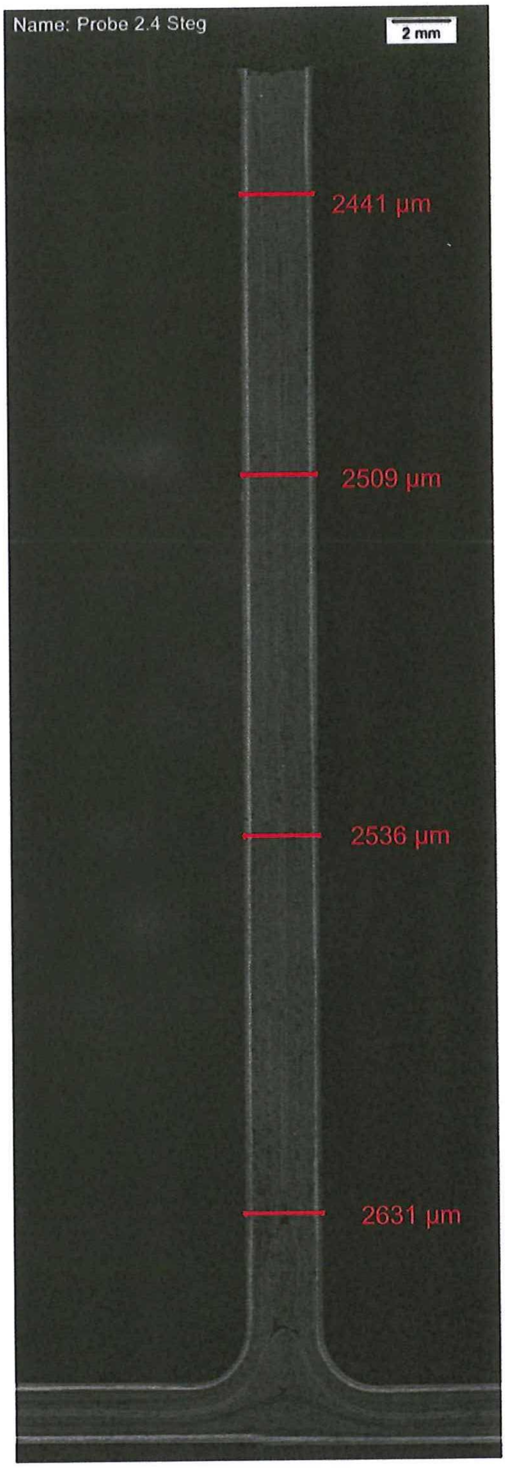


Figure D.66: Cross section of panel 10 stringer 2b

Figure D.67: Panel 11 stringer 1a skin

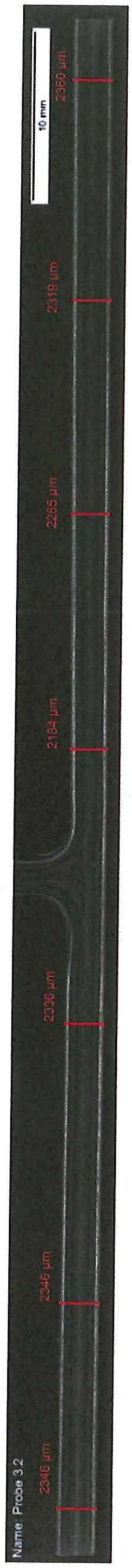


Figure D.68: Panel 11 stringer 2a skin

Figure D.69: Panel 11 stringer 1b skin

Figure D.70: Panel 11 stringer 2b skin

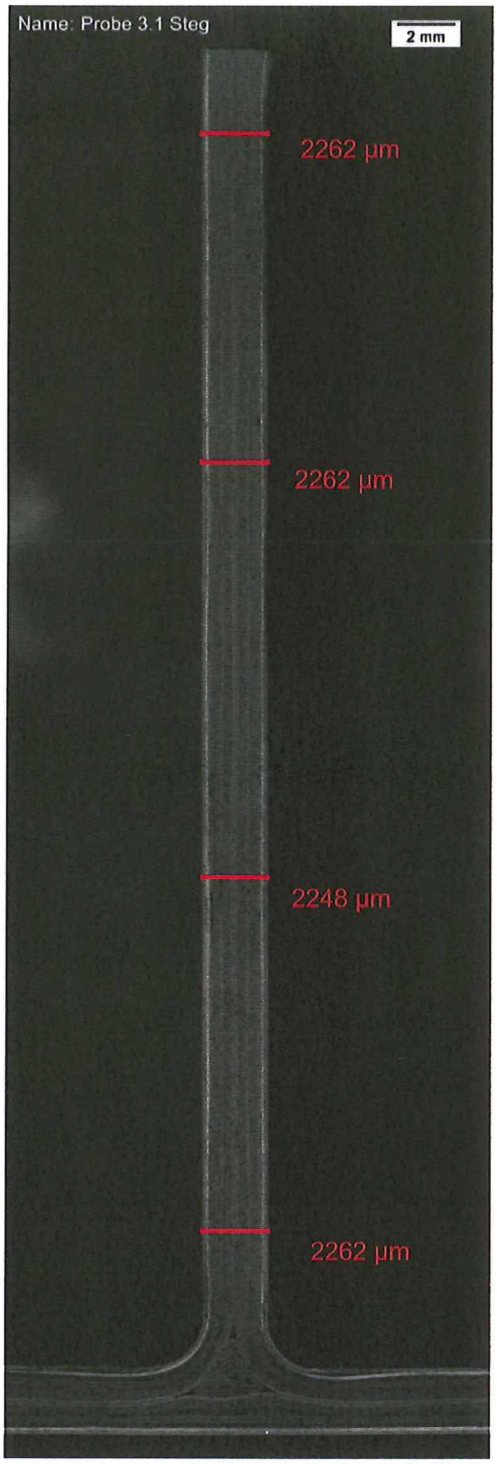


Figure D.71: Cross section of panel 11 stringer 1a

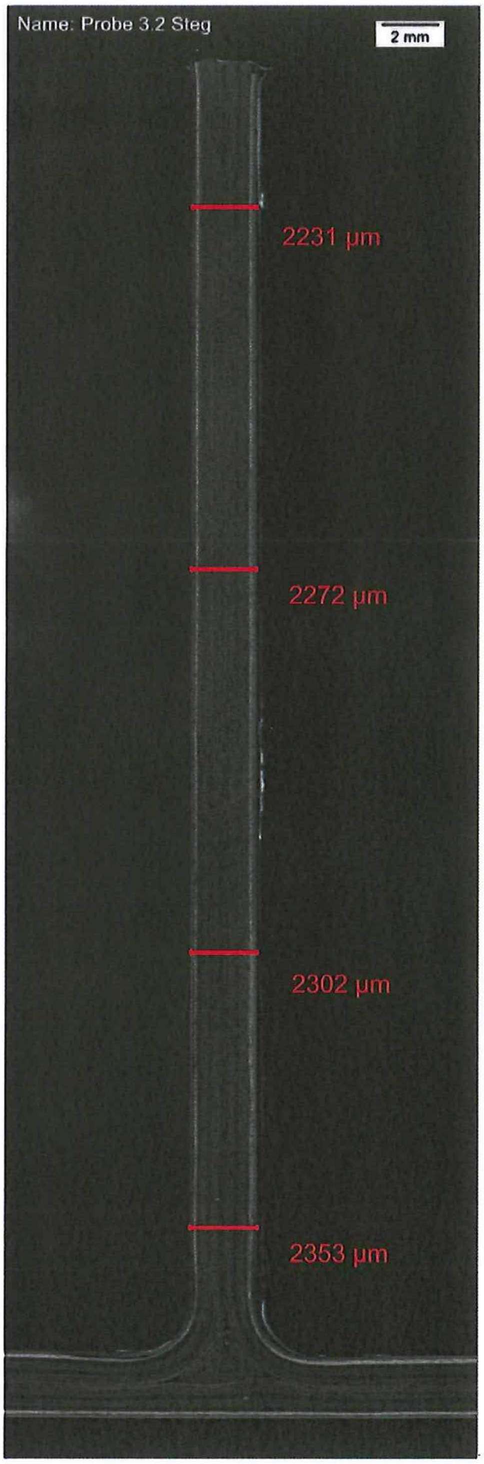


Figure D.72: Cross section of panel 11 stringer 2a

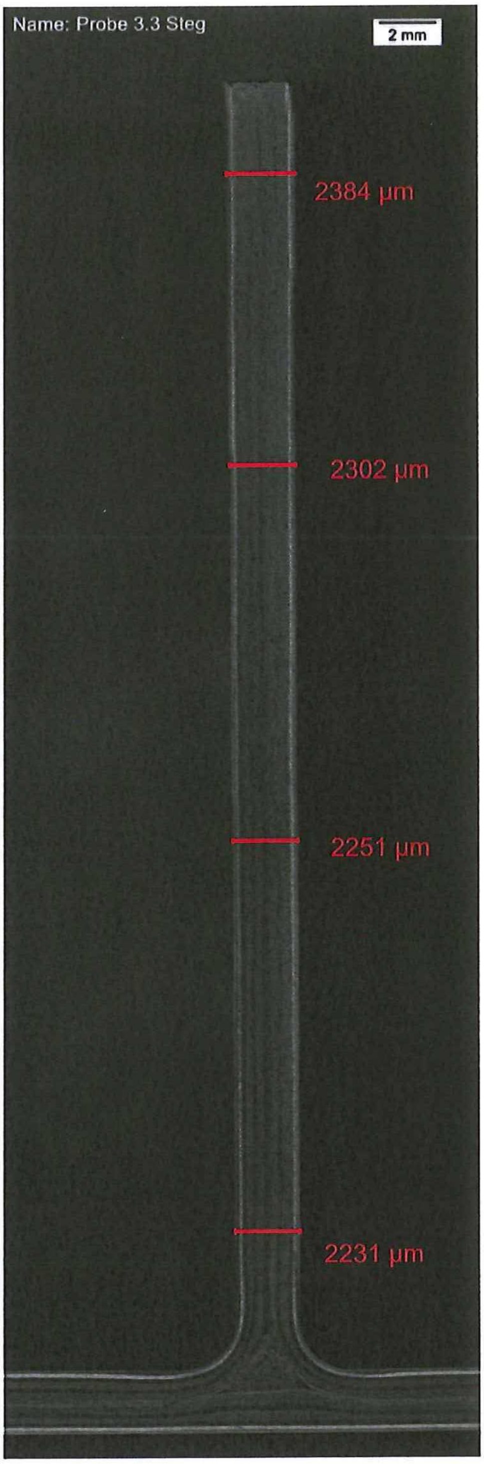


Figure D.73: Cross section of panel 11 stringer 1b

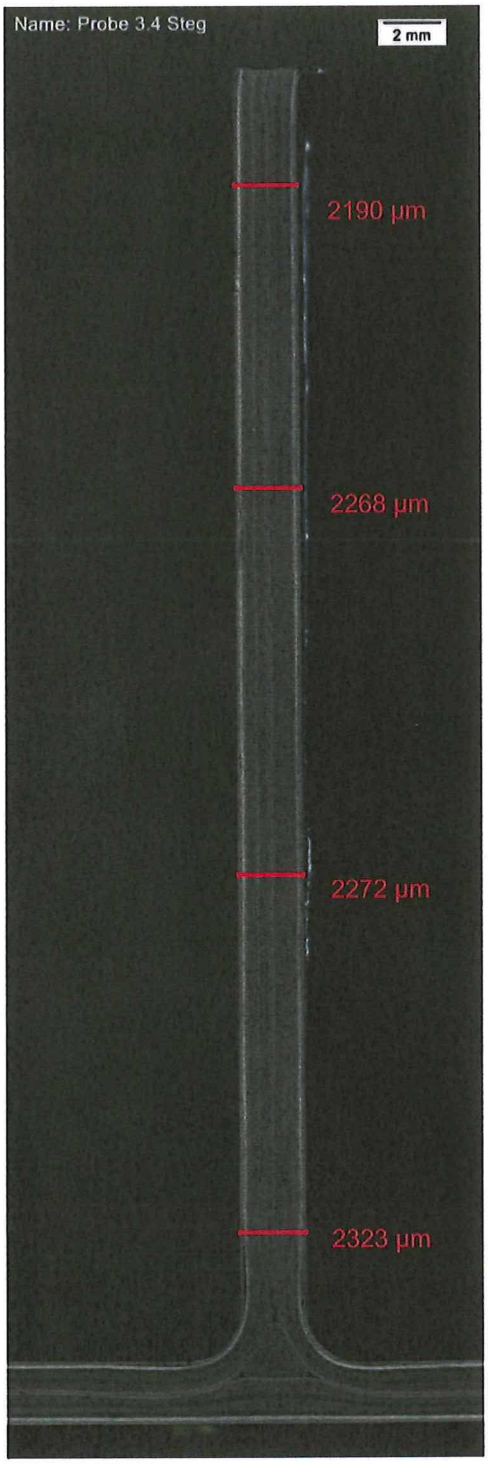


Figure D.74: Cross section of panel 11 stringer 2b

Figure D.75: Cross section of panel 12 stringer 1 skin

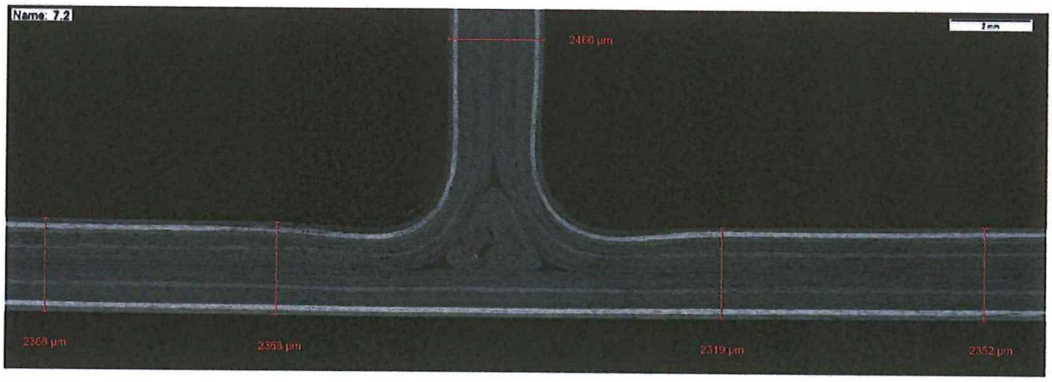


Figure D.76: Cross section of panel 12 stringer 2 skin

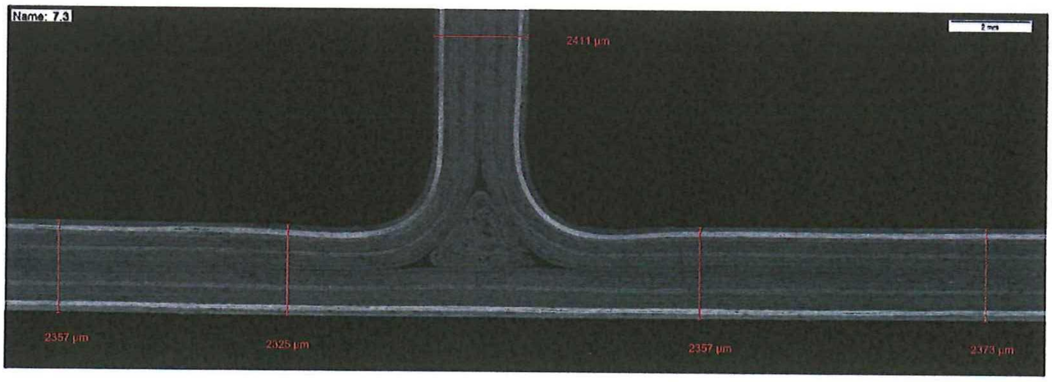


Figure D.77: Cross section of panel 12 stringer 3 skin

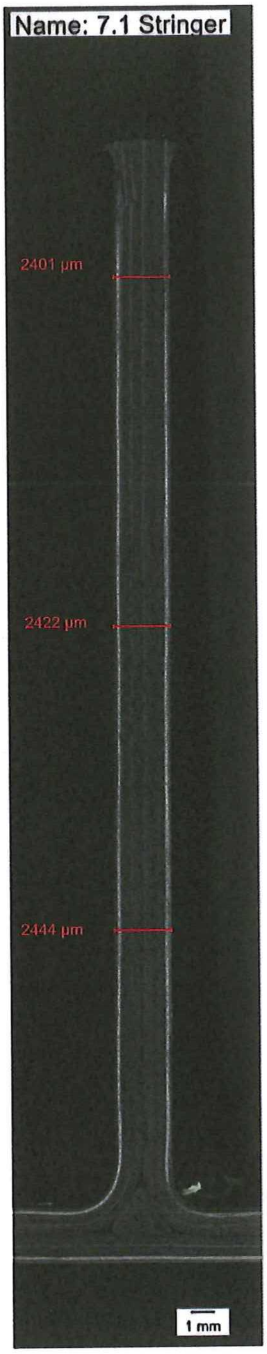


Figure D.78: Cross section of panel 12 stringer 1

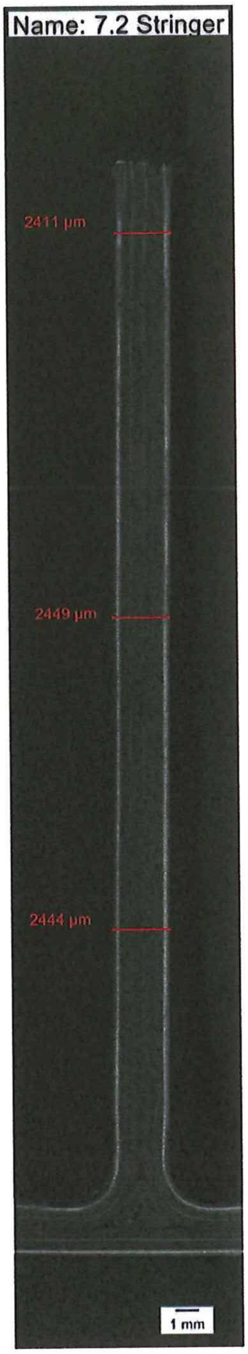


Figure D.79: Cross section of panel 12 stringer 2

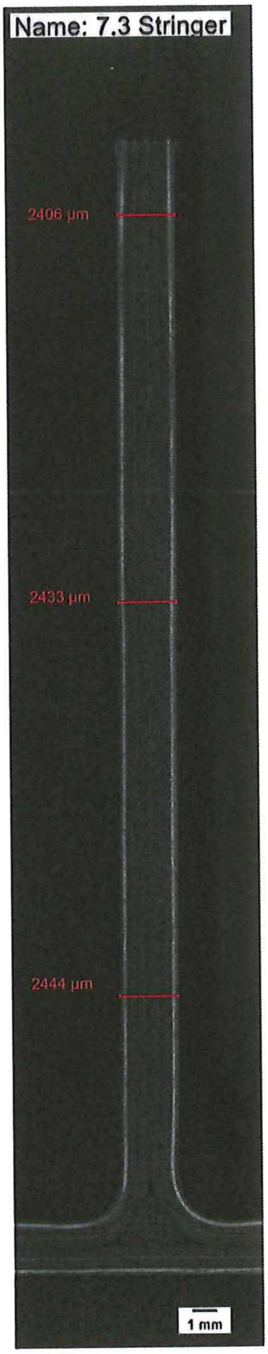


Figure D.80: Cross section of panel 12 stringer 3

Figure D.81: Cross section of panel 13.1 stringer 1 skin

Figure D.82: Cross section of panel 13.1 stringer 2 skin

Figure D.83: Cross section of panel 13.1 stringer 3 skin

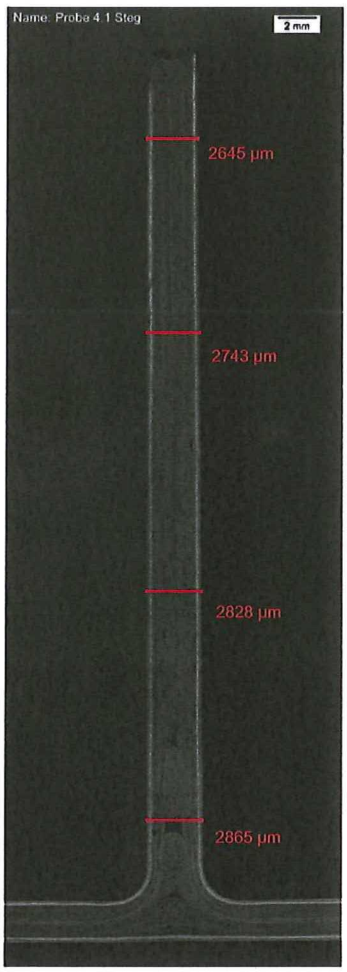


Figure D.84: Cross section of panel 13.1 stringer 1

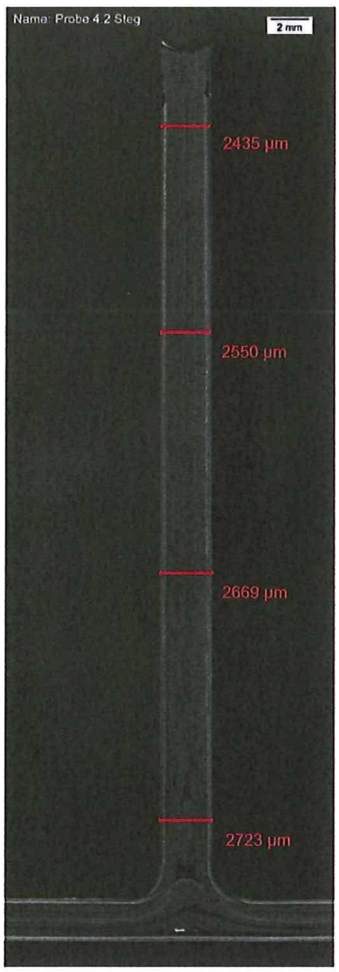


Figure D.85: Cross section of panel 13.1 stringer 2

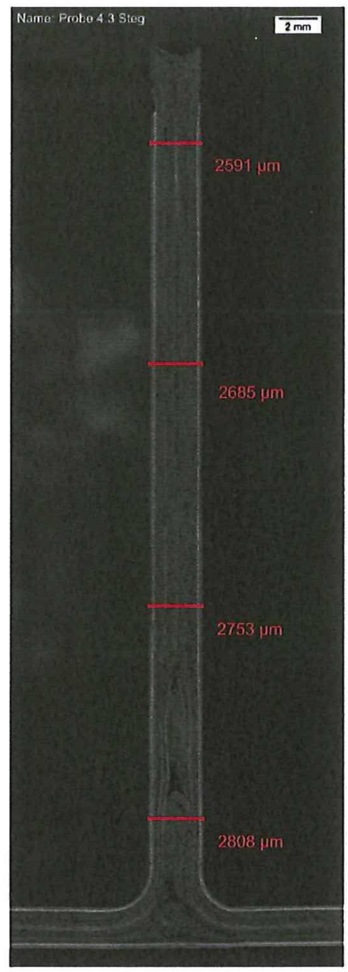


Figure D.86: Cross section of panel 13.1 stringer 3

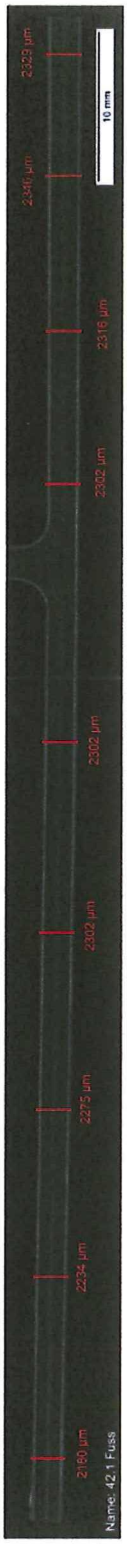


Figure D.87: Cross section of panel 13.2 stringer 1 skin

Figure D.88: Cross section of panel 13.2 stringer 2 skin

Figure D.89: Cross section of panel 13.2 stringer 3 skin

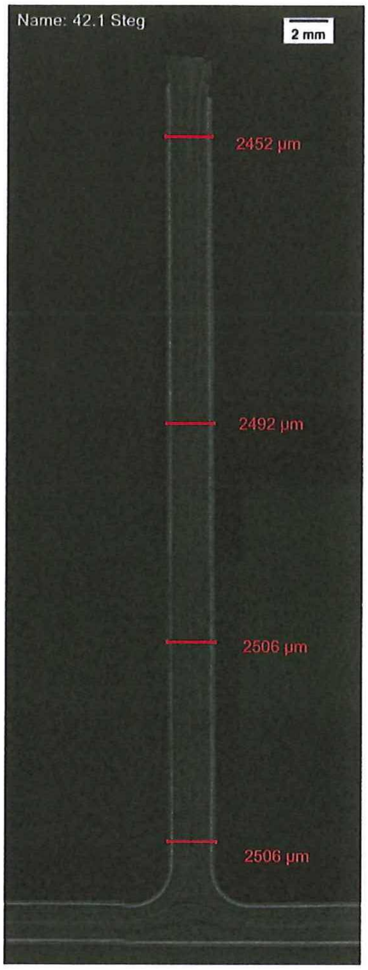


Figure D.90: Cross section of panel 13.2 stringer 1

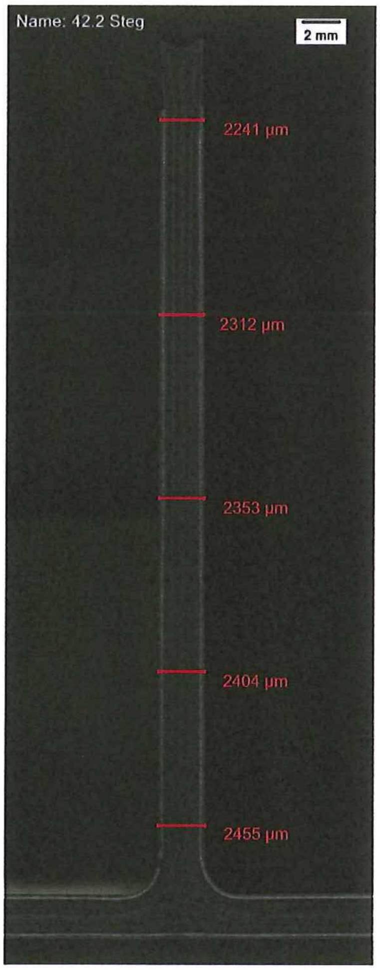


Figure D.91: Cross section of panel 13.2 stringer 2

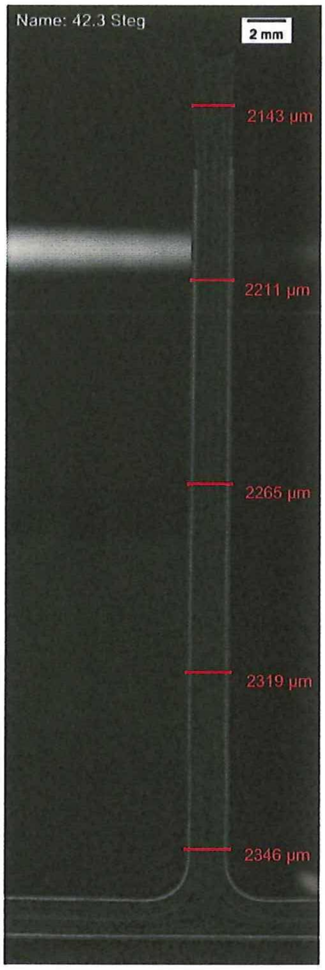


Figure D.92: Cross section of panel 13.2 stringer 3

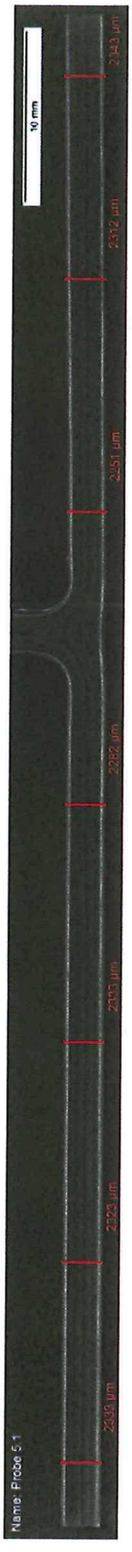


Figure D.93: Cross section of panel 14 stringer 1 skin

Figure D.94: Cross section of panel 14 stringer 2 skin

Figure D.95: Cross section of panel 14 stringer 3 skin

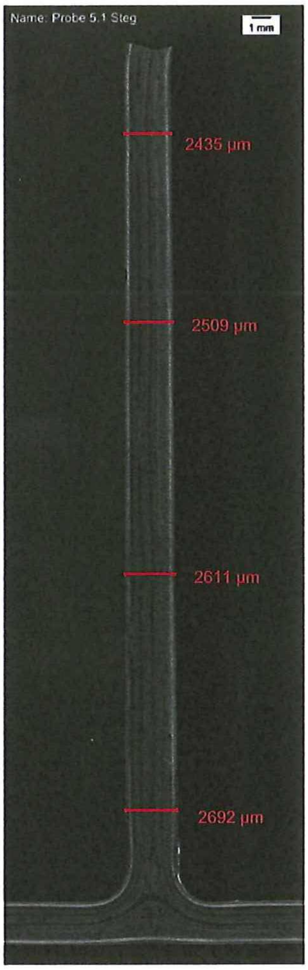


Figure D.96: Cross section of panel 14 stringer 1

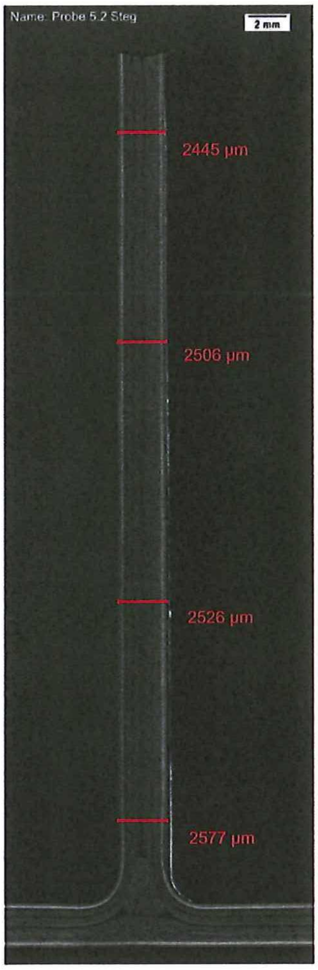


Figure D.97: Cross section of panel 14 stringer 2

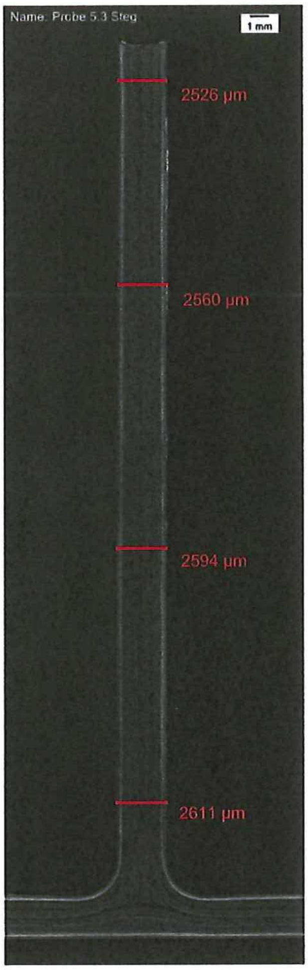


Figure D.98: Cross section of panel 14 stringer 3

Appendix E

Test panel thicknesses

In this appendix, the thickness measurements are given for the individual parts that were manufactured for this thesis. The measured thicknesses are taken from the cross sectional images in D. Form these thicknesses, the shape of the part is portrayed more clearly and it can be determined if the thicknesses fall within the tolerance limits.
The actual measured thickness is portrayed as a percentage of the nominal thickness that the laminate should have. This is namely the cured thickness of a single layer multiplied by the number of layers in the laminate. The total number of layers is 18 and the thickness of one ply is 0,125 mm, coming up to a total thickness of 2,250 mm. This was also explained in chapter 5, just as the corresponding allowed deviations where the part thickness should be within in order for the part to be accepted. In the tables, out of tolerance thicknesses are shown in red and within tolerances in green. The thickness of the standard and the tolerances are shown in figure E.1 This thickness standard and its tolerances are valid for all the parts except for part 10. For part 10, the number of layers changes and thus also the standard and its corresponding tolerances change. These values are given in the table of the part 10 itself.

Standard	2250
Deviation plus	500
Deviation minus	150

Figure E.1: Nominal thickness standard and allowed deviations

Since not all measurement points are taken at the same locations for the different samples and that the samples do not have precisely the same length, the thickness percentages are displayed as a rough fraction of the total sample length. The graphs give an overview of the general shape of the sample by using the measured data points and shows the comparison between the different samples in the parts in the respective thickness measurement sections in chapter 6. The tables of the thickness measurements of the individual parts are given in tables E.2-E.19.

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 1	Stringer 1	Skin	Left	2556	306	113,6	0,00
				2580	330	114,7	0,20
				2629	379	116,8	0,45
			Right	2532	282	112,5	0,55
				2580	330	114,7	0,80
				2561	311	113,8	1,00
		Stringer		2823	573	125,5	0,00
				2751	501	122,3	0,50
				2556	306	113,6	1,00
	Stringer 3	Skin	Left	2556	306	113,6	0,00
				2546	296	113,2	0,15
				2508	258	111,5	0,30
				2469	219	109,7	0,45
			Right	2585	335	114,9	0,55
				2566	316	114,0	0,80
				2546	296	113,2	1,00
		Stringer		2658	408	118,1	0,00
				2648	398	117,7	0,33
				2512	262	111,6	0,67
				2459	209	109,3	1,00

Figure E.2: Measured thicknesses and deviations of test panel 1

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 2	Stringer 1	Skin	Left	2294	44	102,0	0,00
				2235	-15	99,3	0,45
			Right	2177	-73	96,8	0,55
				2216	-34	98,5	0,65
				2274	24	101,1	0,80
				2294	44	102,0	1,00
		Stringer		2566	316	114,0	0,00
				2527	277	112,3	0,25
				2216	-34	98,5	0,50
				2216	-34	98,5	0,75
				2138	-112	95,0	1,00
	Stringer 3	Skin	Left	2294	44	102,0	0,00
				2265	15	100,7	0,20
				2235	-15	99,3	0,45
			Right	2357	107	104,8	0,55
				2294	44	102,0	0,80
				2245	-5	99,8	1,00
		Stringer		2391	141	106,3	0,00
				2391	141	106,3	0,33
				2235	-15	99,3	0,67
				2255	5	100,2	1,00

Figure E.3: Measured thicknesses and deviations of test panel 2

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 3	Stringer 1	Skin	Left	2352	102	104,5	0,00
				2313	63	102,8	0,15
				2352	102	104,5	0,30
				2333	83	103,7	0,45
			Right	2410	160	107,1	0,55
				2430	180	108,0	0,65
				2410	160	107,1	0,80
				2410	160	107,1	1,00
		Stringer		2478	228	110,1	0,00
				2459	209	109,3	0,33
				2498	248	111,0	0,67
				2371	121	105,4	1,00
	Stringer 3	Skin	Left	2425	175	107,8	0,00
				2406	156	106,9	0,15
				2410	160	107,1	0,30
				2357	107	104,8	0,45
			Right	2410	160	107,1	0,55
				2357	107	104,8	0,65
				2376	126	105,6	0,80
				2328	78	103,5	1,00
		Stringer		2090	-160	92,9	0,00
				2099	-151	93,3	0,25
				2090	-160	92,9	0,50
				2099	-151	93,3	0,75
				2119	-131	94,2	1,00

Figure E.4: Measured thicknesses and deviations of test panel 3

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 4	Stringer 2	Skin	Left	2269	19	100,8	0,00
				2250	0	100,0	0,20
				2206	-44	98,0	0,45
			Right	2197	-53	97,6	0,55
				2231	-19	99,2	0,65
				2269	19	100,8	0,80
				2284	34	101,5	1,00
		Stringer		2328	78	103,5	0,00
				2328	78	103,5	0,25
				2328	78	103,5	0,50
				2284	34	101,5	0,75
				2226	-24	98,9	1,00
	Stringer 3	Skin	Left	2342	92	104,1	0,00
				2313	63	102,8	0,15
				2313	63	102,8	0,30
				2255	5	100,2	0,45
			Right	2357	107	104,8	0,55
				2313	63	102,8	0,65
				2299	49	102,2	0,80
				2269	19	100,8	1,00
		Stringer		2235	-15	99,3	0,00
				2255	5	100,2	0,25
				2333	83	103,7	0,50
				2333	83	103,7	0,75
				2294	44	102,0	1,00

Figure E.5: Measured thicknesses and deviations of test panel 4

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 5	Stringer 1	Skin	Left	2390	140	106,2	0,00
				2390	140	106,2	0,45
			Right	2428	178	107,9	0,55
				2422	172	107,6	1,00
		Stringer		2233	-17	99,2	0,00
				2233	-17	99,2	0,33
				2254	4	100,2	0,67
				2298	48	102,1	1,00
	Stringer 2	Skin	Left	2352	102	104,5	0,00
				2352	102	104,5	0,45
			Right	2271	21	100,9	0,55
				2303	53	102,4	1,00
		Stringer		2411	161	107,2	0,00
				2314	64	102,8	0,33
				2308	58	102,6	0,67
				2287	37	101,6	1,00
	Stringer 3a	Skin	Left	2368	118	105,2	0,00
				2373	123	105,5	0,45
			Right	2330	80	103,6	0,55
				2363	113	105,0	1,00
		Stringer		2319	69	103,1	0,00
				2298	48	102,1	0,33
				2330	80	103,6	0,67
				2287	37	101,6	1,00
	Stringer 3b	Skin	Left	2346	96	104,3	0,00
				2341	91	104,0	0,45
			Right	2422	172	107,6	0,55
				2406	156	106,9	1,00
		Stringer		2341	91	104,0	0,00
				2368	118	105,2	0,33
				2368	118	105,2	0,67
				2308	58	102,6	1,00

Figure E.6: Measured thicknesses and deviations of test panel 5

				Thicknes:	Deviation	Thickness % of standard	Fraction of section
Panel 6	Stringer 1	Skin	Left	2333	83	103,7	0,00
				2333	83	103,7	0,20
				2333	83	103,7	0,45
			Right	2371	121	105,4	0,55
				2371	121	105,4	0,80
				2391	141	106,3	1,00
		Stringer		2478	228	110,1	0,00
				2357	107	104,8	0,50
				2357	107	104,8	1,00
	Stringer 2a	Skin	Left	2284	34	101,5	0,00
				2226	-24	98,9	0,20
				2216	-34	98,5	0,45
			Right	2206	-44	98,0	0,55
				2250	0	100,0	0,65
				2265	15	100,7	0,80
				2269	19	100,8	1,00
		Stringer		2430	180	108,0	0,00
				2371	121	105,4	0,33
				2284	34	101,5	0,67
				2197	-53	97,6	1,00
	Stringer 3a	Skin	Left	2235	-15	99,3	0,00
				2221	-29	98,7	0,15
				2182	-68	97,0	0,30
				2182	-68	97,0	0,45
			Right	2284	34	101,5	0,55
				2299	49	102,2	0,65
				2299	49	102,2	0,80
				2299	49	102,2	1,00
		Stringer		2406	156	106,9	0,00
				2362	112	105,0	0,33
				2342	92	104,1	0,67
				2299	49	102,2	1,00
	Stringer 2b	Skin	Left	2313	63	102,8	0,00
				2284	34	101,5	0,15
				2269	19	100,8	0,30
				2255	5	100,2	0,45
			Right	2284	34	101,5	0,55
				2357	107	104,8	0,80
				2376	126	105,6	1,00
		Stringer		2342	92	104,1	0,00
				2299	49	102,2	0,33
				2269	19	100,8	0,67
				2226	-24	98,9	1,00
	Stringer 3b	Skin	Left	2396	146	106,5	0,00
				2357	107	104,8	0,15
				2342	92	104,1	0,30
				2294	44	102,0	0,45
			Right	2250	0	100,0	0,55
				2250	0	100,0	0,65
				2279	29	101,3	0,80
				2284	34	101,5	1,00
		Stringer		2376	126	105,6	0,00
				2352	102	104,5	0,33
				2313	63	102,8	0,67
				2274	24	101,1	1,00

Figure E.7: Measured thicknesses and deviations of test panel 6

				Thickness	Deviation	Thickness % of standard	Fraction of section
Part 7	Stringer 1	Skin	Left	2379	129	105,7	0,00
				2346	96	104,3	0,45
			Right	2276	26	101,2	0,55
				2276	26	101,2	1,00
		Stringer		2525	275	112,2	0,00
				2541	291	112,9	0,33
				2471	221	109,8	0,67
				2384	134	106,0	1,00
	Stringer 2a	Skin	Left	2276	26	101,2	0,00
				2227	-23	99,0	0,45
			Right	2081	-169	92,5	0,55
				2124	-126	94,4	1,00
		Stringer		2558	308	113,7	0,00
				2498	248	111,0	0,33
				2439	189	108,4	0,67
				2308	58	102,6	1,00
	Stringer 3a	Skin	Left	2124	-126	94,4	0,00
				2103	-147	93,5	0,45
			Right	2189	-61	97,3	0,55
				2227	-23	99,0	1,00
		Stringer		2606	356	115,8	0,00
				2536	286	112,7	0,33
				2482	232	110,3	0,67
				2298	48	102,1	1,00
	Stringer 2b	Skin	Left	2271	21	100,9	0,45
			Right	2709	459	120,4	0,55
				2791	541	124,0	1,00
		Stringer		2243	-7	99,7	0,00
				2216	-34	98,5	0,33
				2081	-169	92,5	0,67
				2043	-207	90,8	1,00
	Stringer 3b	Skin	Left	2823	573	125,5	0,00
				2699	449	120,0	0,45
			Right	2227	-23	99,0	0,55
				2287	37	101,6	1,00
		Stringer		2184	-66	97,1	0,00
				2124	-126	94,4	0,33
				2081	-169	92,5	0,67
				1880	-370	83,6	1,00

Figure E.8: Measured thicknesses and deviations of test panel 7

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 8	Stringer 1	Skin	Left	2319	69	103,1	0,00
				2303	53	102,4	0,45
			Right	2265	15	100,7	0,55
				2287	37	101,6	1,00
		Stringer		2531	281	112,5	0,00
				2558	308	113,7	0,33
				2428	178	107,9	0,67
				2368	118	105,2	1,00
	Stringer 2	Skin	Left	2352	102	104,5	0,00
				2319	69	103,1	0,45
			Right	2303	53	102,4	0,55
				2314	64	102,8	1,00
		Stringer		2558	308	113,7	0,00
				2569	319	114,2	0,33
				2514	264	111,7	0,67
				2406	156	106,9	1,00
	Stringer 3	Skin	Left	2287	37	101,6	0,00
				2271	21	100,9	0,45
			Right	2336	86	103,8	0,55
				2336	86	103,8	1,00
		Stringer		2482	232	110,3	0,00
				2514	264	111,7	0,33
				2471	221	109,8	0,67
				2428	178	107,9	1,00

Figure E.9: Measured thicknesses and deviations of test panel 8

						W.r.t. the ramps		W.r.t. ply nr		
			Soll thickness accouding to the ramps	Soll thickness accourding to the ply nr	Ist thickness	Deviation	Thickness % of standard	Deviation	Thickness % of standard	Fraction of section
Panel 9	Core 1 (no movement)	Ramp cavity (Fig 1.8)	2250	2250	2329	79	103,5	79	103,5	0,00
			2250	2250	2370	120	105,3	120	105,3	0,04
			2500	2500	2584	84	103,4	84	103,4	0,07
			2500	2500	2628	128	105,1	128	105,1	0,11
			2750	2750	2838	88	103,2	88	103,2	0,15
			3000	3000	3062	62	102,1	62	102,1	0,19
			3000	3000	3038	38	101,3	38	101,3	0,22
			3250	3250	3255	5	100,2	5	100,2	0,26
			3250	3250	3306	56	101,7	56	101,7	0,30
			3500	3500	3496	-4	99,9	-4	99,9	0,33
			3500	3500	3537	37	101,1	37	101,1	0,37
			3750	3750	3726	-24	99,4	-24	99,4	0,41
			3750	3750	3754	4	100,1	4	100,1	0,44
		Ramp compressive (Fig 1.7)	3750	3750	3757	7	100,2	7	100,2	0,48
			3750	3750	3770	20	100,5	20	100,5	0,52
			3500	3500	3526	26	100,7	26	100,7	0,56
			3500	3500	3526	26	100,7	26	100,7	0,59
			3250	3250	3323	73	102,2	73	102,2	0,63
			3250	3250	3336	86	102,6	86	102,6	0,67
			3000	3000	3086	86	102,9	86	102,9	0,70
			3000	3000	3106	106	103,5	106	103,5	0,74
			2750	3000	2865	115	104,2	-135	95,5	0,78
			2750	2750	2835	85	103,1	85	103,1	0,81
			2500	2750	2658	158	106,3	-92	96,7	0,85
			2500	2500	2645	145	105,8	145	105,8	0,89
			2250	2500	2428	178	107,9	-72	97,1	0,93
			2250	2250	2384	134	106,0	134	106,0	0,96
			2250	2250	2401	151	106,7	151	106,7	1,00

Figure E.10: Measured thicknesses and deviations of test panel 9 core 1

Part 10	Core 2 (6.4mm / 5% movement)	Ramp cavity (Fig 1.6)	2250	2250	2370	120	105,3	120	105,3	0,00
			2250	2250	2384	134	106,0	134	106,0	0,03
			2250	2250	2424	174	107,7	174	107,7	0,07
			2250	2250	2390	140	106,2	140	106,2	0,10
			2500	2500	2645	145	105,8	145	105,8	0,13
			2500	2750	2696	196	107,8	-54	98,0	0,17
			2750	2750	2916	166	106,0	166	106,0	0,20
			3000	3000	3153	153	105,1	153	105,1	0,23
			3000	3250	3153	153	105,1	-97	97,0	0,27
			3250	3250	3391	141	104,3	141	104,3	0,30
			3500	3500	3628	128	103,7	128	103,7	0,33
			3500	3750	3587	87	102,5	-163	95,7	0,37
			3750	3750	3815	65	101,7	65	101,7	0,40
			3750	3750	3832	82	102,2	82	102,2	0,43
			3750	3750	3865	115	103,1	115	103,1	0,47
		Ramp compressive (Fig 1.5)	3750	3750	3798	48	101,3	48	101,3	0,50
			3750	3750	3798	48	101,3	48	101,3	0,53
			3750	3750	3815	65	101,7	48	101,3	0,57
			3500	3500	3560	60	101,7	60	101,7	0,60
			3500	3250	3564	64	101,8	314	109,7	0,63
			3250	3250	3340	90	102,8	90	102,8	0,67
			3250	3000	3323	73	102,2	323	110,8	0,70
			3000	3000	3079	79	102,6	79	102,6	0,73
			3000	3000	3103	103	103,4	103	103,4	0,77
			2750	2750	2814	64	102,3	64	102,3	0,80
			2500	2500	2628	128	105,1	128	105,1	0,83
			2500	2500	2577	77	103,1	77	103,1	0,87
			2250	2250	2357	107	104,8	107	104,8	0,90
			2250	2250	2353	103	104,6	103	104,6	0,93
			2250	2250	2312	62	102,8	62	102,8	0,97
			2250	2250	2272	22	101,0	22	101,0	1,00

Figure E.11: Measured thicknesses and deviations of test panel 9 core 2

Part 10	Core 3 (12.8mm / 10% movement)	Ramp cavity (Fig 1.4)	2250	2250	2411	161	107,2	161	107,2	0,00
			2250	2250	2479	229	110,2	229	110,2	0,04
			2250	2500	2513	263	111,7	13	100,5	0,08
			2500	2750	2716	216	108,6	-34	98,8	0,12
			2750	3000	2936	186	106,8	-64	97,9	0,16
			3000	3000	3191	191	106,4	191	106,4	0,20
			3000	3250	3208	208	106,9	-42	98,7	0,24
			3250	3250	3445	195	106,0	195	106,0	0,28
			3250	3500	3411	161	105,0	-89	97,5	0,32
			3500	3500	3615	115	103,3	115	103,3	0,36
			3500	3750	3648	148	104,2	-102	97,3	0,40
			3750	3750	3869	119	103,2	119	103,2	0,44
			3750	3750	3852	102	102,7	102	102,7	0,48
			3750	3750	3886	136	103,6	136	103,6	0,52
		Ramp compressive (Fig 1.3)	3750	3750	3798	48	101,3	48	101,3	0,56
			3750	3500	3784	34	100,9	284	108,1	0,60
			3500	3250	3581	81	102,3	534	116,4	0,64
			3250	3250	3323	73	102,2	73	102,2	0,68
			3250	3000	3309	59	101,8	309	110,3	0,72
			3000	3000	3092	92	103,1	92	103,1	0,76
			3000	2750	3048	48	101,6	298	110,8	0,80
			2750	2500	2794	44	101,6	294	111,8	0,84
			2500	2500	2523	23	100,9	23	100,9	0,88
			2500	2250	2563	63	102,5	313	113,9	0,92
			2250	2250	2346	96	104,3	96	104,3	0,96
			2250	2250	2384	134	106,0	134	106,0	1,00

Figure E.12: Measured thicknesses and deviations of test panel 9 core 3

Part 10	Core 4 (25.6 mm / 20% movement)	Ramp cavity (Fig 1.2)	2250	2500	2628	378	116,8	128	105,1	0,00
			2250	2750	2641	391	117,4	-109	96,0	0,04
			2500	2750	2845	345	113,8	95	103,5	0,08
			2500	2750	2872	372	114,9	122	104,4	0,12
			2750	3000	3048	298	110,8	48	101,6	0,15
			2750	3000	3062	312	111,3	62	102,1	0,19
			3000	3250	3265	265	108,8	15	100,5	0,23
			3000	3250	3279	279	109,3	29	100,9	0,27
			3250	3500	3496	246	107,6	-4	99,9	0,31
			3250	3750	3482	232	107,1	-268	92,9	0,35
			3500	3750	3686	186	105,3	-64	98,3	0,38
			3500	3750	3662	162	104,6	-88	97,7	0,42
			3750	3750	3848	98	102,6	98	102,6	0,46
			3750	3750	3848	98	102,6	98	102,6	0,50
		Ramp compressive (Fig 1.1)	3750	3750	3730	-20	99,5	-20	99,5	0,54
			3750	3750	3747	-3	99,9	-3	99,9	0,58
			3750	3500	3679	-71	98,1	247	107,1	0,62
			3500	3250	3442	-58	98,3	192	105,9	0,65
			3500	3000	3408	-92	97,4	408	113,6	0,69
			3250	2750	3086	-164	95,0	336	112,2	0,73
			3250	2750	2916	-334	89,7	166	106,0	0,77
			3000	2500	2611	-389	87,0	111	104,4	0,81
			3000	2500	2543	-457	84,8	43	101,7	0,85
			2750	2250	2492	-258	90,6	242	110,8	0,88
			2500	2250	2424	-76	97,0	174	107,7	0,92
			2250	2250	2204	-46	98,0	-46	98,0	0,96
			2250	2250	2153	-97	95,7	-97	95,7	1,00

Figure E.13: Measured thicknesses and deviations of test panel 9 core 4

				Thickness	Deviation	Thickness % of standard	Fraction of section
Part 10	Stringer 1a	Skin	Left	2251	1	100,0	0,00
				2272	22	101,0	0,15
				2262	12	100,5	0,30
				2272	22	101,0	0,45
			Right	2211	-39	98,3	0,55
				2272	22	101,0	0,80
				2292	42	101,9	1,00
		Stringer		2251	1	100,0	0,00
				2211	-39	98,3	0,33
				2207	-43	98,1	0,67
				2167	-83	96,3	1,00
	Stringer 2a	Skin	Left	2292	42	101,9	0,00
				2309	59	102,6	0,15
				2292	42	101,9	0,30
				2251	1	100,0	0,45
			Right	2136	-114	94,9	0,55
				2163	-87	96,1	0,65
				2201	-49	97,8	0,80
				2258	8	100,4	1,00
		Stringer		2346	96	104,3	0,00
				2292	42	101,9	0,33
				2251	1	100,0	0,67
				2218	-32	98,6	1,00
	Stringer 1b	Skin	Left	2197	-53	97,6	0,00
				2211	-39	98,3	0,20
				2170	-80	96,4	0,45
			Right	2102	-148	93,4	0,55
				2089	-161	92,8	0,65
				2116	-134	94,0	0,80
				2102	-148	93,4	1,00
		Stringer		2580	330	114,7	0,00
				2455	205	109,1	0,50
				2509	259	111,5	1,00
	Stringer 2b	Skin	Left	2129	-121	94,6	0,00
				2143	-107	95,2	0,20
				2062	-188	91,6	0,45
			Right	2034	-216	90,4	0,55
				2095	-155	93,1	0,80
				2075	-175	92,2	1,00
		Stringer		2631	381	116,9	0,00
				2536	286	112,7	0,33
				2509	259	111,5	0,67
				2441	191	108,5	1,00

Figure E.14: Measured thicknesses and deviations of test panel 10

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 11	Stringer 1a	Skin	Left	2333	83	103,7	0,00
				2333	83	103,7	0,15
				2346	96	104,3	0,30
				2374	124	105,5	0,45
			Right	2292	42	101,9	0,55
				2292	42	101,9	0,80
				2319	69	103,1	1,00
		Stringer		2262	12	100,5	0,00
				2248	-2	99,9	0,33
				2262	12	100,5	0,67
				2262	12	100,5	1,00
	Stringer 2a	Skin	Left	2346	96	104,3	0,00
				2346	96	104,3	0,20
				2336	86	103,8	0,45
			Right	2184	-66	97,1	0,55
				2265	15	100,7	0,65
				2319	69	103,1	0,80
				2360	110	104,9	1,00
		Stringer		2353	103	104,6	0,00
				2302	52	102,3	0,33
				2272	22	101,0	0,67
				2231	-19	99,2	1,00
	Stringer 1b	Skin	Left	2262	12	100,5	0,00
				2248	-2	99,9	0,15
				2234	-16	99,3	0,30
				2201	-49	97,8	0,45
			Right	2214	-36	98,4	0,55
				2218	-32	98,6	0,80
				2218	-32	98,6	1,00
		Stringer		2231	-19	99,2	0,00
				2251	1	100,0	0,33
				2302	52	102,3	0,67
				2384	134	106,0	1,00
	Stringer 2b	Skin	Left	2238	-12	99,5	0,00
				2224	-26	98,8	0,20
				2201	-49	97,8	0,45
			Right	2146	-104	95,4	0,55
				2180	-70	96,9	0,80
				2228	-22	99,0	1,00
		Stringer		2323	73	103,2	0,00
				2272	22	101,0	0,33
				2268	18	100,8	0,67
				2190	-60	97,3	1,00

Figure E.15: Measured thicknesses and deviations of test panel 11

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 12	Stringer 1	Skin	Left	2352	102	104,5	0,00
				2336	86	103,8	0,45
			Right	2352	102	104,5	0,55
				2357	107	104,8	1,00
		Stringer		2444	194	108,6	0,00
				2444	194	108,6	0,33
				2422	172	107,6	0,67
				2401	151	106,7	1,00
	Stringer 2	Skin	Left	2368	118	105,2	0,00
				2368	118	105,2	0,45
			Right	2319	69	103,1	0,55
				2352	102	104,5	1,00
		Stringer		2466	216	109,6	0,00
				2444	194	108,6	0,33
				2449	199	108,8	0,67
				2411	161	107,2	1,00
	Stringer 3	Skin	Left	2357	107	104,8	0,00
				2325	75	103,3	0,45
			Right	2357	107	104,8	0,55
				2373	123	105,5	1,00
		Stringer		2411	161	107,2	0,00
				2444	194	108,6	0,33
				2433	183	108,1	0,67
				2406	156	106,9	1,00

Figure E.16: Measured thicknesses and deviations of test panel 12

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 13.1	Stringer 1	Skin	Left	2241	-9	99,6	0,00
				2201	-49	97,8	0,20
				2146	-104	95,4	0,45
			Right	2146	-104	95,4	0,55
				2160	-90	96,0	0,65
				2126	-124	94,5	0,80
				2126	-124	94,5	1,00
		Stringer		2865	615	127,3	0,00
				2828	578	125,7	0,33
				2743	493	121,9	0,67
				2645	395	117,6	1,00
	Stringer 2	Skin	Left	2268	18	100,8	0,00
				2251	1	100,0	0,20
				2221	-29	98,7	0,45
			Right	2170	-80	96,4	0,55
				2228	-22	99,0	0,80
				2258	8	100,4	1,00
		Stringer		2723	473	121,0	0,00
				2669	419	118,6	0,33
				2550	300	113,3	0,67
				2435	185	108,2	1,00
	Stringer 3	Skin	Left	2258	8	100,4	0,00
				2224	-26	98,8	0,20
				2153	-97	95,7	0,45
			Right	2109	-141	93,7	0,55
				2102	-148	93,4	0,65
				2082	-168	92,5	0,80
				2031	-219	90,3	1,00
		Stringer		2808	558	124,8	0,00
				2753	503	122,4	0,33
				2685	435	119,3	0,67
				2591	341	115,2	1,00

Figure E.17: Measured thicknesses and deviations of test panel 13.1

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 13.2	Stringer 1	Skin	Left	2180	-70	96,9	0,00
				2234	-16	99,3	0,11
				2275	25	101,1	0,23
				2302	52	102,3	0,34
				2302	52	102,3	0,45
			Right	2302	52	102,3	0,55
				2316	66	102,9	0,65
				2346	96	104,3	0,80
				2329	79	103,5	1,00
		Stringer		2506	256	111,4	0,00
				2506	256	111,4	0,33
				2492	242	110,8	0,67
				2452	202	109,0	1,00
	Stringer 2	Skin	Left	2353	103	104,6	0,00
				2329	79	103,5	0,09
				2340	90	104,0	0,18
				2309	59	102,6	0,27
				2329	79	103,5	0,36
				2289	39	101,7	0,45
			Right	2319	69	103,1	0,55
				2319	69	103,1	0,66
				2333	83	103,7	0,78
				2353	103	104,6	0,89
				2353	103	104,6	1,00
		Stringer		2455	205	109,1	0,00
				2404	154	106,8	0,25
				2353	103	104,6	0,50
				2312	62	102,8	0,75
				2241	-9	99,6	1,00
	Stringer 3	Skin	Left	2333	83	103,7	0,00
				2346	96	104,3	0,15
				2292	42	101,9	0,30
				2251	1	100,0	0,45
			Right	2319	69	103,1	0,55
				2306	56	102,5	0,66
				2265	15	100,7	0,78
				2265	15	100,7	0,89
				2224	-26	98,8	1,00
		Stringer		2346	96	104,3	0,00
				2319	69	103,1	0,25
				2265	15	100,7	0,50
				2211	-39	98,3	0,75
				2143	-107	95,2	1,00

Figure E.18: Measured thicknesses and deviations of test panel 13.2

				Thickness	Deviation	Thickness % of standard	Fraction of section
Panel 14	Stringer 1	Skin	Left	2333	83	103,7	0,00
				2323	73	103,2	0,15
				2333	83	103,7	0,30
				2282	32	101,4	0,45
			Right	2251	1	100,0	0,55
				2312	62	102,8	0,80
				2343	93	104,1	1,00
		Stringer		2692	442	119,6	0,00
				2611	361	116,0	0,33
				2509	259	111,5	0,67
				2435	185	108,2	1,00
	Stringer 2	Skin	Left	2353	103	104,6	0,00
				2374	124	105,5	0,15
				2333	83	103,7	0,30
				2340	90	104,0	0,45
			Right	2285	35	101,6	0,55
				2323	73	103,2	0,80
				2370	120	105,3	1,00
		Stringer		2577	327	114,5	0,00
				2526	276	112,3	0,33
				2506	256	111,4	0,67
				2445	195	108,7	1,00
	Stringer 3	Skin	Left	2343	93	104,1	0,00
				2343	93	104,1	0,20
				2292	42	101,9	0,45
			Right	2292	42	101,9	0,55
				2292	42	101,9	0,65
				2299	49	102,2	0,80
				2262	12	100,5	1,00
		Stringer		2611	361	116,0	0,00
				2594	344	115,3	0,33
				2560	310	113,8	0,67
				2526	276	112,3	1,00

Figure E.19: Measured thicknesses and deviations of test panel 14

Appendix F

Defect map close up figures

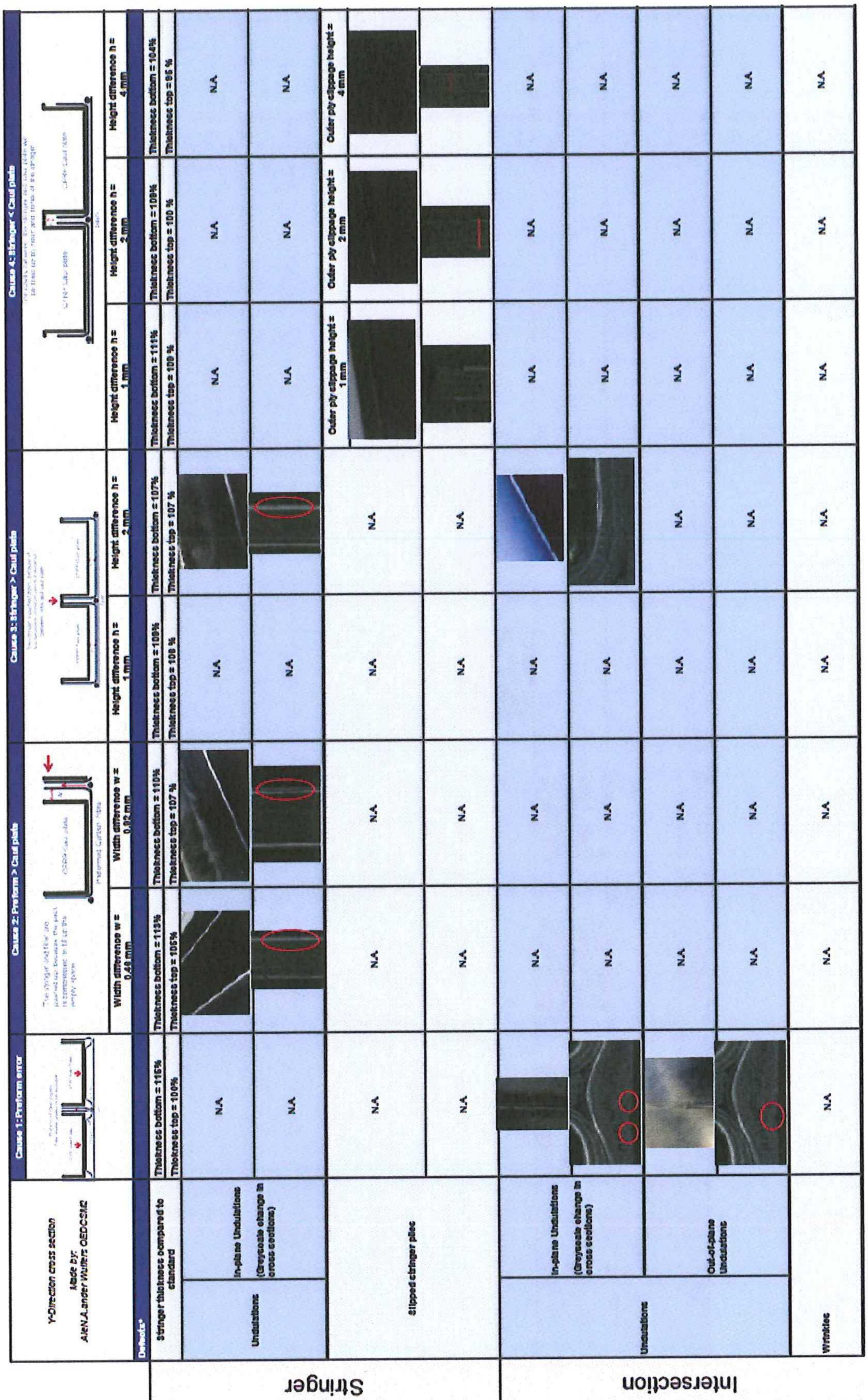
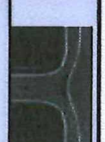
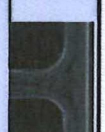
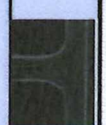


Figure F.1: Defect map close-up upper left

			Filler misalignment = 2,6 mm	Filler misalignment = 1 mm	Filler misalignment = 1,6 mm					
Skin	Filler misalignment	Filler misalignment sideways	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A
		Filler misalignment upwards				N.A	N.A	N.A	N.A	N.A
	Resin rich corner areas in radius		N.A	N.A	N.A			N.A	N.A	N.A
	Undulations	In-plane Undulations (Greyscale change in cross sections)	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A
			N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A
		Out-of-plane Undulations	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A
			N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A

* When N.A., then the part is identical to the reference part

Figure F.2: Defect map close-up lower left

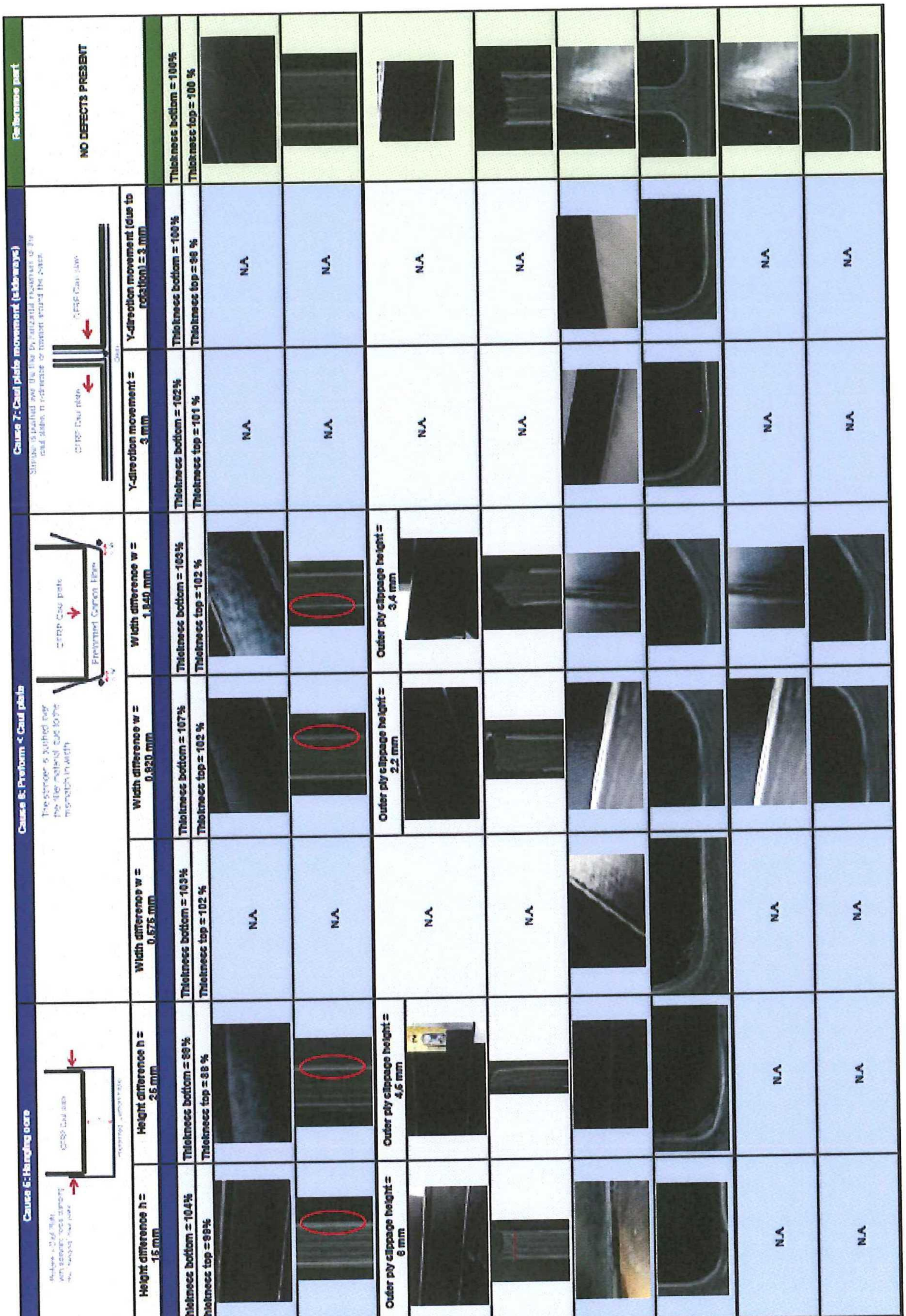


Figure F.3: Defect map close-up upper right