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FORMATION OF DEFECTS IN FLAT LAMINATES DURING AUTOMATIC TAPE LAYING

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ABSTRACT

In this paper, the formation of defects during the lay-up of flat laminates using an automatic tape layer machine is investigated. These defects primarily occur when tape laying with a very thin, low tack carbon reinforced prepreg and lead to qualitative rejection of the final laminate. Theoretical and experimental research leads to the formation of 7 distinct hypotheses on the causes of these defects. Experiments in the lab as well as on the tape layer itself comparing similar prepregs and release films show the importance of numerous factors contributing to the defect origins. The most important of these contributing factors are shown to be the laydown table surface, the head alignment and the tensile and compressive forces during the lay-up. Further, a series of recommendations to alter process parameters and tape laying methods are suggested to reduce the defect formation. Since not all suspected influence parameters could be tested, a framework for further research is provided should the defects reoccur.

Keywords

Automatic tape laying, Prepreg, Uncured, Defects, Wrinkling, Aerospace

1 INTRODUCTION

Sabca Limburg has been struggling with the manufacturing of a specific type of flat laminates on their Automatic Tape Layer (ATL) machine. Some of these flat laminates, destined for clients in the aviation industry, exhibit a permanent deformation during and after completion of the layup. A direct relation was found by Sabca Limburg between deformations in uncured laminates and delaminations after curing, leading to rejection of deformed uncured laminates [1]. Previous research regarding these defects was never able to pinpoint the full range of potential causes, and defects kept occurring which made further research necessary.

The defects primarily occur when tape laying these specific laminates using a particular very thin carbonreinforced prepreg UD-tape (prepreg A). Due to the specifications of the client, a material change is not possible and a workaround solution had to be found.

The aim of this research was to get a better understanding of the causes and formation of defects during tape laying these laminates comprised of prepreg A.

Sections 2 to 5 introduce the tape laying process, the materials and the laminate build-up. Subsequently, section 6 lists the hypotheses on the cause of these deformations and section 7 the experiments to substantiate them. In section 8 the conclusion of the experiments is provided and section 9 lists the recommendations to reduce the defect rates. In section 10 a framework for further research is provided, while the final conclusion of the research is drawn in section 11.

2 THE TAPE LAYING PROCESS

The molds on which the laminates are laid are flat tables that were designed and produced in-house at Sabca Limburg. These consist of an aluminum plate with 6000 holes with a diameter of 1mm, on which a release film is rolled out by the operators. This film is fixed into place by slightly stretching it and taping it onto the table. A vacuum is then applied to keep the release film in place during the tape laying as well as to straighten the slightly convex plate. Table heating can be switched on by the operator if deemed favorable.

The tape layer head used for the automatic tape laying process is sketched in Figure 1.



Figure 1: Schematic of a tape layer head [2]

A prepreg roll, comprised of UD-tape and a backing paper, is mounted on the supply reel. This coiled UD-tape with backing paper is then pulled out to underneath the laydown shoe and the surplus backing paper is fixed onto the takeup reel. The backing paper's non-stick properties warrant that the layers of tape do not stick to each other on the roll or to the guide surfaces. A slight pretension is applied by the machine to ensure correct supply of the material through the machine.

The guide surfaces feed the tape to the laydown shoe in a straight manner. When heated they warm up the tape to improve its surface tackiness.

The whole head, weighing approx. 900kg, is mounted on air pistons which largely counteract the weight of the head. The remaining downward force is called the head pressure force and acts via the laydown shoe on the laminate or table. The head pressure presses the tape at the laydown shoe onto the laminate so that the courses of tape stick properly to the lower layers (plies). The tackiness between the tape and the lower laminate ensures that the tape does not slip over the laydown shoe and that it releases smoothly from the backing paper.

The tape layer head is fixed onto a vertical cylinder able to move over an overhead beam which moves on the overhead guide rails (cf. gantry crane). This allows movement in the x, y and z-directions to lay courses of tape in all directions. The speed at which the machine head moves forward in a certain direction is called the feed rate and is expressed in mm/min. To align the tape layer head for course laying a rotational movement of the head is used.

When nearing the end of a course the tape has to be cut. This is done by dual roller knives that cut the tape 620 mm from the laydown shoe. They have to be carefully aligned and adjusted in order to cut only through the tape and not the backing paper. To achieve this a supplemental pretension has to be applied on the tape and backing paper to press them onto the guide surface to avoid paper tear when cutting. This pretension is achieved by putting a positive torque on the supply reel and take-up reel. There are two different modes of tape laying: in M84 mode there is little pretension and the machine rolls off tape at the correct speed to match the feed rate of the head by rotating the supply and take-up reels. In M85 mode a pretension is applied and the friction between the tape underneath the shoe and the underlying laminate/release film causes the tape to be rolled off as the machine moves forward at a certain feed rate (cf. a correction roller). This M85 mode is the standard tape laying mode described in the operating manuals of the ATL machines.

M85 course tape laying process (prior to December 2014)

- 1. The machine moves the head down until the shoe touches the table.
- 2. It starts moving forward in M84 at a certain feed rate.
- 3. After 150mm the machine comes to a stop to apply pretension (M85). This stop lasts for ± 3 sec.
- 4. The machine moves forward in M85 at a certain feed rate.
- 5. 620mm before the end of the course the machine stops again for ± 3 sec to cut the tape using the roller knives.
- 6. After cutting the pretension is removed and the machine continues in M84 until the end of the course.

M84 course tape laying process (post December 2014)

- 1. The machine moves the head down until the shoe touches the table.
- 2. It starts moving forward in M84 at a certain feed rate.
- 3. 620mm before the end of the course the machine stops, applies pretension (M85) and cuts the tape. This stop lasts ±3sec.
- 4. After cutting the pretension is removed and the machine continues in M84 until the end of the course.

The last part of the course in M84 can either be laid with the regular fixed shoe or with a compaction roller. This is a cylindrical roller that can be folded down to replace the shoe to prevent slip and ensure good course adhesion to the laminate. Its primary usage is for laying tapered course ends.

Every 5 to 10 plies a compacting of the laminate is done by the operators to remove air between the layers and improve interply adhesion. This is done by switching off the vacuum of the table and punching holes into the lower release film around the contour of the laminate. On top of the laminate a compression mat is laid and an extra release film is applied in a similar manner as the lower one. The vacuum is then reapplied for ± 15 minutes to suck the air from between the two release films, compacting the laminate in between. When the laminate is finished a final compacting is done. Finally, with the top release film still in place, the laminate gets cut into smaller laminates by a roller knife fixed on the ATL head instead of the laydown shoe.

3 MATERIALS

The tape considered in this project, prepreg A, is one of the world's thinnest prepreg UD tapes with a cured ply thickness of 0,125 mm and a width of 150 mm. The prepreg has a tensile modulus of 137,5GPa and a tensile strength of 2,3GPa. It consists of carbon fibers impregnated with an epoxy resin at a resin content of 35%. The scrap rate of laminates produced with prepreg A varies between 10 and 60%.

Comparisons are made with a prepreg B from the same manufacturer. This tape has the same width, carbon fibers and resin at respectively the same fiber fraction and percent resin content. The difference is that prepreg B is twice the thickness of prepreg A at a cured ply thickness of 0,250mm. Manufacturing of flat laminates with prepreg B exhibits very low scrap rates, even though the laminates are manufactured with the same process- and machine parameters.

Table 1: Prepreg properties

Prepreg	Cured ply	Width	Tack	Shelf	
	thickness		life	life	
	(mm)	(mm)	(days)	(months)	
А	0,125	150	30	12	
B 0,250		150	30	12	
Prepreg	Areal	Fiber	Resin	Scrap	
	weight	density density		rate	
	(g/m²)	(g/cm ³)	(g/cm ³)		
А	203	1,77	1,25	10-60%	
	±12	±0,02	±0,01		
В	406	1,77	1,25	< 5%	
	±24	±0,02	±0,01		

The most striking difference between the two prepregs is the quality. Prepreg A exhibits dry zones and a lower surface tackiness than prepreg B. It also shows clear signs of residual tensions in the dry zones due to the manufacturing process. This expresses itself in bubbles in the dry zones when the tape is pressed flat when it comes off the roll (fig. 2). The number and magnitude of these bubbles appear strongly batch-dependent. Research by Potter links the batch dependency of the incoming materials to the void content of the final laminate [3]. Prepreg B does not show these dry zones but does show

Prepreg B does not show these dry zones but does show these bubbles, although they are up to a factor 10 smaller in height as well as in diameter (fig. 3). There appears to be much less batch dependency in prepreg B quality.



Figure 2: Prepreg A showing dry zones with bubbles



Figure 3: Prepreg B showing a more uniform resin distribution

Laminates with prepreg A are laid on a polyvinyl fluoride release film A, those with prepreg B are laid on the polypropylene release film B. The release films are bought from different manufacturers. The client specifies a short list of approved release films for use with the prepregs. While laminates A can be laid on either release film A and B, they use release film A because of the lower cost.

Table 2: Release film properties

Release	Thickness	Tensile	Elongation
film	(mm)	strength	at break
		(N/mm²)	(%)
А	0,04	75	50
В	0,025	62	100

An important property of release films for ATL processes is their tensile strength and elasticity since they have to withstand forces during the automatic tape laying. Second, they should be able to withstand the curing cycle as they are cured together with the cut laminates. Last and foremost, they should be sticky enough so the first layer of tape can adhere to the film, yet nonadhesive enough to peel the film off after curing. No adhesive properties are listed in either of the datasheets of the release films.

4 TAPELAYER DIFFERENCES

At Sabca Limburg, there are two different Cincinnati automatic tape laying machines. The first was installed in 1991 (ATL1) and the second in 2007 (ATL2). The older tape layer uses a rubber laydown shoe covered by a glass fiber strip. It was later modified by Sabca engineers by adding Teflon strips to reduce friction and a copper wire to facilitate peeling the tape from the backing paper. The newer tape layer uses a segmented steel laydown shoe to better adapt to the tape laying surface.

The setting of head pressure on ATL2 is manipulated by the operator via a digital control circuit which manipulates the head weight counteracting air pistons. The digitally displayed setting is the true pressure the laydown shoe exerts on the table or laminate as measured by a pressure sensor in the ATL head. On ATL1 however the head pressure is manipulated by the operator via a manual rotary control. The analog pressure gauge measures the counteracting pressure the air pistons provide, which is converted into head pressure force via a conversion table [annex 15]. Hysteresis of the air pistons however leads to significant uncertainties on the actual head pressure force.

Before 2013 the programs for tape laying on ATL1 and ATL2 were programmed separately using different programming suites resulting in different CNC coding. After an update of the ATL2 programming suite it became possible to program ATL1 using the newer program. Initially this resulted in restrictions in the usable program functions for ATL1 but as of 2014 the transitional problems have been solved.

Last, the airtight sealing of the table of ATL1 had degraded due to ageing, resulting in a lower vacuum. Repairs on the table were done early 2015 restoring the vacuum capability to its original level.

Despite the differences both tape layers exhibit the deformations when tape laying laminates comprised of prepreg A.

5 LAMINATE BUILD-UP

Project A uses prepreg A and release film A. It consists of eight types of flat laminates with the number of plies ranging from 10 to 34. They also differ in size and shape from 2,4m² to 14m². The lay-up duration for laminates A ranges from 5h to 17h30.

Project B uses prepreg B and release film B. It consists of a single flat laminate of $7,4m^2$ and 12 plies. The lay-up duration for a laminate B is approximately 6h.

At the start of the research the laminates for both projects were comprised of $+45^{\circ}$ and -45° layers. They were laid in a unidirectional layup, meaning that the tape layer always starts a ply at the start of the x-axis. This is equivalent to always starting at the same side of the table.

Early 2015, a ply book update for project A was introduced. Laminates A now consist of $+45^{\circ}$, -45° , $+135^{\circ}$ and -135° layers. There is no orientation change (e.g. between $+45^{\circ}$ and -135°) within a layer and the unidirectional layup method was not changed.



Figure 4: Sketch of the ply orientation and table axes conventions

6 HYPOTHESES

6.1 Hypothesis 1: Displacement

Because of the unidirectional ±45° lay-up, the resulting global shear force has an orientation of 0° in accordance with the x-axis of the table. This causes the laminate to displace along the x-axis relative to the release film. The magnitude of displacement varies due to the local differences in friction coefficient between the first layer of prepreg and the release film. Possible contributing factors are the prepreg's dry spots and inferior resin distribution, variations in head pressure, head alignment and release film choice. These variations create local compressive stresses leading to a normal (z-axis) displacement of the material, causing the laminate to locally exhibit wrinkling [4]. The existence of displacement between the first layer of the laminate and the release film has been confirmed in 2000 by D. Hoff [5] (fig. 6) and in 2007 by F. Camps [annex 1].

With $\pm 45^{\circ}$, $\pm 135^{\circ}$ ply orientations the resulting global shear force equals 0. The 45° lay-up forces cancel out the stress build-up of the -135° plies and the -45° lay-up forces cancel out the stress build-up of the 135° plies.



Figure 5: Wrinkling possibly caused by displacement of the whole laminate [5]



Figure 6: Displacement of the first ply after completion of the layup, sensitive information was edited out [5]

6.2 Hypothesis 2: Compression

When using M85 tape laying, the first 150mm are laid in M84 without pretension. Because head alignment prior to 2015 was corrected during the application of pretension, the alignment for the first 150mm was non-optimal. From January 2015 to March 2015 a head alignment issue due to a hard impact made the problem even worse.

Further degradation of course adhesion is caused by the temperature dependency of the tackiness of prepregs [2] [7], and its effect on insufficient backing paper from tape separation, and the inferior resin distribution of prepreg A. Together with the aforementioned head alignment problem this causes problems in course adhesion to its surface; either the release film as in figure 9 or the underlying ply of prepreg tape. When this is not adequately corrected by the operators, the laydown shoe will traverse this low adhesion area in the next ply with a compressive force comprised of the axial force and the head pressure normal force. This local compression is built up gradually during ±45° lay-up, resulting in buckling of the layers. With $\pm 45^{\circ}$, $\pm 135^{\circ}$ lay-up the compressive forces cancel eachother out as long as no displacement or buckling has already occured. Depending on the interply friction this could lead to one of the following two out of plane deformations, as defined by Akermo, Mattei et al [8]:

If the interply friction is higher than the tape-release film friction, the laminate will wrinkle (fig. 7). This means the first layer will buckle and detach from the release film when faced with axial compression, with all layers exhibiting an out of plane z-axis deformation.



Figure 7: Out of plane deformation - Wrinkling

If the interply friction is lower than the tape-release film friction, the laminate will exhibit waviness (fig. 8). Waviness happens when a course or ply exhibits inferior adhesion with its lower surface yet good adhesion with the layer on top. When the laydown shoe moves over the top layer it will axially displace the top layer over the inferior layer. This causes the top layers to buckle under the compression, leaving the lower layers flat. This delamination fills itself with air, which afterwards is removed by the compacting procedure.

Operator testimonies revealed that some defects disappear after compacting, only to reappear at the same spot after a few layers. This could point to waviness-type defects.



Figure 8: Out of plane deformation - Waviness



Figure 9: Insufficient adhesion of the tape to the release film due to the head alignment, even with double-sided adhesive applied - 06/02/2015



Figure 10: Wrinkling/waviness at the start of the course due to insufficient adhesion [5]

6.3 Hypothesis 3: Elongation & shrinkage

When, opposed to hypothesis 2, good adhesion is obtained at the beginning of the course, the first 150mm in M84 will remain static during the course laying. When the tape layer stops and applies a pretension, the 3 second static compression further improves the interlaminar adhesion [7].

After this 3 second dwell time it starts moving again at a feed rate of 30.000 mm/min with pretension applied, resulting in a higher tensile force. This tensile force will induce a significant extension in the tape course being laid in M85 [3] [9] [10]. When this stressed tape course is laid on an already relaxed layer the interply friction will induce a compressive interlaminar force as it contracts over time, leaving residual stresses [11] [12]. This time-dependant behavior of the tape is due to the viscoelastic properties of the epoxy resin. The effect can be observed when laminating on top of a ply of the same orientation, resulting in wrinkling perpendicular to the course orientation. When laminating on a ply differing 90°, the resulting wrinkles will be parallel to the course direction [4]. This process repeats itself as the plies build up, each time increasing the compression of the lowest ply. This results in the compressive interlaminar force on the first ply becoming so high that the tape-release film friction is exceeded and buckling starts to occur, resulting in wrinkling of the laminate [3] [8].

The fact that wrinkling usually starts to show after approx. 7-10 layers is an indication for the wrinkling process to be time- and ply build-up dependent.

Experimental research by Sabca Limburg into the ideal value of the pretension for M85 cutting was conducted in 2013 by K. Verjans and F. Camps. They demonstrated the ideal value to be 111,2N (25lbs). Tests at 15 and 20lbs showed that at lower values of the pretension there wasn't enough tension to cut the tape without tearing the backing paper. Tests at 30lbs, 35lbs and 40lbs showed that the higher the pretension value, the more quickly wrinkling was observed. At 40lbs wrinkles were already visible at layer 4.



Figure 11: Left side of a completed laminate showing wrinkling at the M84-M85 transition - 20/09/2007



Figure 12: The right side of the same completed laminate showed no defects - 20/09/2007

6.4 Hypothesis 4: Head pressure

Head pressure force is necessary to ensure good adhesion between plies of prepreg. As referenced in Ward et al [13], too high head pressure layup "could result in delamination during layup, as the material is pushed and pulled apart in front of and behind the layup roller...".

This bow-wave effect and resulting delaminations were also observed by Sabca Limburg engineers during head pressure tests at a high load of 60kg (588,4N). Too low a load at 30kg (294,2N) resulted in insuficcient tack between the prepreg layers and delaminations. A trialand-error method led them to the ideal head pressure value of 45kg (441,3N).

As previously mentioned the head pressure is not precisely determinable on ATL1 and is set by the operator based on his judgement. Because of the pulsation and hysteresis of the air pistons, the uncertainty is 0,1bar. At the time of observation, 08/12/2014, the set 4,0 to 4,1 bar pressure resulted in an uncertainty of 29kg according to annex 15. The true head pressure force could be anywhere between 82kg when coming from a higher pressure to 53kg when coming from a lower pressure.

When applying pretension at the M84 to M85 transition and when cutting the tape, the tapelayer stands still for approximately 3 seconds. The prolonged head pressure force at this point causes a deformation in the z-axis by leaving an imprint of the laydown shoe in the laminate. This effect is further amplified on ATL1 where the copper wire to improve peeling increases the imprinted area, as shown in figure 13.

6.5 Hypothesis 5: Laps & gaps

6.5.1 Laps

A lap is an overlap of two adjacent courses due to various alignment issues, producing a double thickness or raised edge. It can also be caused by excessive head pressure force resulting in head of course steering or by tail hooking, which occurs when "the fibers are not properly cut and are pulled in an overlap condition with the adjacent course during tail roll-out" [14]. When not properly corrected by the operator, this raised edge propagates through the plies and stays visible until completion (fig. 14). When the laydown shoe moves perpendicular over this raised edge it can be compressed to a wave or wrinkle.

6.5.2 Gaps

Because of the same alignment and head pressure problems as laps, gaps will occur between the courses that exceed the 2mm tolerance (fig. 15). When the laydown shoe moves perpendicular over this gap a transversal force could alter the axial fiber alignment of the lower ply, in plane as well as out of plane.



Figure 13: Laydown shoe imprint at the location of the standstill for cutting - 13/04/2015



Figure 14: Insufficiently corrected laps in the first ply visible in ply #2 - 06/02/2015



Figure 15: Laps and gaps between courses are clearly visible in the first ply - 06/02/2015

6.6 Hypothesis 6: Release film

6.6.1 Air bubbles

Some of the 6000 vacuum holes in the table surface become clogged with resin, burrs and other contaminations. This creates air bubbles between the release film and the table which do not shift during the layup. They are equally visible in the laminate during layup. Figure 16 shows such a bubble.

6.6.2 Deformation

Because of the axial forces on the release film during the lay-up of the first plies, the release film could exhibit plastic deformation [15]. The wrinkling tendency of the release film under loads due to perpendicular contraction could show in the laminate. Figure 17 shows release film A after undergoing a manual tensile stress and figure 18 shows release film B after undergoing approx. the same manual stress.

6.6.3 Application

The release film application is done by the ATL operator. When this is not carefully done, by not tensioning or fixating it properly or even allowing wrinkles, its out of plane deformations show in the laminate (fig. 19).



Figure 19: Wrinkle in the release film visible before start of the lay-up $- \frac{13}{04}$



Figure 16: Air bubble between the release film and the table surface - 06/02/2015



Figure 17: Release film A wrinkling after manual tensile load – 06/02/2015



Figure 18: Release film B wrinkling after manual tensile load - 06/02/2015

6.7 Hypothesis 7: Table surface

Guzman et al. [16] points to one of the possible origins of wrinkling being the mold surface on which the composite prepreg is applied, in this case the table surface.

6.7.1 Spherical shape of table

When no vacuum is applied, the table surface is convex. The release film is applied, tensioned and then fixated on this convex table surface. Insufficient tensioning will lead to excess release film when the vacuum is applied and the table surface is straightened out. This excess release film is visible as wrinkles and bubbles in the film, which are also visible in the laminate during the lay-up.

When insufficient vacuum is applied to the table, as was the case on ATL1 prior to 2015, the table is not completely straightened out leading to head alignment issues.

6.7.2 Ridges

Contrary to other companies, the ATL machines at Sabca Limburg have the ability to cut the laminates after completion into smaller laminates. The cutting grooves (fig. 20) in the table surface, created by the high force required to cut the laminate, have raised flanks and burrs and fill up with resin which hardens over time. This resin build-up over time creates protruding ridges (fig. 21). When the laydown shoe during tape laying moves under an angle of 45° over these ridges, the head pressure force will locally be higher on the ridge and lower next to the ridge, creating areas with lower adhesion. These low adhesion areas will create defects through the principle explained in hypothesis 2.

6.7.3 Imperfections

The table surface also exhibits imperfections, being not perfectly smooth across its area. Scratches, burrs, local elevations and impressions are visible on its surface.

Figure 22 shows such a local elevation and some cutting grooves in close-up.



Figure 20: cutting grooves visible in the table surface - 13/04/2015



Figure 21: A resin-clogged ridge on the ATL1 table – 02/03/2015



Figure 22: An elevation imperfection and cutting grooves in the table of ATL1 - 02/03/2015

7. EXPERIMENTS

7.1 Experiment 1: Tensile forces

Hypotheses 1, 2 and 3

The aim of this experiment, in cooperation with Mr. Camps, was to quantify the tensile force on the prepreg courses during the ATL-proces. This tensile force depends on the laydown mode (M85/M84), the feed rate and the type of laydown shoe. Since the head pressure setting isn't changed the influence of this variable was omitted from the experiment to save time and related cost.

7.1.1 Setup

- ATL machine
- UD prepreg tape
- Laydown table
- Dynamometer
- Static fixation object
- Metal cylinder

To measure the tensile force in the prepreg tape during tape laying, F_{tack} , the tape end was rolled around a metal cylinder. To this cylinder an analog dynamometer was fixed (fig. 23). The analog dynamometer shows the maximal force encountered during the test, yet to measure the variation over time of the tensile forces the dynamometer was filmed.



Figure 23: Tensile force tests showing the dynamometer fixation -08/12/2014

Since no laydown roller was available at Sabca Limburg, the compaction roller was substituted to mimic this laydown process (fig. 24). The compactor roller's bearings are not suitable for continuous laydown, yet Mr. Camps deemed it a suitable replacement for these short tests.



Figure 24: Laydown shoe (below right) and compaction roller (top left) - 08/12/2014

The experiment was repeated for different processing conditions: layup with a laydown shoe at a feed rate of 20.000mm/min and at 30.000mm/min, as well as layup with the compactor roller substituting for the laydown roller at 20.000mm/min and at 30.000mm/min. A feed rate of 30.000mm/min is used at Sabca Limburg for all flat laminates, the lower feed rate tested was to quantify the influence of the feed rate on the total tensile force (fig. 25 and fig. 26).



Figure 25: Overview of the tensile forces during layup



Figure 26: Free body diagram of the forces during layup

 F_{head} : The head pressure force

 F_{table} : The reaction force of the table to the head pressure force

 $F_{guide \ surface}$: The friction force over the guide surfaces $F_{feed \ rate}$: The feed rate depentant friction force over the laydown shoe or roller

 $F_{pretension}$: The pretension force

 F_{tack} : The tackiness force between the laid prepreg and its lower surface, either the lower ply or the release film

Equation 1: The measured force F_{tack}

 $F_{tack} = F_{x,guide \ surface} + F_{feed \ rate} + F_{x,pretension}$

Equation 2: Displacement of the prepreg

$$F_{x,guide \ surface} + F_{feed \ rate} + F_{x,pretension} > F_{tack,max}$$

As long as the prepreg/laminate can generate enough tack force to counter the forces in the course direction, either to the lower ply or the release film, the prepreg/laminate will remain static. This is described by equation 1. If the maximal tack force the prepreg can generate is exceeded the prepreg will displace, as described by equation 2.

7.1.2 Results

Table 3: Tensile forces (F_{tack}) using different laydown methods at varying feed rates

Feed rate	M85 with	M85 with	M84 with
(mm/min)	laydown	laydown	laydown
	shoe force	roller force	shoe force
	(N)	(N)	(N)
20.000	206	157	49
30.000	235	167	59

M85 pretension value setpoint: 111N

7.1.3 Measurement uncertainty

Since the analog dynamometer had a resolution of 1kg, the results have a measurement uncertainty of at least 0,5kg or 4,9N. The videos showed no visible variation in the maximal force during the test. Due to time and cost constraints every test was performed only once.

7.1.4 Conclusion

The use of a laydown roller in M85 mode reduces the tensile force on the tape by 28,9% (68N) compared to the M85 mode using the laydown shoe. Yet the best reduction in tensile force is observed with the use of M84 tape laying, which amounts to a 70,6% (166N) reduction.

The tensile force in M84 is dominated by the guide surface friction, while the force in M85 is dominated by the pretension. When comparing the M85 laydown shoe force to the M85 laydown roller force the difference of 68N is the feed rate force. This means the feed rate force is cancelled out when using a laydown roller. When comparing the M85 laydown roller force with the M84 laydown shoe force the difference of 108N is to be attributed to the pretension ($F_{x,pretension} = 96,35N$).

7.2 Experiment 2: Tackiness of prepregs on release films

Hypotheses 1, 2 and 3

Previous research by D. Hoff and F. Camps already demonstrated the existence of relative displacement between the laminate and the release film. Since friction testing on a full length course of tape is impractical, a lab experiment was set up to compare the different prepregrelease film friction coefficients on a smaller scale. Tests were performed 2 times for each of the following combinations:

- Prepreg A on release film A
- Prepreg A on release film B
- Prepreg B on release film A
- Prepreg B on release film B

7.2.1 Setup

- Uniaxial tensile testing machine: Instron 5567
- Twintex tensile plate setup (200mm x 300mm)
- 4 samples prepreg A: 450mm x 75mm
- 4 samples prepreg B: 450mm x 75 mm
- 8 samples release film A: 300mm x 200mm
- 8 samples release film B: 300mm x 200mm
- Adhesive transparant tape
- Double-sided adhesive tape
- Digital caliper: Top Craft GT-DC-02



Figure 27: Sketch of the twintex tensile test setup

The twintex tensile plate setup consists of two 300mm x 200mm plates able to clamp together with a set amount of pressure (fig. 27). On these two plates the release film was applied and fixated using a combination of regular transparent adhesive tape and double-sided adhesive tape (fig. 28). The prepreg sample was clamped in the upper clamp of the uniaxial testing machine using sandpaper roster, after which the twintex setup was closed and a pressure of ± 80 kPa was applied for ± 2 seconds.

The real head pressure during tape laying that the shoe exerts on the laminate is calculated in equation 3. A test was performed at this closing pressure revealing that the tensile force required to pull the prepreg after this laminating pressure exceeded the 1kN load cell limits. Therefore a comparative test at 80kPa closing pressure was carried out.

Equation 3: Calculation of the pressure for the twintex tensile test

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$$P = \frac{F}{A} = \frac{m.g}{A} = \frac{50kg.9,81\frac{N}{kg}}{0,16m.0,0075m} = 408,75 \ kPa$$

The pressure was relieved without moving the plates, after which the tensile test was initiated. This pulled the tape out from between the two release films at a rate of 2mm/min. The temperature in the lab was 22°C for all tests. After every test the release film and prepreg sample were removed and new ones put in place.

The measured parameters were:

- Static friction: the maximal friction force encountered during the test
- Dynamic friction: the average friction force over time in regime conditions after the static friction was exceeded
- Quasi static slip: the extension (slip) value at the point of maximal friction force



Figure 28: Twintex tensile test setup with release film applied and double-sided adhesives pointed out

7.2.2 Results

For every test the average of the two results is displayed with the individual test values indicated with variability bars (fig. 29-31) For the graphs of the individual tests, see annex 2.



Figure 29: Static friction results



Figure 30: Dynamic friction results



Figure 31: Quasi static slip results

7.2.3 Measurement uncertainty

The ball joint between the load cell and the upper clamp of the machine caused an alignent error since it had to be manually aligned to compensate for the off-center compressed air connection. These alignment errors cause unwanted shear forces in the tape. Though the utmost care was provided in the fixation of the samples, a small alignment error could not be avoided. No digital image corrolation test to measure slip was performed here, though manual markings showed no visible slip between the prepreg and the sandpaper roster. Measurements with a digital caliper before and after the test revealed no slip between the sandpaper roster and the clamps.

The application of double-sided adhesive results in a locally higher pressure at the adhesive and a lower pressure in between them. The deviation was kept the same by applying the adhesives at the exact same spot every time through the use of markings.

The manipulation of the twintex plates pressure had to be done manually via a rotary valve, resulting in small differences in pressure and time differences as to how long it took before pressure was completely removed. This pressure removal took between 1,5 and 3 seconds, with an average of 2 seconds.

A pressure of ± 80 kPa was necessary to overcome the static friction in the twintex plate setup when closing the plates. Sometimes it started closing at 70kPa, sometimes a pressure as high as 140kPa was necessary. When a high pressure was needed it was subsequently reduced to 80kPa during the closing.

Due to time constraints each combination of prepreg and release film was only tested twice.

7.2.4 Conclusion

A high static friction and low quasi static slip is considered desirable because it reduces the tendancy of the prepreg to slide over the release film.

According to K. Potter a low friction coëfficient between the mold surface (the release film in this case) and the laminate results in defects and misalignment of the fibers [3]. Even though his research was done during consolidation regarding thermal stress relaxation, the same principle applies here with hydrodynamic friction displacements.

Prepreg A exhibits a varying static friction coefficient on release film A, though its average value is lower than that on release film B. The dynamic friction coefficient is however lower on release film A for both tests. As a result release film B is considered to be a more suitable release film for lay-up with prepreg A because of its better friction coefficients and very low variability, though further testing to eliminate or define the reasons of the variability should be carried out.

Prepreg B exhibits overall higher static and dynamic friction coefficients than prepeg A. Its dynamic friction is much higher on release film A than on release film B. The comparison of static friction results of prepreg B on both release films are inconclusive as their variability ranges overlap. Further research is required.

Release film A shows a large variability in all the results, indicating it exhibits greater sensitivity to the head pressure setting and duration.

Release film B shows little variation in the results. These characteristics show that the more expensive release film B is a suitable film for both prepregs.

7.3 Experiment 3: Contourtest

Hypotheses 1 and 2

In April 2015 a contourtest was performed to see whether the laminate still displaced over the release film during the lay-up. It was done during the lay-up of a laminate comprised of prepreg A on release film A. This is done by marking the contours of the first 5 plies on the release film and then checking these contours after completion of the laminate for displacement of the ply relative to the marking. This contourtest was then compared to earlier contourtests perfomed at Sabca Limburg to see whether the new M84 tape laying method and ply orientation change amounted to different results than the old M85 tape laying method with the old ply orientations where a displacement was visible [annex 1].

7.3.1 Results

No displacement was visible between the laminate and the release film (fig. 32).



Figure 32: One of the markings applied at ply 1 after completion of the lay-up - 14/04/2015

7.3.2 Conclusion

The lack of a displacement is most probably due to the addition of a double-sided adhesive tape around the contour of the laminate before the lay-up of the first ply (fig. 33). While this was used during the contourtest laminate lay-up, it is not a standard operator practice.



Figure 33: Double-sided adhesive tape is applied for the first ply -13/04/2015

7.4 Experiment 4: Interply friction

Hypotheses 2 and 3

An experiment was performed to assess the differences in interply friction between the two prepregs. This provided a framework for the comparison of tackiness levels of the prepregs, as well as their static and hydrodynamic friction behaviour. The temperature at which the tests were carried out was 22°C.

7.4.1 Setup

- Uniaxial tensile testing machine: Instron 5567
- 3 samples prepreg A: 400mm x 75mm
- 3 samples prepreg B: 400mm x 75mm
- Steel roll
- Digital caliper: Top Craft GT-DC-02
- Digital image corrolation setup: Limess Q400-2D

The prepreg samples were laminated onto eachother with an axial shift of 75mm. This was done using a steel roller on which a manual pressure was exerted. The backing papers were peeled off carefully and then the sample was clamped in the uniaxial testing machine (fig. 34). A standard axial tension test was performed at a rate of 2mm/min.



Figure 34: Sketch of the samples for the interply friction tests

The measured parameters were:

- Static friction: the maximal friction force encountered during the test
- Quasi static slip: the extension (slip) value at the point of maximal friction force
- Full separation displacement: the extension (displacement) value where the load dips below the 13N threshold. This is the point at which the sample was almost completely delaminated.

7.4.2 Results

The averages of the static interply friction force, the quasi static interply slip and the full separation displacement are displayed for each prepreg sample in table 4. The graphs of each test are shown on figure 35 and in annex 3.

Table 4: Averages and variability of the static interply friction, the quasi static interply slip and the full separation displacement for both prepreg types.

			Full
	Static		separation
	friction	Quasi static slip	displacement
Prepreg	(N)	(mm)	(mm)
	123 67	0.43	2 33
А	[+21;-38]	[+0,053;-0,067]	[+0,21;-0,36]
	243	0,53	8,8
В	[+28;-45]	[+0,053;-0,037]	[+1,12;-1,04]



Figure 35: Interply friction test results

7.4.3 Measurement uncertainty

The alignment of the samples in the machine had to be done manually, so a small alignment error is presumed probable. The ball joint between the load cell and the upper clamp of the machine caused a further alignment error. These alignment errors cause unwanted shear forces in the sample. Though the utmost care was taken in the fixation of the samples, a very small alignment error could probably not be avoided. Since the lamination of the prepregs was done manually, a slight difference in asserted pressure on the steel roller might be possible. All care was taken to reduce this difference to a minimum, yet this caused small deviations in the results.

When peeling the backing papers, a small out of plane force is exerted on the prepreg sample. The peeling was done as carefully as possible, yet this might have caused small deviations in the results.

Since the samples were clamped in the machine using a sandpaper roster, a limited slip was thought possible. A digital image corrolation test was performed with two of the tensile tests, which showed no measurable slip between the prepreg and sandpaper roster. Measurements with a digital caliper before and after the test revealed no slip between the sandpaper roster and the clamps.

Due to time constrains each prepreg was only tested three times.

7.4.4 Conclusion

Prepreg A exhibits a lower interply friction than prepreg B. The interply adhesion quickly deteriorates at small displacements of the prepregs relative to eachother. This was visible as large areas of the prepreg sample started to separate at low extensions. This amounts to prepreg A having a friction coefficient dominated by dry (Coulomb) friction [6]. It points to prepreg A having a thinner layer of resin on the surfaces of the tape, as well as a dryer contact area [7]. This is consistant with the existance of the dry zones in prepreg A.

Prepreg B exhibits an almost 2 times (196,49%) higher average static interply friction than prepreg A, and its average dynamic friction coefficient remains higher at larger displacements. This amounts to prepreg B having a larger hydrodynamic friction component. It points to prepreg B having a thicker layer of resin on the surfaces of the tape. The full separation point of the tapes is at approx. 3,7 times the separation displacement of prepeg A. According to Akermo et al. this, together with the more hydrodynamic friction tendancy, leads to a better stress relaxation capability of prepreg B [8].

7.5 Experiment 5: Elongation & shrinkage behaviour of unidirectional prepregs

Hypothesis 3

An experiment was conducted to compare the elongation and shrinkage behaviour of the prepregs over time when exposed to tape laying conditions. The tensile forces exerted on the tape were those from experiment 1. The tensile stress in a course of prepreg during the tape laying process varies with the position of the studied point relative to the laydown shoe and the start of the course. A simplification to a uniform stress state of the course was made to allow lab testing. For the M85 tape laying process test a further simplification was made by removing the first dwell time for pretension application. These adaptations were deemed representative enough to allow for comparisons between the prepregs and processing conditions.

7.5.1 Setup

- Uniaxial tensile testing machine: Instron 5567
- 6 samples prepreg A
- 6 samples prepreg B
- Digital image corrolation setup: Limess Q400-2D

Before each test, the load cell was calibrated to 0,0000N. A sample was prepared with sandpaper rosters at the top and bottom, and was then clamped in the upper clamp of the uniaxial testing machine. Its weight in newtons was measured and the test program was then altered to keep the load of the 10 minutes shrinkage time at the measured weight. The upper clamp was then brought down and the sample was clamped in the lower clamp of the machine, and the alignment of the sample was carefully adjusted untill it was axially aligned with the load direction. The load on the sample was set to the sample weight again, the gauge length set to zero and then the test program was run.

There were three different test programs mimicing the tape laying loads on a prepreg course during M85 tape laying with the laydown shoe, M85 tape laying with the laydown roller and M84 tape laying with the laydown shoe. A graphical representation of the applied tensile load of these test programs can be found in annex 4 and fig. 36 below.



Figure 36: Applied forces during the tensile test programs

A general description of the load-driven program for the tensile testing machine is as follows:

- 1. A ramp up to the tensile load in 1,8 seconds, representing the start of a course
- 2. Holding of the tensile load during 10,7 seconds, representing the movement at a feed rate of 30.000mm/min
- 3. A ramp up/down to 111,25N in 1,5 seconds, representing the application of pretension for cutting the prepreg
- 4. Holding 111,25N during 1,5 seconds, representing the cutting process dwell time
- 5. Ramp up/down to the tensile load in 1,5 seconds, representing the start of the last part of a course
- 6. Holding the tensile load during 1,5 seconds, representing the last part of a course
- 7. A ramp down to 7N in 2 seconds, this is a machine constraint to counter overshoots
- 8. A ramp down to the set sample weight load in 2 seconds, this time is also a machine constraint to counter overshoots
- 9. Holding the sample weight load during 10 minutes representing the relaxation time

During this process the extensions and loads were measured as a function of time, from which the following parameters were calculated:

- Maximal extension under load:
 - For the M85 tests this is the maximal extension at the end of the second M85 load hold after pretension
 - For the M84 tests this is the maximal extension at the end of the first M84 load hold before pretension
- Immediate shrinkage: the difference between the maximal extension under load and the extension at load removal
- Shrinkage over time: the difference between the extension at load removal and the extension at the end of the test
- 7.5.2 Results

Figures 37, 38 and 40 show the calculated parameters in absolute values. Figures 39 and 41 show the shrinkage values in percentage of the maximal extension. Figure 41 shows the extension left at the end of the 10 minutes shrinkage time as a percentage of the maximal extension. For the graphs of the individual tests, see annex 4.



Figure 37: Mean maximal extension under load



Figure 38: Mean immediate shrinkage after load removal



Figure 39: Mean immediate shrinkage after load removal in percentages



Figure 40: Mean shrinkage over time







Figure 42: Mean leftover extension in percentages

7.5.3 Measurement uncertainty

Like in experiment 3 the samples were clamped in the machine using a sandpaper roster and a limited slip was thought possible. A digital image corrolation test was performed with two of the tensile tests, which showed no measurable slip between the prepreg and sandpaper roster. While no slip was observed here, slip between the sandpaper roster and the clamps might have occurred. This would influence the extension causing the final relaxation extension to be different from 0.

Since the alignment of the samples in the machine had to be done manually, a small alignment error is presumed probable. The ball joint between the load cell and the upper clamp of the machine caused a further alignment error. These alignment errors cause unwanted shear forces in the tape. Though the utmost care was provided in the fixation of the samples, a small alignment error could not be avoided.

The resolution of the load measurement was 1 mN, yet the load control programming of the machine did not have this precision. Extended times had to be used to ramp up and ramp down loads to avoid excessive overshoots, yet still some tests had significant overshoots. These overshoot timeframes were omitted from the relaxation results.

The setting of the load to the measured sample weight before the test had to be done manually. With fine position increments of the machine being in the order of μ m, they caused load increments of approximately 0,1N for prepreg A and up to 1N for prepreg B. These different starting points resulted in a significant error in the final relaxation extensions after the test (fig. 41) and slightly different results in maximal extension values. This can be seen in the variation of the shrinkage over time results in fig. 38.

The load control of the final relaxation time was slightly influenced by the precision of the machine. A precise load equal to the weight was not obtained, the load exhibited an average ripple of 0,031N [annex 4].

Last, the wrinkling tendancy of the prepreg after load removal caused loads on the machine similar to the weight of the sample. This is similar to a shrinkage process and the machine subsequently compensated the extension for this load, resulting in negative final relaxation extensions.

Due to time constraints each combination of prepreg and load cycle was only tested twice.

7.5.4 Conclusion

As expected the prepregs extension values increase with increasing tensional force and their immediate shrinkage follows the same behaviour. This is corroborated by Potter [17]. The percentage of immediate shrink to the maximal extension is roughly independent of prepreg and load profile choice. This is to be expected since the prepregs both consist of the same carbon fibers and resin composition.

As earlier mentioned, the shrinkage over time results are influenced by i.a. the starting point of the pretension applied before the test. The large percentile leftover extension indicates this. Though they exhibit large variations in their results, a trend can be observed that the larger the applied load the larger the shrinkage will be over time. Further research is required to investigate this trend.

7.6 Experiment 6: Resistance to plastic deformation of the release films

Hypothesis 6

To characterize the elastic and plastic deformation behaviour of the release films they were subjected to standard tensile tests until break. Each type of release film was tested three times at 6mm/min (fig. 43) [annex 5].

7.6.1 Setup

- Tensile testing machine: Instron 5567
- 3 Samples release film A: 300mm x 75mm
- 3 Samples release film B: 300mm x 75mm
- Digital image corrolation setup: Limess Q400-2D

7.6.2 Results



Figure 43: Tensile test results for the release films

Table 5: Yield strength and break elongation of the release films

Release film	Yield strength (N)	Break elongation	Break elongation		
		(mm)	(%)		
А	191,6 [+9,3;-10,7]	26,9 [+3,4;-4,2]	8,97 [+1,13;-1,41]		
В	96,7 [+6,3;-8,7]	47,2 [+2,3;-1,7]	15,73 [+0,76;-0,57]		

Equation 3: Young's modulus calculation for release film A

$$E_{A} = \frac{\sigma}{\varepsilon} = \frac{\frac{F}{A_{0}}}{\frac{\Delta L}{L_{0}}} = \frac{F \cdot L_{0}}{A_{0} \cdot \Delta L} = \frac{70,67N \cdot 300mm}{75mm \cdot 0,04mm \cdot 2mm}$$
$$= \frac{3533,5N}{mm^{2}} = 3,5 \ GPa$$

Equation 4: Young's modulus calculation for release film B

$$E_B = \frac{\sigma}{\varepsilon} = \frac{\frac{F}{A_0}}{\frac{\Delta L}{L_0}} = \frac{F.L_0}{A_0.\Delta L} = \frac{36,25N.300mm}{75mm.0,025mm.2mm}$$
$$= \frac{2900N}{mm^2} = 2,9 \ GPa$$

7.6.3 Measurement uncertainty

The same alignment problems as in experiments 2, 3 and 4 are present in this experiment.

Manual markings and a digital image corrolation measurement showed a slip between the sandpaper roster and the release film developing during the test. Final slip results after the test varied between 0,5mm and 1,5mm and were independent of the release film choice.

Due to time constraits each release film was only tested three times.

7.6.4 Conclusion

Release film A is stiffer than release film B and has a larger yield strength, though it has a 43% lower ductility than release film B (table 5). The more elastic properties of release film B could allow extension and shrinkage together with the first ply.

7.7 Experiment 7: Measuring the spherical shape of the table

Hypothesis 7

The spherical shape of the table with and without vacuum applied was measured with a digital probe indicator attached to the ATL (fig. 44). The machine was programmed to follow a straight path in the x-direction.

Since this test had to happen between production slots, measuring the full extent of the x-axis was not possible. The measurement starts and ends at the contour of the next programmed laminate of project A. Fortunately this was one of the largest, though the final x-position was still 3 to 4m from the end of the table x-axis.



Figure 44: The digital probe indicator fixated to the ATL head

7.7.1 Setup

- Digital probe indicator: Mitutoyo Absolute 543-690
- ATL machine
- Laydown table
- Release film A

7.7.2 Results







Figure 46: Table height along the x-axis with vacuum applied

7.7.3 Measurement uncertainty

Stick-slip between the probe needle and the release film has probably occurred, leading to slight measurement errors.

Due to time constraints the test was only performed once.

7.7.4 Conclusion

Keeping in mind the end of the measurements was at just over half the length of the table, the spherical shape is clearly visible when the vacuum is switched off. When the vacuum is switched on the table is less spherical, though not completely flat (fig. 45 and fig. 46).

7.8 Experiment 8: Table ridges and imperfections

Hypothesis 7

Using the same setup as experiment 7, the height of the laydown table ridges and imperfections was measured. The dimensions were measured with a caliper and their influence on the laminate was tracked throughout and after the lay-up.

7.8.1 Setup

- Digital probe indicator: Mitutoyo Absolute 543-690
- Digital caliper: Top Craft GT-DC-02
- ATL machine
- Laydown table
- Prepreg A
- Release film A

7.8.2 Results

Table 6: Dimensions of the table defects

Table defect	Height	Length	Width
	(mm)	(mm)	(mm)
Ridge 1 x-	0,08	Not	2,8
direction		measured	
Ridge 2 y-	0,08	Not	2,3
direction		measured	
Imperfection 1	0,11	22,0	18,7
Imperfection 2	0,20	26,3	12,1

A close inspection of the ridges showed burrs (fig. 47) and resin build-up in the grooves (fig. 48). Fig. 48 shows the measured imperfection 2.



Figure 47: Close-up of ridge 1 showing burrs - 14/04/2015



Figure 48: Close-up of imperfection 2 in the table surface (left) and resin build-up in a cutting groove (right) - 14/04/2015

These ridges were visible in the laminate during lay-up [annex 6] and caused bubbles in their vicinity, though were not visible anymore on top after completion. In the bottom however they caused deep impressions in the final laminate and the bubbles they caused were visible (fig. 49).

The imperfections tracked [annex 6] were also visible during the lay-up though not anymore after completion, and they also left impressions on the bottom of the final laminate (fig. 50).



Figure 49: Bottom of the completed laminate showing the ridge 1 impressions and bubbles – 14/04/2015



Figure 50: The impressions of imperfection 2 (left), other imperfections and ridges in the laminate bottom after completion -14/04/2015

7.8.3 Measurement uncertainty

Stick-slip between the probe needle and the release film might have occurred, leading to slight measurement errors.

Due to time constraints only two ridges and two imperfections were measured.

7.8.4 Conclusion

The table ridges and imperfections cause impressions in the final laminate and lead to formation of bubbles and other defects in their vicinity.

7.9 Experiment 9: Ultrasound images

Since during the production supervisions in February, March and April lap and gap problems were visible they were tracked throughout the lay-up [annex 7] and the ultrasound inspection images of the cured laminates were studied.

The laps and gaps remained visible throughout the lay-up and were visible in the final laminate (fig. 51)



Figure 51: A gap/lap in a lower ply visible after completion of the laminate -14/04/2015

The ultrasound images showed no signs of internal air pockets or delaminations, so all laminate parts cleared inspection standards. While they cleared inspection standards, the influence of the laps and gaps on the achieved duty cycles during the lifespan of the laminate should be tracked, as Croft et al. indicates laps and gaps decrease laminate performance [18].

7.10 Experiment 10: Production supervisions

Hypothesis 2

As shown in figure 9, the head alignment issues prior to March 2015 caused adhesion problems of the prepreg to the release film.

In April 2015 adhesion problems while laying the first ply were still occuring at the start of the courses. They were due to the head alignment and a lack of table heating. The table heating was out of service since the beginning of 2015. Figure 52 shows such a course start. Figures 53 and 54 show bubbles in a course of the first ply due to improper and late head alignment and the intrinsic residual tensions in prepreg A. The late head alignment is visible in fig. 55 when comparing the gap between the course start and further down the course.



Figure 52: Improper adhesion between prepreg A and release film A at the start of a course due to a lack of table heating -13/04/2015



Figure 53: Bubbles in the first part of a course of the first ply - 13/04/2015



Figure 54: The head alignment caused bubbles in a course of the first ply - 13/04/2015

At the locations of the course starts and at the course edges wrinkles formed during the layup (fig. 56). These were compressed to more severe wrinkles during the lay-up, as can be seen after ply 6 in figure 56. They were particularly visible in the short courses at the start of the x-axis in the corners of the laminate [annex 7]. The wrinkles were no longer apparent in the final laminate.



Figure 55: Wrinkling in ply 2 at the start of a course - 13/04/2015



Figure 56: Compressed wrinkles at the start of the course at ply 6 - 13/04/2015

Hypothesis 4

The impressions of the laydown shoe in the laminate due to the dwell times were tracked throughout the layup of the laminate. The impressions became deeper as the plies stacked, though the impression depth was not measured. Figures 13 and 57 show some of these impressions left after completion of the laminate.



Figure 57: Laydown shoe imprints at the locations of the standstill for cutting - 13/04/2015

Hypotheses 6

Wrinkles and bubbles in the release film were tracked throughout the lay-up [annex 8]. They could still be observed in the release film after cutting the final laminate though they showed no deformation to the laminate itself (fig. 58).



Figure 58: Wrinkles and bubble in the lower release film after cutting of the final laminate -02/03/2015

On April 13 some wrinkles in the release film were observed, see figure 16. One of these wrinkles extended into the laminate area, clearly showing in the laminate itself as can be seen in figure 59. It was not visible in the final laminate though it left an impression on the bottom side.



Figure 59: A wrinkle in the release film visible in the laminate -13/04/2015

7.11 Experiment 11: Tape laying method change

In December 2014, in conjunction with F. Camps, a change to the ATL programs was implemented. This changed the ATL laydown method from M85 course tape laying to the M84 course tape laying as explained in Section 2. Removing the supplemental pretension strain on the tape and adjusting the unrolling speed of the tape to the feed rate drastically lowers the total strain on a tape course by almost 75% (experiment 7.1). Removing the supplemental pretension also improves the rate of wear of the Teflon strips on the laydown shoe [5].

Since the change in tape laying method and ply orientation the scrap rate of laminates A have been reduced to zero at the time of writing, according to verbal accounts by Sabca Limburg engineers and operators. These changes were made in close succession so their effects cannot be separated.

7.12 Experiment 12: Ply orientation change

During the meetings with F. Camps in December 2014, the possibility of changing the ply orientations from $\pm 45^{\circ}$ to $\pm 45^{\circ}$, $\pm 135^{\circ}$ was discussed. Early 2015 this ply orientation change was successfully implemented (fig. 60).

Since the change in ply orientation and tape laying method the scrap rate of laminates A have been reduced to zero at the time of writing, according to verbal accounts by Sabca Limburg engineers and operators. These changes were made in close succession so their effects cannot be separated.



Figure 60: Sketch of the $\pm 45^{\circ}$, $\pm 135^{\circ}$ layup method at Sabca Limburg since January 2015

8. CONCLUSION

The defects in the flat laminates using prepreg A are due to numerous reasons as they originate through a combination of the hypotheses of Section 6.

Hypothesis 1: Displacement

While displacement of the laminate over the release film occurred in the past, it no longer does with the use of double-sided adhesive contours. The introduction of the M84 tape laying method further improves the adhesion of the prepreg to the release film because of the lower tensional forces.

The table heating and guide surface heating improve the tackiness of the prepreg thus improving laminate-release film adhesion. When the table heating was inoperative issues with this adhesion of the first ply was most striking with the use of prepreg A.

The head alignment is critical to the sufficient adhesion of the courses to the release film, which was observed on many occasions.

Hypothesis 2: Compression

The compression of wrinkles and bubbles to more severe wrinkling was observed during production supervisions.

As earlier mentioned, the head alignment and heating elements are critical to the good adhesion of the prepreg courses of the first ply to the release film.

Motives for using release film B with prepreg A were found in the results of the lab tests. It had a lower variability in its results meaning it probably has a lower sensitivity to head pressure changes. It also exhibited a more elastic behaviour and it doesn't exhibit wrinkling after completion of the lay-up.

The change in ply orientations from $\pm 45^{\circ}$ to $\pm 45^{\circ}$, $\pm 135^{\circ}$ seems to have a positive effect on the formation of wrinkling defects, providing a presumption that the global shear forces indeed cancel eachother out.

The application of double-sided adhesive between the release film and the contour of the first ply ensures better adhesion of the prepreg to the release film thus limiting the allowance for wrinkling at the start of the course.

Prepreg B also exhibits a larger allowance for displacements since it delaminates at 3,7 times the displacement of prepreg A. Its interply friction is much higher than prepreg A and is dominated by hydrodynamic friction which means it has better adhesive properties and has a larger ability to compensate the compressive stresses rather than buckling.

Hypothesis 3: Elongation & shrinkage

Results show that reducing the tensile forces on the prepreg by using a laydown roller or M84 tape laying have a positive effect on the induced elongation during tape laying. The relaxation tests of the prepreg were influenced by numerous factors, though a trend was observed that the larger the applied load the larger the shrinkage over time will be. Further research is required to substantiate this.

The interply friction tests show that prepreg B has a better ability to compensate the process-induced tensile stresses through its larger hydrodynamic component of its friction coefficient. This means the plies can displace relative to eachother to compensate the applied stress rather than buckling. Prepreg A has a predominantly dry friction component because of the dry zones and thinner outer resin layer, leading it to a reduced ability to compensate interply stress.

While the effects of elongation and shrinkage were demonstrated in the experiments, definitive proof that this concept causes wrinkling was not observed. The disappearance of the wrinkles since the introduction of the lower tensional force M84 mode provides an indication the shrinkage might be the cause of some of the wrinkling defects of the past. Further research is thus required.

Hypothesis 4: Head pressure

The head pressure ensures the good adhesion of the prepreg though too high settings lead to compressive stresses in the tape as described by hypothesis 2.

The dwell time for the cutting of the prepreg results in an imprint in the laminate that deepens as the plies build up. Ultrasound imaging however showed no delaminations due to these head pressure imprints.

Furthermore, the head pressure force setting has a large uncertainty on ATL1 due to the hysteresis of the pistons and the low resolution analog manipulation.

Hypothesis 5: Laps & gaps

Laps and gaps formed due to late head alignments, head alignment issues and improper settings of the guide surfaces. On some occasions they were subsequently compressed to wrinkles.

By tracking the laps and gaps throughout the lay-up of the laminate their visible influence was demonstrated. An analysis of the ultrasound images after completion however indicated that the observed laps and gaps did not result in any delaminations and the laminate passed quality control standards.

Hypothesis 6: Release film

The existance of air bubbles between the release film and the laydown table has been demonstrated. While they were visible during the first plies, they had no effect on the final laminate.

The existance of wrinkles in the release film due to operator negligence has been demonstrated on one account, they translated into a one-to-one impression in the laminate.

Through tensile testing it was proven that release film A is stiffer than release film B. This could mean that release film B has the ability to stretch and shrink together with the first ply, resulting in a lower allowance for prepregrelease film stress build-up.

Hypothesis 7: Table surface

The influence of the table ridges and imperfections on the laminate bottom after completion of the lay-up has been demonstrated on numerous accounts by means of a visual check. They left a one-to-one impression in the laminate, and one occasion even resulted in bubbling of the laminate next to the ridge impressions. This provides a strong motive to the hypothesis that the ridges and imperfections of the table result in a local head pressure force increase on the defect and a decrease right next to it, leading to improper adhesion spots and subsequent laminate defect formation.

The spherical shape of the table was mapped. It showed that even with the vacuum applied the table isn't completely flat. Correct head alignment is thus critical to ensure good course adhesion. Further research is required into the effect of the straightening of the table on the release film tension.

9. **RECOMMENDATIONS**

9.1 Recommendation 1: M84 tapelaying

The lower tensional forces in the M84 tape laying method seem to have a positive effect on the elongation, shrinkage and residual stresses in the tape courses. The current scrap rate of 0 leads us to believe this successfully counters the formation of wrinkles and defects in the laminate.

9.2 Recommendation 2: Ply orientation

The change to $\pm 45^{\circ}$, $\pm 135^{\circ}$ laminating seem to successfully counter the intra- and interply tensile and compressive stresses that build up in $\pm 45^{\circ}$ laminates.

9.3 Recommendation 3: Table surface

Since the table ridges, resin depositions, burrs and imperfections cause imprints, wrinkles and bubbles in the laminates they should be removed by scraping the table surface on a (more) regular basis.

Though the ridges and cutting grooves act as grippers for the release film, accurately tensioning the film as well as applying a sufficient vacuum should remove their need.

9.4 Recommendation 4: Sacrificial cutting surfaces

According to the operating manual of ATL2 a sacrificial cutting surface should be used when the laminates have to be cut after the lay-up [14]. This sacrificial mat is placed between the table surface and the release film before the start of the lay-up. To ensure the vacuum reaches the release film and keep it in place it would need to be air permeable and have anti-slip characteristics. For an example of such a sacrificial cutting mat, see annex 14.

9.5 Recommendation 5: Laydown roller

A further reduction in tensile stresses can be obtained by using a laydown roller. This roller is more sympathetic to the fibers [9] and reduces friction between the shoe/roller and the backing paper (the feed rate force) resulting in a 28,9% lower tensile force on the tape compared to regular M85 tape laying with the fixed shoe. Due to the larger contact area with the laminate a lower head pressure setting can be used according to annex 16, reducing head pressure related defects. A laydown roller is currently under development at Sabca Limburg.

9.6 Recommendation 6: Feed rate of the first 2 plies

Since the first 2 plies are critical to the adhesion of the first layer to the release film, a lower feed rate for these plies is suggested. This lower feed rate results in lower tensional forces in the tape courses, improved adhesion and limited the sliding tendancy of the tape over the release film [17]. A reduction from 30.000mm/min to 20.000mm/min reduces the tensional force by 12,34% in M85 mode and by 17% in M84 mode. As a result of the improved adhesion the machine should spend less time in idle while the operators fix the incorrect courses.

9.7 Recommendation 7: Adhesive contours

The application of double-sided adhesive tape around the contour of the laminate succesfully counters the displacement of the laminate over the release film, thus limiting allowance for wrinkling. It also provides an adhesive start for the course, improving the adhesion over the rest of the course length.

9.8 Recommendation 8: Heating

To further improve adhesion of the first ply to the release film the table heating should be switched on for tape laying the first 2 plies. From ply 3 on, if adhesive contours are used, the table heating can be switched off to reduce hydrodynamic displacement in the lower plies. The guide surface heating should stay on during the lay-up to improve the tackiness of the course being laid to the laminate and allow hydrodynamic displacement of the higher plies to compensate the induced compressive stresses.

An important thing to pay attention to is that the guide surface heating should be switched off every time the machine stops for a lengthy period to avoid overheating the prepreg. Examples of these periods are when the operator stops the machine to correct certain imperfections in a course or when a fault like backing paper tear occurs.

The resulting tackiness increase of the tape allows for the head pressure force to be reduced [2], resulting in less head pressure related defects (e.g. the impressions of the laydown shoe and course head steering) [14].

9.9 Recommendation 9: Release film choice

Though it is more expensive release film B is more suitable for the lay-up of flat laminates because of its better elasticity and adhesive properties. It is therefore recommended to use release film B for both projects.

When cost constraints are taken into account it is deemed best to use the cheaper release film A with prepreg B since prepreg B has better tackiness. Prepreg A should be used with the more expensive release film B, meaning the release film usage should be switched.

9.10 Recommendation 10: Compacting film choice

At the moment compacting of all flat laminates is done with release film B. Since release film B is more expensive than release film A, the possibility of compacting with release film A should be researched. The change in compacting film can create the necessary budget to use release film B as the lower release film for project A.

9.11 Recommendation 11: Cleaning resin buildup

Resin builds up on the guide surfaces resulting in elevated friction. It also builds up on the counter wheel of the tape supply, resulting in stick-slip and subsequent incorrect readings. Especially with the new M84 tape laying method this reading is of vital importance to keep the prepreg feed rate equal to the head feed rate. The counter wheel and guide surfaces should be inspected and if necessary cleaned after every laminate [14].

9.12 Recommendation 12: Vacuum holes

Since the holes in the table become obstructed with resin and other contaminations they should be checked and cleaned on a regular basis. A table blow-off feature could be installed to speed up this process by applying a positive pressure to the table after the cutting process of the laminate [14]. Since no release film is present at this moment the holes get blown clean of contaminations and clogged holes can easily be recognized by the operators by simply moving their hand over the table.

9.13 Recommendation 13: Head pressure on ATL1

9.13.1 Calibration

The last calibration of the head pressure on ATL1 was on 08/12/2009 [annex 15]. A recalibration is deemed necessary to exert an accurate ideal head pressure force on the laminate. The calibration interval should be 1 year [14].

9.13.2 Digital control system

The manipulation of the head pressure on ATL1 is done manually by the operator via the manipulation of a rotary valve. The pressure is read on a scale in bar with 0,1bar resolution. A digital control system to set the head pressure force would greatly improve the accuracy of the head pressure force exerted on the laminate. Such a system is present on ATL2. A further improvement can be implemented by automatically reducing the head pressure force when the tape layer is at a standstill (e.g. during cutting of a tape course).

9.14 Recommendation 14: Dry zones

Prepreg A exhibits dry zones with residual tensions due to the manufacturing process of the prepreg (see Section 3). These are probably caused by the rollers that pull the fibers through the manufacturing process. The surface quality, material choice, alignment and vertical separation of the rollers should be investigated by the manufacturer to pinpoint the cause of the residual tensions and dry zones.

9.15 Recommendation 15: Standardisation of operator practices

9.15.1 Peeling of an incorrect course

The peeling of incorrect courses is sometimes done by simply pulling it upwards towards the operator. This damages the adhesive properties and potentially even the fibers of the ply below. The correct peeling method should be researched and applied by all operators.

9.15.2 Removing bubbles in the laminate

Removing air bubbles in the laminate has to be done with care for the fibers. Sometimes a putty knife is used to smooth the bubble, other times holes are pierced in the bubble with an awl and then smoothed over with the putty knife and once the smoothing was even done perpendicular to the fiber direction.

Carefully piercing a hole in the bubble without damaging the fibers, smoothing it over and then compacting the whole laminate with the table heat on is suspected to be the best method to remove the bubbles. Though the correct method and tools should be researched and applied by all operators. According to Guzman et al. [16], a better way to remove bubbles is done by the application of pressure and high frequency low amplitude vibrations to the surface of the laminate in the area of the wrinkle.

9.15.3 Removing laps

Removing laps should be done by using a putty knife parallel to the fiber direction. During one observation the operator tried to remove the lap by using the putty knife perpendicular to the fiber direction, resulting in in-plane deformation of the fibers. The correct method and tools for removing laps should be researched and applied by all operators.

10. FRAMEWORK FOR FURTHER RESEARCH

Due to the limited timespan of the research, not all parameters and their influence on defects could be quantified and studied in depth. Therefore a framework for further research was made to provide further researchers an understanding of the ATL process parameters and their influence on eachother, as well as unexplored defect formation possibilites.

10.1 Flowchart

To get a comprehensive understanding of the ATL process and its parameters, a flowchart [annex 9] was made containing all parameters and their influences on each other as well as their role in the formation of defects. From this flowchart the hypotheses were derived, and it provides a solid foundation for further research into the defects during lay-up.

10.2 Risk analysis

To understand the magnitude of influence of each parameter on the possible formation of defects, a standard risk analysis [annex 10] was performed. A cost effectiveness study was taken into account in this risk analysis due to the fact that the machine runs 24 hours per day, 7 days a week.

10.3 Digital Image Correlation (DIC)

2D digital image corrolation (DIC) tests to characterize the elongation and shrinkage behaviour of prepregs were performed in the lab. However, they didn't result in usable data, see annex 11.

10.4 Fiber Bragg grating

An accurate strain measurement method for reinforced composites is the fiber Bragg grating technology [annex 12]. An experiment was designed in association with Com&Sense [19] for Sabca Limburg in February 2015 using this technology, yet it was deemed too time-consuming and expensive since the worst problems already disappeared. For a description of the proposed experiment, see annex 13.

10.5 Temperature

As earlier mentioned, the tackiness of prepregs is highly dependent on their temperature. An increase of 0,5°C already has a significant influence [2] (fig. 61). Sun et al. showed that an increase in temperature resulted in an increased hydrodynamic friction component of the total frictional force [7]. A more hydrodynamic friction component allows the plies to move relative to eachother without delaminating, thus reducing the compressive stress build-up and subsequent wrinkling.



Figure 61: Temperature effects on ATL carbon prepreg tack [2]

At Sabca Limburg both ATL machines have a table heating and guide surface heating capability. The influence of the prepreg temperature on the interply and prepreg-release film friction was not investigated due to its cost. It would result in the ideal settings for the table and guide surface heating.

11. FINAL CONCLUSION

In this paper the cause of defect formation during automatic tape laying was investigated. Several types of defects have been identified and their cause determined. Hypotheses were made and confirmed through experiments and production supervision. Some of the hypotheses require further research as our lab experiments are only an approximation of the tape laying process, for which we proposed a fiber bragg grating experiment. The displacement hypothesis was invalidated by means of a contourtest and the release film deformation showed no visible effect on the laminate, though further research into the latter is required.

The defects originate mainly because of a damaged and contaminated mold surface in combination with high tensile forces on the prepreg and compressive stress on the laminate during the lay-up. The alignment of the head also proved critical.

The limited slip allowance, low tackiness and low bending stiffness of prepreg A causes it to buckle under these conditions rather than compensating the induced stresses by displacing like prepreg B most probably does.

A number of recommendations have been made of which some are already implemented at the time of writing. A tapelaying mode change resulted in lower tensional forces on the prepreg and together with the ply orientation change they appear to reduce the formation of defects. This successfully reduced the scrap rate of the laminates A to 0.

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FORMATION OF DEFECTS IN FLAT LAMINATES DURING AUTOMATIC TAPE LAYING

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Annex

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ANNEX 1: CONTOURTEST



The results of the contourtest of F. Camps in 2007 are shown in figure 1 and 2.

Figure 1: Overview of the contourtest markings

Figure 2: Close-up of the contourtest result





Figure 3: Test results of tensile testing prepregs on release films

ANNEX 3: TEST RESULTS INTERPLY FRICTION



Figure 4: Test results interply friction

4.1. EXTENSIONS AT LOAD/SHRINKAGE



Figure 5: Test results elongation and shrinkage M85



Figure 6: Test results elongation and shrinkage M85 roller



Figure 7: Test results elongation and shrinkage M84

4.2. TENSILE TEST PROGRAMS



Figure 8: Tensile test program for laydown shoe M85



Figure 9: Tensile test program for laydown roller M85



Figure 10: Tensile test program for laydown shoe M84

4.3. LOAD RIPPLE



Figure 11: A representative load ripple during the shrinkage time due to machine limitations



ANNEX 5: TEST RESULTS TENSILE STRENGTH OF RELEASE FILMS

Figure 12: Test results tensile strength of release films

ANNEX 6: TABLE RIDGES AND IMPERFECTIONS TRACKING

Earlier photos by Sabca Limburg show clear wrinkle formation between laydown table ridges, as visible in figure 13.



Figure 13: Wrinkles apparent between table ridges - date unknown

The ridges of the laydown table were visible in the laminate top and bottom sides during and after all production supervisions. The production supervision of 13/04/2015 to 14/04/2015 is used for the figures. Figures 14, 15, 16 and 17 show the ridges respectively after ply 3, ply 5, after ply 30 and on the bottom side. From ply 4 on bubbles started to form left and right of the ridges as can be seen in figure 15. The ridges and bubbles were no longer visible on the laminate surface after completion of the layup (fig. 16), yet they were visible on the bottom after the cutting of the laminate (fig. 17).



Figure 14: Table ridges visible in ply 3 – 13/04/2015

Figure 15: Table ridges and bubbles visible in ply 5 - 13/04/2015



Figure 16: The table ridges were no longer visible on the surface after completion of the layup (ply 30) – 14/04/2015



Figure 17: Bottom of the laminate showing the ridge impressions and bubbles – 14/04/2015

Some ridges even had burrs, which translated to even deeper impressions in the laminate bottom, see figures 18 and 19.



Figure 18: Bottom of the laminate showing deep ridge impressions - 14/04/2015



Figure 19: Close-up of the ridges responsible for the impressions in the laminate of figure 18 showing burrs -14/04/2015

Most of the bubbles visible in the laminate were directly tracable to imperfections in the table surface. Figure 21 shows the impression of the imperfection of figure 20 in the laminate bottom.



Figure 20: Close-up of an imperfection in the table surface leading to one of the figure 60 impressions -14/04/2015



Figure 21: The effect of the imperfection of figure 20 on the laminate bottom $- \frac{14}{04}/2015$

ANNEX 7: LAP AND GAP TRACKING

Laps and gaps occurred during all production supervisions in 2015. They were tracked thoughout the layup of the laminate. Figures 22 and 23 show laps and gaps in the first and second plies. On 02/03/2015 a lap in one of the lower plies was visible after completion of the laminate, see figure 24. On 13/04/2015 large lap/gap problems occurred which were visible after completion of the layup, as can be seen in figures 25 and 26. These resulted in wrinkles during the lay-up, though they were not visible anymore after completion of the lay-up, as can be seen in figure 27.



Figure 22: Insufficiently corrected laps in the first ply visible in ply #2 - 06/02/2015

Figure 23: Laps between courses are clearly visible in the first ply - 06/02/2015



Figure 24: A lap visible after completion of the laminate -02/03/2015

Figure 25: A gap/lap in a lower ply visible after completion of the laminate - 14/04/2015



Figure 26: A gap in a lower ply visible after completion of the laminate – 14/04/2015



Figure 27: Laps and gaps were compressed to wrinkles during the layup as seen here at ply 6 - 13/04/2015

ANNEX 8: RELEASE FILM TRACKING

On 06/02/2015 bubbles were observed in the release film. Their progress was tracked thoughout the layup. Figure 28 shows the location of the bubble after ply 2. The bubble was no longer visible after completion of the layup (fig. 29).



Figure 28: Bubble visible at the location of the air bubble after ply 2 - 06/02/2015



Figure 29: The bubble was no longer visible after completion of the layup $- \frac{06}{02}{2015}$

ANNEX 9: FLOWCHART



Figure 30 : Flowchart

ANNEX 10: RISK ANALYSIS

Cause	Hazard	Threat level	Exposure	Risk	Ability to change	Ability to test	Test score
Shoe type	Tensile force + displacement tape	4	4	5	4	4 4	
Feed rate	Tensile force + displacement tape	e + 4 4 5 4 4		4	20		
Ideal value	Elongation/shrinka	4	4	5	4	4	20
Table surface	Local defects	4	3	5	4	4	20
Ridges	Local defects	4	3	5	4	4	20
Ideal value head	Local defects +						
pressure	adhesion tape	4	4	5	4	4	20
Layup direction	Displacement tape	4	4	5	4	3	17,5
Calibration head pressure	Tackiness + compression defects	2	4	4	4	4	16
Temperature tape	Tackiness	4	4	5	4	2	15
Release film	Displacement to	4	Å	-	2		15
material	Displacement tape	4	4	5	2	4	15
Vacuum distribution	Bubbles in release foil + displacement release film	4	4	5	4	2	15
Tape quality	Tackiness	4	4	5	1	4	12,5
Head alignment	Laps & gaps	4	2	4	4	2	12
Acceleration	Tensile force + displacement tape	2	4	4	4	2	12
Incorrect setting	Elongation/shrinka	4	1	3	4	3	10.5
pretension	ge tape	·	-	5		3	10,5
Inaccurate setting head pressure	Tackiness + compression defects	3	3	4	2	3	10
Temperature table	Adhesion first layer	4	2	4	3	2	10
Resin distribution tape	Tackiness + resin deposition	4	4	5	1	3	10
Elongation release film	Deformation and wrinkling release film	4	2	4	2	3	10
Vacuum pressure	Displacement release film + bubbles	4	1	3	4	2	9
Release film application	Deformation and bubbling release film	4	2	4	3	1	8
Resin deposition counter wheel	Incorrect distance	4	1	3	4	1	7,5
Tape thickness	Bending stiffness	4	4	5	1	2	7,5
Improper	Interply friction	Λ	1	2	2	2	7.5
compacting	and air bubbles	4	T	2	3	2	7,5
Backing paper material	Resin deposition	1	4	3	1	3	6
Plastic film	Resin deposition	3	4	5	1	1	5
Displacement							
release film	Displacement tape	3	1	2	1	4	5
Room temperature	Tackiness	3	2	3	2	1	4,5
Waviness tape roll	Variation pretension	1	2	1	1	3	2

Figure 31: Risk analysis

ANNEX 11: DIGITAL IMAGE CORROLATION

2D digital image corrolation (DIC) tests to characterize the elongation and shrinkage behaviour of prepregs were performed in the lab. However, they didn't result in usable data as the prepreg wrinkled after the removal of the load, causing wrong interpretations of the speckle patterns. The low torsional stiffness of the prepreg and influences of the slightest vibration from other machines in the lab and wind from closing doors made the 2D-DIC setup not a suitable method of investigation. A 3D digital image corrolation setup could provide usable data in combination with a rigid mounting of the prepreg samples and the usage of a more accurate load-controlled tensile testing machine. There was not enough time left to explore the 3D DIC option. Further, the fiber bragg grating technology of 11.4 provides a direct measurement in the laminate leading it to be a more suitable candidate for elongation and shrinkage behaviour mapping during automatic tape lay-up.

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FBG sensing principle

Fibre Bragg Grating technology

Optical Fibre Bragg Grating (FBG) technology is not a novelty and exists for already more than three decades. During this period, they have had an enormous impact on optical communication systems, fibre lasers and last but not least fibre optic sensors and sensing systems. They are commonly being used as reflective filters for dispersion compensation for high bit-rate data communication (i.e. internet) and discrete fibre optic sensors, mostly for (point) measuring of strain and temperature. In the last decade, the properties of FBGs and their advantages over electrical sensors are more and more exploited for composite materials. They can for instance be applied as an optical strain gauge, as surface mounted sensor or even as an embedded (multi-axial) sensing element.

1. FBG principle

The FBG is a passive and discrete optical component at a specific spot in an optical fibre. An optical fibre consists of a fibre core and a fibre cladding. The Bragg grating is an area in the fibre core with a pre-defined length, Lg and an alternating periodic refractive index change, i.e. n1,n2 (Figure 1). An FBG acts as an optical filter or reflection filter and provides a frequency dependent reflection spectrum or stop band to the incident signal over a specific bandwidth. The stop band is centered at the Bragg wavelength, λ_B , and is given by the well-known Bragg condition , where Λ_{FBG} is the grating period and is the mode index or effective refractive index of the fibre.



2. Strain sensing

The very basic principle of strain sensing of a fibre Bragg grating is shown in Figure 2. When the fibre, having a nominal length, L_o , is being elongated to a certain length L, the grating period will be strained and the refractive index of the fibre will change as well. As a consequence, a positive Bragg peak shift is induced from λ_{B0} to λ_B . In fact, an FBG forms the optical equivalent for a resistive strain gage (RSG). The basic principle of both types of sensor is the same: only one parameter will change when being strained. For an RSG, it is the resistance of the wire which changes as a function of strain and for the optical counterpart, it is the Bragg wavelength which shifts.



The main difference between an RSG and an FBG is the fact that the FBG is a passive optical component with absolute sensor properties (i.e. no drift in time). This means that once it is calibrated for a specific temperature region there is no need to re-calibrate it, which is a major advantage once it is in service .

Another interesting aspect is the multiplexing ability of fibre optic sensors. One can put up to more than 20 FBGs in series configuration in one optical fibre (or channel), with each sensor having its unique reflected Bragg wavelength (i.e. "color").

COMASIENS®

FBG sensing principle

FBG sensors in one sensing network using a limited number of optical lines. The principle of an FBG-interrogator based on Wavelength Division Multiplexing (WDM) principle with 8 channels is shown in Figure 3. Here only one optical channel is connected to an optical fibre, which can be 100meters in length, with 1 up to N+1 FBGs. The ASE (amplified spontaneous emission) optical source sends light via the optical circulator (passive) and via the optical switch (active) to the optical fibre with one or multiple FBGs, with each FBG reflecting a unique Bragg wavelength. The Bragg wavelength(s) are reflected back via the optical circulator to the Optical Spectrum Analyser (OSA) which reads out the peak wavelength and wavelength shifts. The interrogator is operated using a standard PC or laptop with a Labview based software to record the FBG wavelengths.



Figure 3: FBG interrogator with 8 channels and multiplexing principle with N+1 FBGs in one optical channel

[1] Com&Sense bvba." Available: http://www.com-sens.eu.

ANNEX 13: FIBER BRAGG GRATING TEST

An accurate strain measurement method for reinforced composites is the fiber Bragg grating technology. Each fiber of $80-125\mu m$ diameter contains up to 20 sensors per running meter, with each sensor capable of measuring strain, compression, elongation, shear and temperature at high resolutions. They can be embedded between the plies of a laminate or can be attached to a course still on the ATL machine to measure the intra- and interply forces during tape laying and the subsequent displacement, elongation, shrinkage and shear behaviour of the prepreg plies.

Research has proven that small diameter optical fibers do not cause any significant reduction in the strength of composites and standard $125\mu m$ optical fiber produce a minimum perturbation of the host material when embedded parallel to the reinforcing fibres in the laminate [2]. While this may be true, the embedding of foreign materials on or in production laminates destined for the aerospace-industry client is not allowed, so a test laminate would need to be used.

An experiment was designed in association with Com&Sense [3] for Sabca Limburg in February 2015 using this technology, yet it was deemed too time-consuming and expensive since the worst problems already disappeared. The experiment design consisted of embedding 5 fiber sensors in a test laminate of 20 plies at 1,2m by 1,2m at key locations:

- Fiber sensor 1 between ply 1 and ply 2, aligned with the M84-M85 transistion. If a course shows reduced adhesion to the release film the fiber is embedded on this course.
 - Measuring the influence of the M84-M85 transistion.
 - Measuring the influence of the tensile forces in a course as a function of its distance to the origin.
 - Measuring the influence of the reduced adhesion.
- Fiber sensor 2 between ply 3 and ply 4, aligned with one sensor on a table ridge and one right next to a ridge.
 - Measuring the influence of the table ridges on the local head pressure force.
- Fiber sensor 3 between ply 7 and ply 8, aligned with the location of the prepreg cutting process.
 - Measuring the influence of the head pressure force on the laminate during the cutting dwell time.
- Fiber sensor 4 between ply 10 and 11, aligned with a table imperfection or a visible wrinkle/bubble. The sensor is embedded on ply 10 after which compacting is performed.
 - Measuring the influence of the compacting on the stress state of the laminate on top of a table imperfection.
 - Measuring the influence of compacting on the stress state of the laminate with the other sensory fibers.
- Fiber sensor 5 is used for measuring any other interesting locations or effects that arise during the layup of the test laminate, e.g. a lap/gap issue.

[2] G. Luyckx, "Multi-axial strain monitoring of fibre reinforced thermosetting plastics using embedded highly birefringent optical fibre Bragg sensors," Ghent University, 2009.

^{[3] &}quot;Com&Sense bvba." Available: http://www.com-sens.eu.

ANNEX 14: SACRIFICIAL CUTTING MAT

The vacuum table has a sacrificial cutting surface which will be covered with a plastic film and held in place with vacuum to the table surface, see Fig. 178. See Sections below for vacuum table Set–up and Maintenance.



Figure 32 : Vacuum table sacrificial cutting surface [4]

ANNEX 15: HEAD PRESSURE TO FORCE CONVERSION TABLE

Co - pres	bal sure	Drukkracht tapelayer	Co - pres	bal sure	Drukkracht
Bar	psi	Kg	Bar	psi	Ka
4,8	68	0	4.8	68	0
4,7	67	0	4,7	67	3
4,6	66	0	4,6	66	13,1
4,6	65	10,2	4,6	65	20
4,5	64	16,1	4,5	64	29.6
4,4	63	25,2	4,4	63	37,6
4,3	62	32,2	4,3	62	43,8
4,3	61	39,1	4,3	61	50,6
4,2	60	46,3	4,2	60	59,8
4,1	59	53	4,1	59	65
4,1	58	63	4,1	58	73,8
4.0	57	70,3	4,0	57	82
3,9	56	80,3	3,9	56	87,7
3,9	55	87,7	3,9	55	96,8
3.8	54	97,5	3,8	54	105,3
3.7	53	104,2	3,7	53	110,5
3.6	52	113,6	3,6	52	116,4
3.6	51	121,5	3,6	51	121,5
3.5	50	129.2	3,5	50	128,6

Figure 33 : Head pressure conversion table

[4] "Operating manual for Cincinnati multi axis low rail tape laying machine with CM100 CNC control." Cincinnati.

			3	Total Force(mass)						
Blac	ladder Pressure		Pressure 150 mm Shoe		300 mm shoe		150 mm roller		300 mm roller	
[psi]	[kPa]	[Bar]	[lbs]	[kg]	[lbs]	[kg]	[lbs]	[kg]	[lbs]	[kg]
0	0,00	0,00							75,00	34,02
1	6,89	0,07			80,00	36,29			112,00	50,80
2	13,79	0,14			98,00	44,45			150,00	68,04
3	20,68	0,21			116,00	52,62			195,00	88,45
4	27,58	0,28			140,00	63,50			235,00	106,59
5	34,47	0,34			161,00	73,03			270,00	122,47
6	41,37	0,41			182,00	82,55			309,00	140,16
7	48,26	0,48	50,00	22,68	202,00	91,63	173,00	78,47	347,00	157,40
8	55,16	0,55	62,00	28,12	222,00	100,70	200,00	90,72	382,00	173,27
9	62,05	0,62	76,00	34,47	242,00	109,77	230,00	104,33	413,00	187,33
10	68,95	0,69	90,00	40,82	265,00	120,20	259,00	117,48	455,00	206,38
11	75,84	0,76	107,00	48,53	285,00	129,27	290,00	131,54	496,00	224,98
12	82,74	0,83	120,00	54,43	306,00	138,80	318,00	144,24	532,00	241,31

Figure 34: Table of head pressure force using shoe/roller