Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

A New Fibre Placement Architecture for Improved Damage Tolerance

Problem Area

Composite laminates made with woven fabric are known to have better damage resistance characteristics than unidirectional laminates. Due to the recent development in fibre placement and tape laying machines, laminates with unidirectional plies are favoured because of the automated production process.

Description of Work

AP-PLY combines the advantages of fabrics and unidirectional layers in an automated production process. AP-PLY is a laminate configuration obtained by placing the fibre tows in special patterns that mimic the construction of a woven layer. Any material system can be used for the construction, including glass fibre, carbon fibre, thermoset and thermoplastic resins and even dry fibre placement. No adaptations to current fibre placement machines are necessary.

Results and Conclusions

Tests show smaller delaminations and higher residual strength for every tested AP-PLY configuration and lay-up compared to baseline laminates with unidirectional plies. An energy dissipation redistribution

is observed between fibre breakage and delaminations. Both thermoset and thermoplastic materials were tested.

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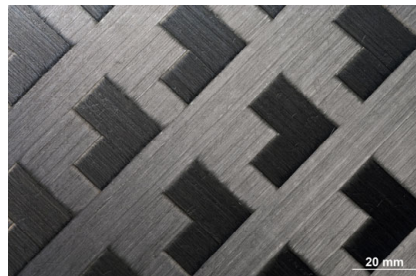
Applicability

Possible applications include fuselage and wing outer surface plies, sandwich panel face sheets. It is also possible that entire laminate structures where the design is driven by damage tolerance can be constructed by AP-PLY. In addition, the prospect of eliminating or minimizing the use of fabric plies, which is a labour intensive process and replacing them with equivalent AP-PLY configurations, makes the present concept attractive for other applications where impact damage may not be the driver.

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A New Fibre Placement Architecture for Improved Damage Tolerance

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Summary

To improve the damage tolerance characteristics of composite structures made by a fibre placement process a new fibre architecture called AP-PLY is developed. AP-PLY combines the advantages of woven fabrics and unidirectional laminates in an automated production process.

Instead of placing parallel fibre bands directly adjacent to each other, room is left in between which is filled up after first placing fibres in a different direction. A pattern is created that mimics a woven fabric, improving the out-of-plane strength of fibre placed laminates.

Compression after impact tests are performed on several AP-PLY patterns for both thermoset and thermoplastic material systems, comparing them to unidirectional baseline laminates. Tests show that indentation depth and delamination size are influenced by the pattern, indicating a redistribution of damage mechanisms and a different BVID value. Residual strength is higher for all AP-PLY patterns with respect to their unidirectional counterparts, varying from 4-7% depending on pattern, lay-up and material system.

Possible applications include damage tolerance dominated structures, but also the replacement of woven fabrics for amongst others outer surface plies and sandwich facesheets. Further research includes optimization of the pattern and lay-up as well as testing properties such as bearing and open hole compression strength.

Contents

Abbreviations

AP-PLY	Advanced Placed Ply
ASTM	American Society for the Testing of Materials
BVID	Barely Visible Impact Damage
CAI	Compression After Impact
LVDT	Linear Variable Differential Transformers
TP	Thermoplastic
TS	Thermoset
UD	Unidirectional

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1 Introduction

One of the challenges composite aircraft structures face is damage tolerance. High or low speed impacts may cause large delaminations and other damage, which cannot be detected easily. Current composite aircraft do not exploit the advantages of composites to the fullest as they are often overly dimensioned to meet the damage tolerance requirements. Automated production processes, such as fibre placement, have made the cost-effective production of composite aircraft possible. They have also made possible the use of more complicated fibre architectures than the traditional unidirectional laminates. These unidirectional laminates are known to have a higher in-plane stiffness than woven fabrics. A downside is that woven fabrics, which exhibit better impact behaviour than unidirectional laminates[1], cannot be used with a fibre placement machine.

Recent advances in non-conventional fibre patterns that can be fabricated via fibre placement machines are variable stiffness laminates and dispersed laminates. Variable stiffness laminates[2] make use of curved fibre paths, dictated by stress distribution patterns and thus resulting in a tailor-made laminate for specific loading conditions. All fibres are placed in the same plane, which results in gaps and/or overlaps between fibre bands. Dispersed laminates[3] reduce the angle difference between adjacent plies in order to reduce interlaminar stresses and thus delaminations. These plies however are still unidirectional with straight fibres. So far, variable stiffness laminates have been used for improved strength and buckling performance with or without cut-outs present, whereas dispersed laminates have been designed for improved damage tolerance.

This paper presents a fibre architecture that combines the superior impact resistance of woven fabrics with the advantages of fibre placement. Compression after impact test results are presented for thermoset specimens with different AP-PLY patterns and compared with baseline unidirectional laminates. The best performing pattern is also made from thermoplastic material and compared to a thermoplastic baseline laminate.

2 AP-PLY Concept

Traditionally fibre placed laminates consist of unidirectional layers, each constructed by aligning all the passes of the machine head to be parallel to one another, and ensuring that each pass is adjacent to the previous pass without leaving any gap between them. In this new concept, instead of placing multiple fibre bands directly next to each other, bands are placed in two directions leaving space in between adjacent bands. These spaces are filled up with alternating bands in both directions, such that on every location two bands are positioned on top of each other. Basically two plies are interwoven, where the number of bands to skip and the angle between them can be infinitely varied, resulting in an endless amount of possible patterns. For example, the pattern in Figure 1 is created by placing a group of fibre bands in one direction, leaving a gap of exactly one bandwidth in between. A second group of fibre bands is placed in a second direction, creating the pattern shown in Figure 1 B. Next the empty spaces shown in Figure 1 A are filled up by a second group of fibre bands in the first direction shifted over one bandwidth. Finally in Figure 1 D the second direction is filled up creating a two-ply laminate with a uniform thickness.
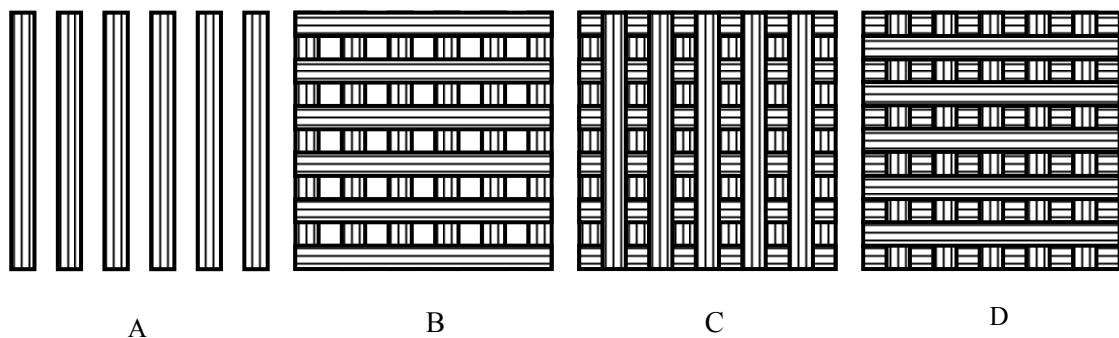

A   B   C   D

Figure 1: A woven pattern created using fibre placement

In this example only two layers are interwoven, whereas in theory an arbitrary amount of layers with different angles can be interwoven. Also instead of this 90 degree angle between the two plies, any angle is possible. A photo example of one possible configuration with a 45° pattern is shown in Figure 2. Depending on the application and preferred layup, this can be varied. Any layup can be created with this approach, and the location of the interwoven layers can be chosen at will, even combining unidirectional plies and AP-plies. Finally the width of the bands used determines the resolution of the pattern, which influences the homogeneity of the laminate, performance and production time. As this fibre architecture does not involve curved fibre paths it does not have to deal with the gap and overlap issues often encountered in new fibre placement concepts[4].
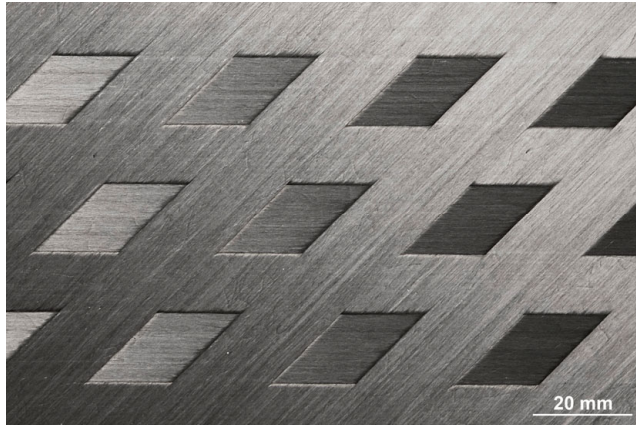
Figure 2: Example of one of the possible patterns

3 Manufacturing

For the compression after impact tests, specimens were manufactured according to ASTM standard 7136[5]. Several options exist to make the prescribed quasi-isotropic laminate with a thickness of 4 mm. Two widely used lay-ups are [-45/45/90/0]$_S$ and [-45/90/45/0] $_S$, which are also described in the ASTM standard. These are well suited for the proposed pattern and allow for two different interface angles in the pattern, namely 45° and 90°. Two layers are interwoven, which could be described as [(-45/45)/(90/0)]$_S$ and [(-45/90)/(45/0)]$_S$.

To let the machine place the desired pattern, a points file is created in Matlab and Excel which is used as input for the Fibre Placement Manager software. This creates the file with trajectories, head orientations and cutting commands for the Automated Dynamics Corporation automated fibre placement machine of the National Aerospace Laboratory NLR. Large 500 x 550 mm plates are manufactured from which the specimens are cut.

The thermoset material used is Hexcel AS4/8552 prepreg slit tape, supplied as 1/8" slit tape and 4 tapes placed together resulting in a bandwidth of ½" or 12.7 mm. As this material has a cured ply thickness of 0.18 mm the laminates were built up from 24 layers, resulting in a laminate thickness of 4.3 mm. The autoclave cycle recommended by the supplier is 60 minutes at 110° C followed by 120 minutes at 180° C.

For the thermoplastic specimens the Automated Dynamics Corporation fibre placement machine was fitted with the thermoplastic processing head. Again, the AS4 fibre was used, but this time in a pre-preg with Cytec APC-2 PEEK thermoplastic resin, supplied as 1/2 inch tape with a final ply thickness of 0.125 mm. To reach the desired laminate thickness of 4 mm in a quasi-isotropic layup 32 layers were needed. The material is heated to 380° C just before placing it into the mould. As it

cools down rapidly it does not stick to the mould, which makes placement challenging, especially patterns skipping bands. This results in slightly more closely spaced bands in the lower layers as compared to the upper layers. To ensure a high consistent quality the plates were heated in the autoclave at 380° C for 60 minutes.

An increase in fabrication time is expected, but the difference at this stage is very small. Whereas the time on the mould is exactly the same as for unidirectional plies, only slightly more time is spent by the machine head in the air. With a minor adaptation to the machine head, practically the same manufacturing speeds can be accomplished.

During curing a metal top-plate was used, which ensured a smooth surface and no difference in surface quality was found between the baseline and the AP-PLY. After cure, all plates were C-scanned to verify specimen quality. A water-cooled diamond saw cut the specimens to the dimensions presented in Table 1, as specified by ASTM 3176.

Table 1: Specimen Dimensions

Length	150 mm
Width	100 mm
Thickness	4.3 mm (TS) 4.0 mm (TP)

4 Tests

Two stages can be identified in the testing procedure: impact and compression. After impact and before compression all specimens are C-scanned to determine the size of the delaminations.

4.1 Impact

The NLR-designed drop tower was used together with the clamping device shown in Figure 3 which has an unsupported rectangular cut-out of 125 mm by 75 mm. Impactor mass is 2.31 kg and the tup has a diameter of 16 mm. The impactor head is equipped with a strain gauge to measure impact force, and its velocity is measured just before and after impact.
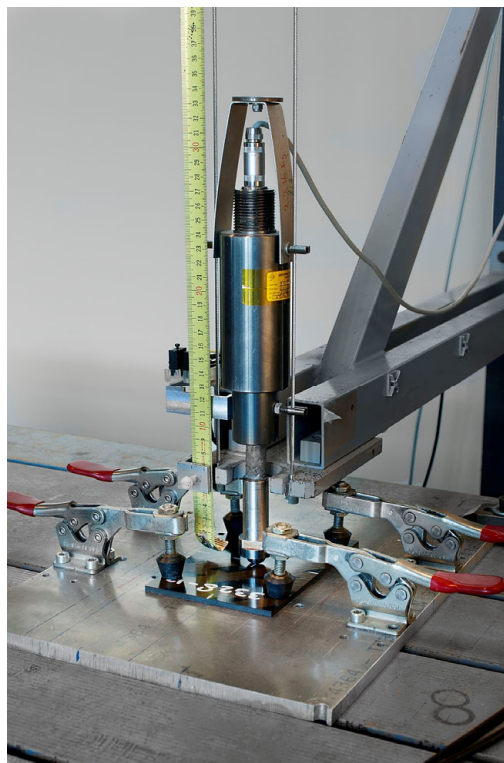

Figure 3: Impact Test Clamping Device

From the first three tested specimens in one series the Barely Visible Impact Damage (BVID) level was estimated by fitting a curve through the Impact Energy vs Indentation Depth curve. BVID is prescribed as an indentation depth of 1 mm directly after impact. As can be seen in Table 2 the energy levels used are, typically, higher for the thermoplastic specimens, as BVID was reached early for the thermoset specimens. Several thermoset configurations are tested, leading to different BVID levels.

Table 2: Test Impact Energy Levels for all specimens

| Specimen | Impact Energy [J] | |
	TS	TP
1	40	40
2	15	BVID (35-39)
3	20	BVID (35-39)
4	25	BVID (35-39)
5	30	30
6	30	40
7	30	40
8	BVID (25-28)	30
9	BVID (25-28)	30
10	BVID (25-28)	50
11	20	25
12	20	20

After impact the indentation depth was measured and photographs were taken of both sides of the specimens. In order to determine the delamination size and shape, all specimens were C-scanned which is described in the next section. In Figure 4 and Figure 5 it can be seen that, from the outside, the difference in damage can already be observed. In contrast to most baseline specimens, which have delaminations and other damage in the bottom (backside) layer along the fibre direction, the damage in the AP-PLY specimens seems more confined to a small region in the vicinity of the impact point.
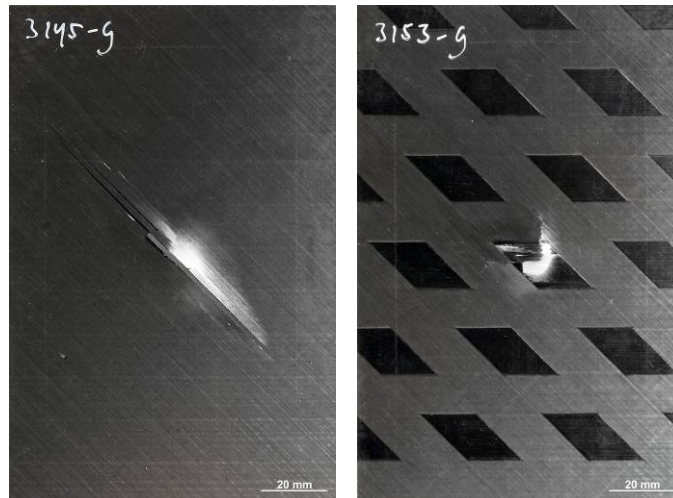
Figure 4: Backside of TS baseline(left) and AP-PLY (right) specimens at BVID
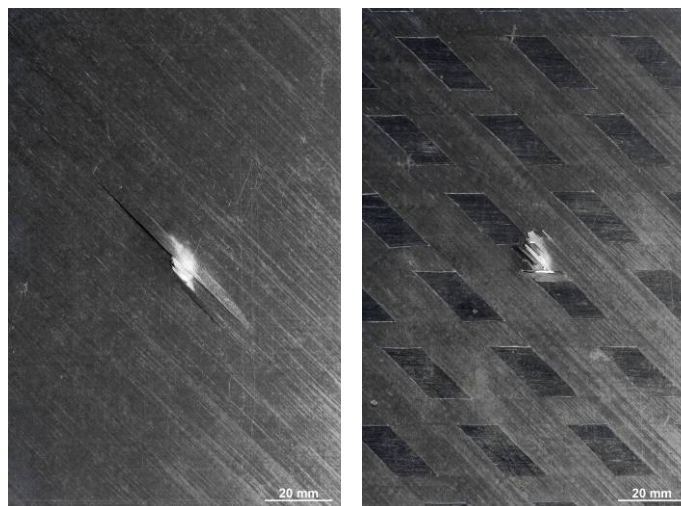

Figure 5: Backside of TP baseline (left) and AP-PLY (right) specimens at BVID

Three more specimens were also impacted, but at different locations to determine the influence of impact location. Instead of compression testing, a cross cut of these specimens was made to determine the through-the-thickness damage.

4.2 Compression

Using the prescribed test fixture shown in
Figure 6 the impacted specimens were tested in the Instron 5887 300 kN test equipment according to ASTM D7137[6]. Two Linear Variable Differential Transformers (LVDT) were used to measure the displacement of the machine compression platens more accurately and the loading rate was set at 1.25 mm/min.
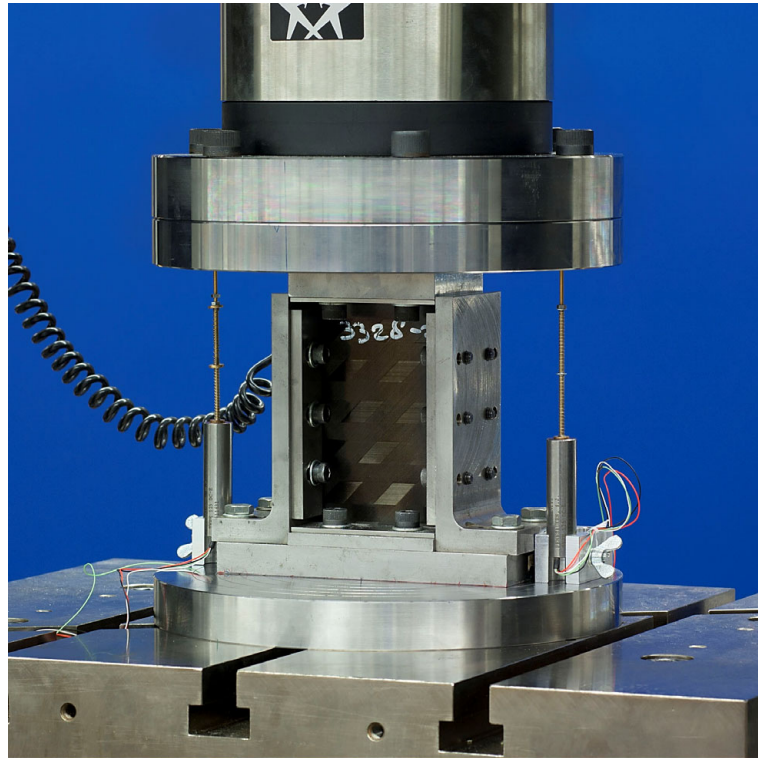
Figure 6: Compression test set-up

5 Results

In determining the performance of the various patterns three factors play an important role. First, the indentation influences the detectability of the induced damage. Second, the delamination size and other damage such as matrix cracks and broken fibres determine the size and severity of the damage. And most important, the residual strength determines the ability of the structure to carry loads in a damaged state.

5.1 Indentation

Directly after impact, the indentation was measured. As can be seen in Figure 7 the indentations are higher for the AP-PLY configuration than for the baseline laminate at the same energy levels. A possible explanation is that more energy is dissipated by fibre breakage instead of delaminations, resulting in more localized but deeper damage. The section cuts discussed later support this explanation. Whether fibre breakage or delaminations are favourable depends on the application. In tension fibre breakage is more critical than delaminations, whereas in compression fibre breakage is favoured[7]. An advantage of deeper indentations could be that for the same energy level damage can be detected at an earlier stage: the Barely Visible Impact Damage threshold is lower.

For the BVID level the damage is smaller for two reasons: the lower impact energy and the smaller delaminations resulting from the AP-PLY pattern.
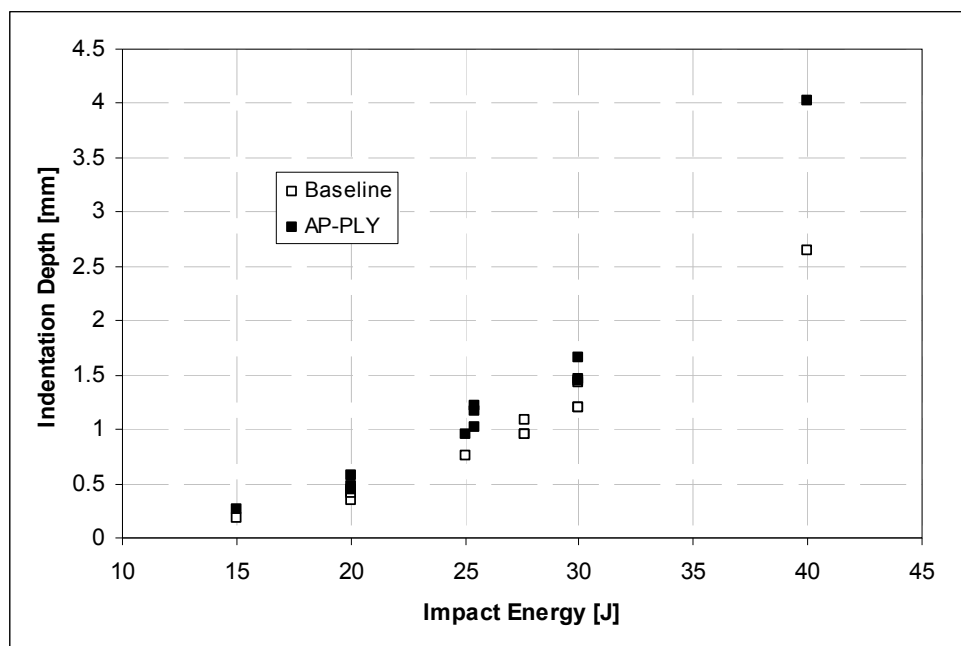

Figure 7: TS Indentation of Pattern D vs Impact Energy

The thermoplastic specimens show exactly the opposite behaviour: AP-PLY has a smaller indentation than the baseline laminate for the same impact energy level. Also a crack (broken fibres) in the top layer was observed, aligned with the length direction of the specimens.
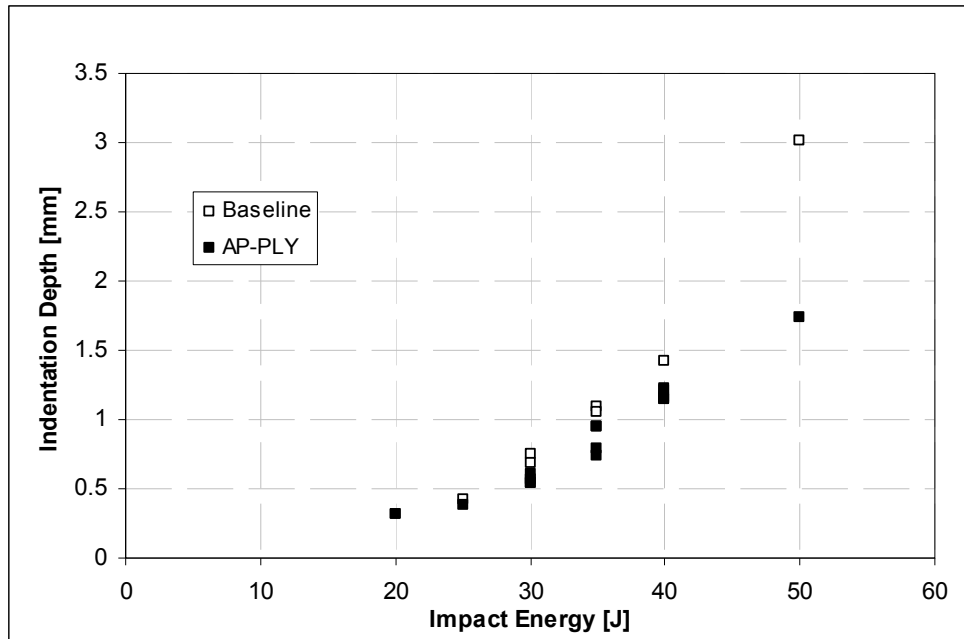

Figure 8: TP Indentation of Pattern D vs Impact Energy

Figure 9 shows these longitudinal cracks right next to the impact location. Main differences between the TS and TP specimens are, apart from the tougher matrix material, the smaller ply thickness resulting in more layers and a 7% smaller laminate thickness. The bending deformation caused during impact results in compression of the top layer of the specimen. Due to the increased out of plane strength and toughness of the TP material, less energy is dissipated in delamination and more is available to break fibres.

Figure 9: Longitudinal cracks in TP specimen

5.2 Delamination

After impact all specimens were C-scanned with the impacted side up to inspect the extent of the delaminations. NLR's Ultrasonic Sciences C-scan system was used with a 6 dB reference level. Delaminations were measured and two examples are shown in Figure 10 for the same energy level.
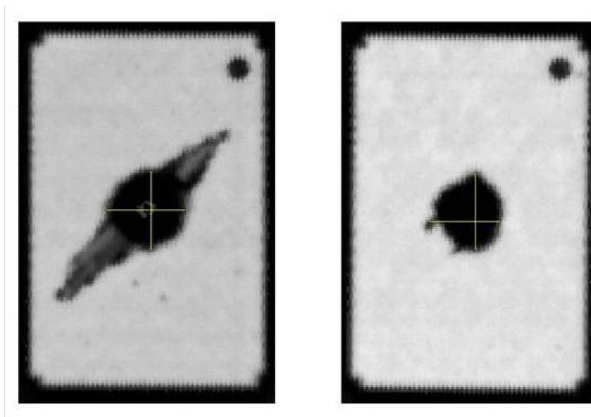

Figure 10: Delamination C-Scan for Baseline (Left) and AP-PLY Pattern A (Right)

On the left hand C-Scan of the unidirectional specimen clearly a diagonal extension of the delamination can be seen while the right C-scan of pattern A shows only a circular delamination. For the determination of the size of the delamination, only the circular part of the C-Scans was taken. It is assumed that for thick specimens as the ones used here, the non-circular backside delamination does not play a large role in the strength degradation.

For the thermoset material system all AP-PLY pattern delaminations are smaller than the unidirectional lay-ups at an equal energy impact, as can be seen in Figure 11.
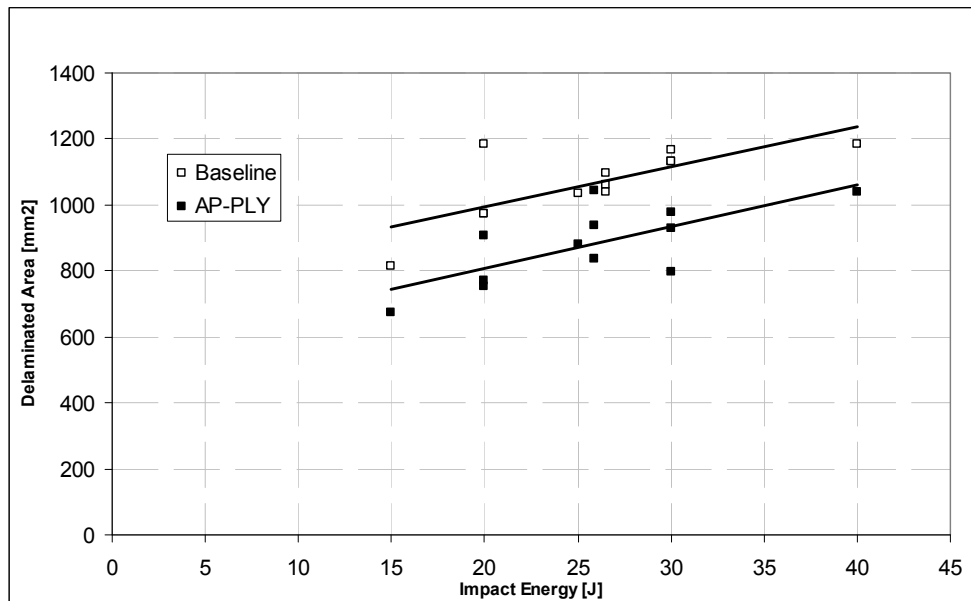
Figure 11: TS Delaminated Area Pattern B vs Impact Energy

Figure 12 shows the same information on the thermoplastic material system, where a lot more scatter is present, also in the baseline (UD) specimens. Scatter is inherent to impact testing, and makes judging by delamination size in this case difficult.

It must be noted that this measured area is in fact a 'projection' of all delaminations through the layers. In general this can be treated however as a measure of the induced damage.
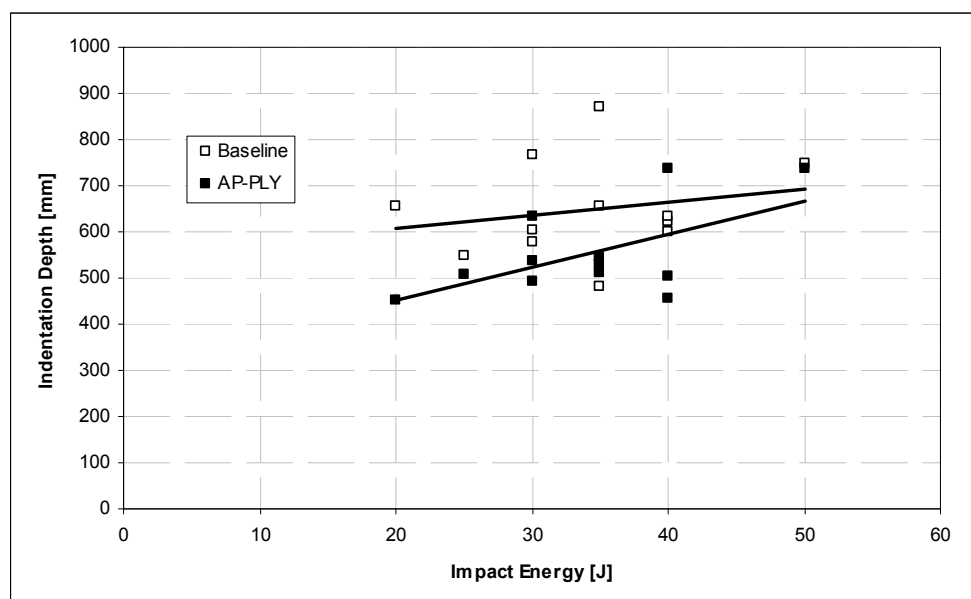

Figure 12: TP Delaminated Area Pattern D vs Impact Energy

5.3 Residual Strength

Although only showing a selection of results, compression tests of the impacted specimens made clear that all interwoven laminates examined so far perform better than their unidirectional counterparts. In general the 45° interface laminates with ply orientations in adjacent plies differing by no more than 45° perform better than laminates where some adjacent plies may have fibre orientations that differ by 90°; even the unidirectional laminate with 45° angle difference performs better than the best AP-PLY laminate with 90° difference. It is well known that the smaller the angle between adjacent plies, the smaller the interlaminar stresses[7]. As these interlaminar stresses cause delaminations, it explains the better performance of the 45° interface laminates.
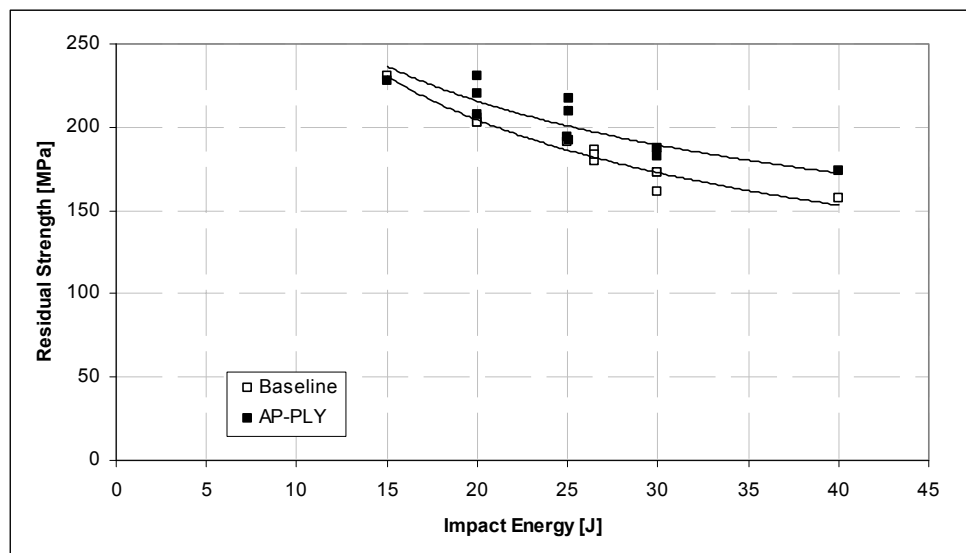

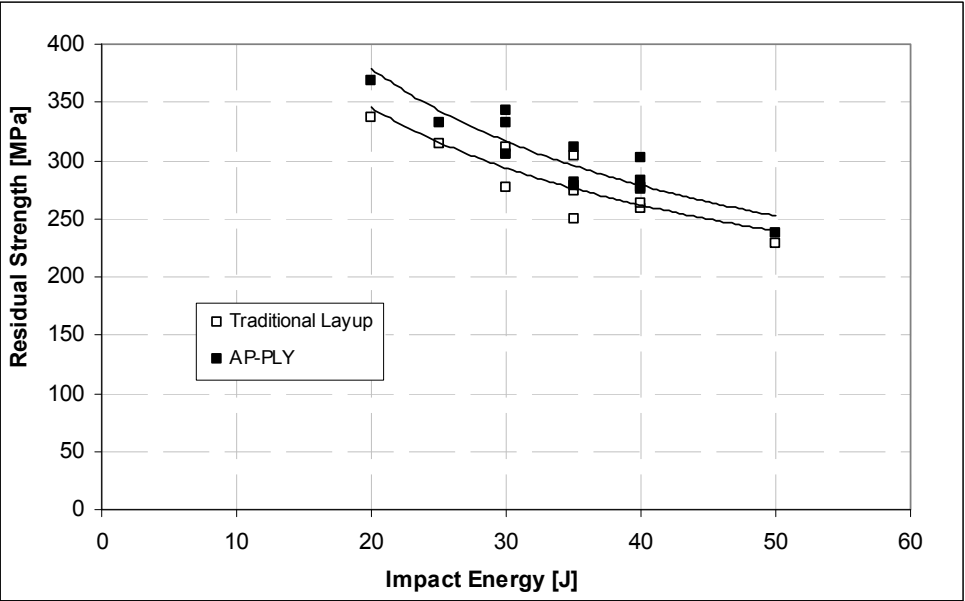*Figure 13: TS Residual Strength Pattern A vs Impact Energy*

Figure 14: TP Residual Strength Pattern D vs Impact Energy

For both material systems AP-PLY performs better than unidirectional laminates with the same layup, and all tested thermoplastic laminates perform better than the thermoset laminates.

6 Comparison

To have a clear comparison between the two material systems and the two placement patterns, the averaged residual strength values after a barely visible impact are shown in Table 3. For reasons of confidentiality the patterns tested are not specified, but vary in lay-up and pattern.

AP-PLY performs better, where the increase in performance (7 %) is larger for the thermoplastic material system than for the thermoset material system (4 %). These differences are relatively small because the AP-PLY patterns are not fully optimized. Additional improvements are anticipated with new patterns currently under investigation. It should also be pointed out that the AP-PLY laminates seem to have more scatter in the test results (see Figures 10-13). This is mainly due to the relatively wide band used here (12.7 mm). The residual strength might be affected by the position with respect to the pattern where the specimen was impacted. Using narrower bands should minimize this effect.

Table 3: Comparison at BVID Level (1 mm)

		Baseline	**AP-PLY**
TS	**BVID Impact Energy [J]**	27.6	25.4
	Residual Maximum Stress [MPa]	201	210
TP	**BVID Impact Energy [J]**	35.5	38.8
	Residual Maximum Stress [MPa]	276	289

6.1 Stiffness

The stiffnesses of the undamaged specimens were measured using CAI specimens loaded under compression to 30 % of the failure load. Machine head displacement was taken for simplicity and the stiffness was calculated using the slope of the linear part of the stress-displacement curve.

Although not suitable for determining the absolute strain in the specimen, the normalised value is used for comparison purposes. As can be seen in the table below there is no significant difference in stiffness between the different patterns, for both material systems. All results are well within experimental scatter.

Table 4: TS Normalised Stiffnesses

Laminate	Normalised Stiffness
Unidirectional 90° interface	100.0
Pattern A	101.0
Pattern B	100.5
Pattern C	101.7
Unidirectional 45° interface	100.2
Pattern D	100.7
Pattern E	101.7
Coefficient of variation	0.68 %

Table 5: TP Normalised Stiffnesses

Laminate	Normalised Stiffness
Unidirectional 45° interface	100.0
Pattern D	98.1
Coefficient of variation	1.39 %

When looking at the cross-section of an AP-PLY laminate under a Zeiss Axioplan 2 optical microscope it is clear that the undulation is very small as the bands are very thin. Only a 7 degree angle is observed in TS, with very small resin rich areas. For the thinner thermoplastic layers the angle is even smaller. Fibre bands are slightly deformed at the edges to accommodate the crossing of the fibre bands to another layer. Since the undulation is very small, tensile properties of these laminates are not expected to be different from standard unidirectional laminates.
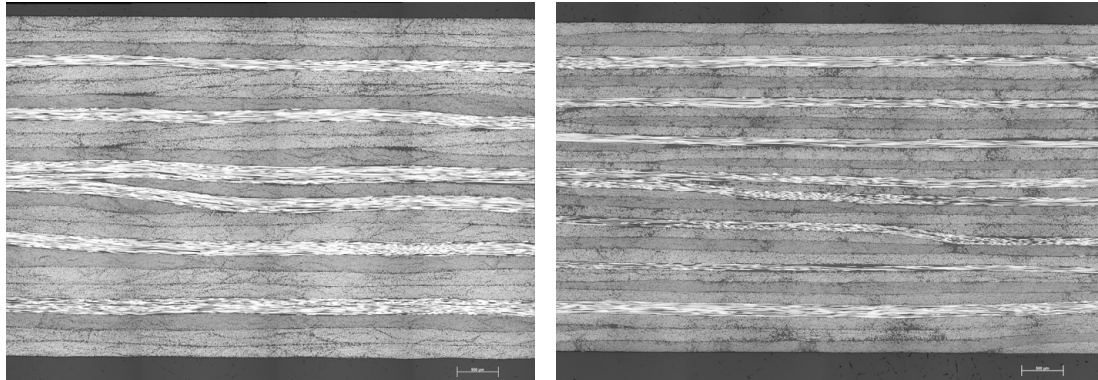
Figure 15: Microscopic images (25x) of an AP-PLY laminate cross-section in TS (left) and TP (right)

6.2 Thickness

Due to the more complicated layup of AP-PLY, its thickness could be expected to be larger. For all 12 specimens of each pattern the thickness was measured at three locations, after which the average was taken. As is shown in Table 6, in the case of the thermoset material system the thickness was actually smaller, however with such a small difference that it may be considered within scatter. The thermoplastic AP-PLY was slightly thicker however, but again a small enough difference to be within experimental scatter.

Table 6: Thicknesses [mm] (TP and TS) for Baseline and AP-PLY

	Average Thickness [mm]	St. Deviation [%]
TS		
Unidirectional 90° interface	4.46	0.70
Pattern A	4.35	0.84
Pattern B	4.45	0.73
Pattern C	4.29	0.59
Unidirectional 45° interface	4.38	0.43
Pattern D	4.32	0.85
Pattern E	4.39	0.50
TP		
Unidirectional 45° interface	3.96	0.43
Pattern D	4.10	0.42

6.3 Section Cuts

Of all patterns of the thermoset specimens a section cut of an impacted specimen with 25 J was made for both the baseline and AP-PLY specimens to get a clear view of the delaminations

through-the-thickness. The specimens were cut through at an angle perpendicular to the loading direction, 1 cm away from the heart of the impact. Next the specimens were poured in resin and sanded to get to the middle of the delamination.

Thermoset

At first sight there seems to be more damage in the AP-PLY specimen, which seems to be fibre breakage. This is consistent with the earlier observation that the indentation is deeper for AP-PLY, which was then also attributed to fibre breakage. When looking at the delaminations they seem to be fewer and smaller in AP-PLY. At the location of a cross-over of the fibre band, the delamination seems to end. This suggests that these cross-overs act as built-in delamination arresting mechanisms and may account for the reduced delamination size of AP-PLY laminates.
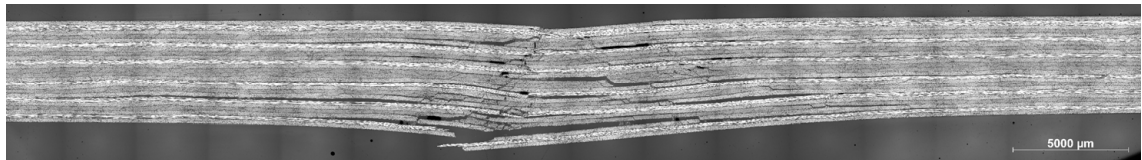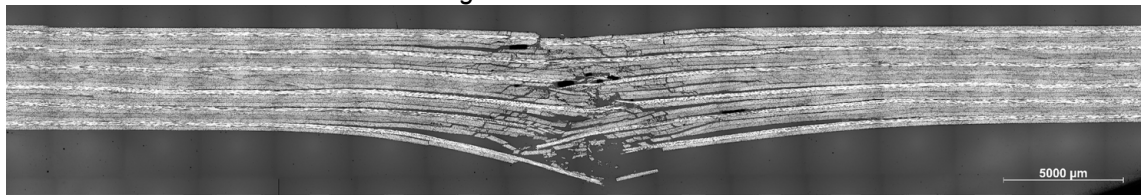

Figure 16: TS Baseline

Figure 17: TS AP-PLY Pattern D

Thermoplastic

Figure 18 and Figure 19 show the section cuts for the TP specimens impacted at 25 J. As BVID is considerably higher for the TP specimens overall less damage is visible, as well as less difference for both laminate configurations. It is clear however that less and smaller delaminations are present in the AP-PLY configuration as compared to the Baseline. Also slightly more fibre breakage in the Baseline seems contrary to the deeper indentation.
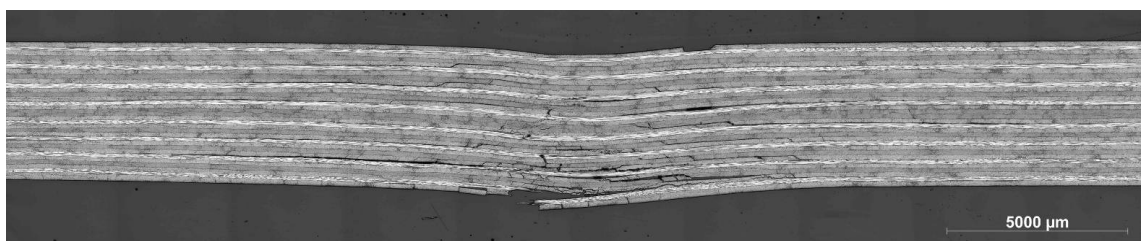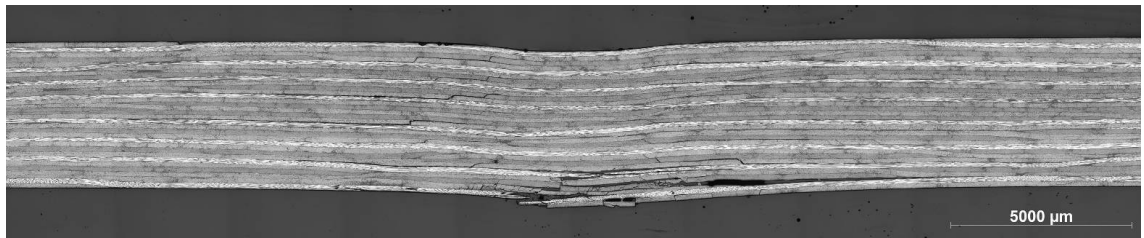

Figure 18: TP Baseline

25

Figure 19: TP AP-PLY Pattern D

Whether fibre breakage or delaminations are favourable depends on the application. In general, delaminations are more of a problem in compression whereas fibre breakage causes more concern in tension. As these specimens were not tailored to any specific application but do show interestingly different behaviour, there seems to be enough room for optimizing a lay-up with all known characteristics.

7 Conclusions

A new fibre architecture is presented that shows improved damage tolerance for all the patterns tested compared to its unidirectional counterparts, for two material systems. This can be explained by the multiple load path provided by the interweaving, halving the number of ply interfaces and the creation of physical barriers for a delamination to grow.

The influence of impact location is an important topic for future research. Although the worst case of the new pattern has the same residual strength as its unidirectional counterpart, a solution for the heterogeneity of the pattern could make it even more damage tolerant. A smaller bandwidth or a different stacking sequence could be the solution for this.

Only quasi-isotropic lay-ups were compared in this research. More often other lay-ups are used, to meet specific loading conditions. Other lay-ups should be tested, and perhaps a combination with the earlier described dispersed stacking sequences could be beneficial.

In this research only 45 and 90 degree angles were tested, where in theory all angles are possible. It could be the case that for very small angles matrix rich areas are created as the fibres do not fit up properly, as well as for more than two interwoven layers. Further research will be focused on determining the best pattern and the influence of AP-PLY patterns on properties such as open hole compression and bolt-bearing

Possible applications include damage tolerance dominated structures, (fuselage or wing), but the applications are not limited to that. The ability to replace woven fabrics, which are often used for improved bearing properties or (on the surface) for improving hole quality during drilling, makes this concept usable to a large variety of applications including sandwich with thin facesheets.

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