DAMAGE TOLERANCE OF STRUCTURAL STITCHED CFRP LAMINATES

A. Erber, V. Witzel, Prof. K. Drechsler
Universität Stuttgart, Institut für Flugzeugbau
Pfaffenwaldring 31, 70569 Stuttgart, Deutschland

Abstract

Damage Tolerance - a very important property for structural materials. In aerospace applications materials have to resist different impacts during the life cycle of a product. There are impacts due to tool drop, bird strike, tire burst or hailstorm just to name a few. Depending on the impactor velocity they can be divided into two different categories, **H**igh **V**elocity **I**mpacts (HVI) and **L**ow **V**elocity **I**mpacts (LVI).
Especially for **C**arbon **F**ibre **R**einforced **P**lastics (CFRP) the damage tolerance is a challenge even today. Structural stitching of the preform material can increase the residual strength and damage tolerance respectively. With the standardised **C**ompression **A**fter **I**mpact (CAI) test procedure an evaluation of different materials on test coupon level is possible. The residual compression strength of the test samples is a measure for the damage tolerance of the tested material.
In the scope of this work the influence of the resin system and different stitch pattern on the damage tolerance were investigated for two different fibre orientations and fibre architectures. Therefore two different epoxy resin systems and two different semi-finished products were used. In order to investigate the influence of the structural stitching three different stitch pattern configurations were tested. The impact energy levels were zero Joule as a reference as well as 25 Joule and 40 Joule representing LVI impact scenarios.
In this paper it is shown that the influence of the matrix on the damage tolerance is on a lower level. However the preform architecture and the stitch pattern configuration have a considerable effect on the damage tolerance of the CFRP materials. By variation of the stitch pattern and the semi-finished material the residual compression strength and the damage tolerance respectively can differ up to 15%.

1. INTRODUCTION

Composites are state of the art for high performance lightweight applications in multiple industries. Due to their high specific strength and stiffness **C**arbon **F**ibre **R**einforced **P**lastics (CFRP) are used both in several structural parts and as crash absorbing elements in aerospace and automotive [1].

Beside many advantages of CFRP like large scale integration, damping properties or lightweight potential there are some challenges for the industry as well as for research facilities. The advancement of the damage tolerance and at the same time the reduction of manufacturing costs are two of the most important topics currently.

Already during the design process it should be taken into account that there can be one or more impact on the structure during the life cycle. There are impacts due to tool drop, tire burst, runway debris or bird strike just to name a few of the foreign object damage scenarios [2].

Preforming technologies based on textile techniques like braiding, tailored fibre placement or two- and three dimensional stitching offer different solutions for the manufacturing of damage tolerant as well as cost-efficient composite parts.

In order to increase the residual strength after impact the 3D-stitching technology can be used. By means of this highly automated manufacturing technique the out of plane properties are raised due to fibres in the third dimension (z-direction).

In this paper the influence of different stitch pattern on the damage tolerance is presented. Therefore the standardised **C**ompression **A**fter **I**mpact (CAI) test is used at laminates with different preform material architectures and resin systems.

Here the residual compression strength of impacted test specimens is a measure for the damage tolerance of the preform configuration.

2. CAI-TEST PROCEDURE

The CAI test is a test procedure for flat plate test specimens described for example in the “AITM 1-0010” or “DIN EN 6038” test standard. The dimensions of the samples and the used test tools are accordingly to these standards.

The residual compression strength is a measure for the damage tolerance of different materials. The test procedure is used to get both quantitative and qualitative information of different materials in comparison.

2.1. Impact Configuration

In this measurement campaign the test specimens are impacted by a drop weight tower with two levels of energy, E_1 = 25 J and E_2 = 40 J. Additionally samples without impact, thus E_0 = 0 J, were tested in order to measure the initial strength of the material. The weight of the impactor is constant m = 3.5 kg. The energy is regulated by the initial height of the impactor accordingly to equation (1).

(1) $E = m \times g \times h$

Here E is the impact energy, m the mass of the impactor, g the gravitational acceleration and h the initial height of the impactor.

Figure 1 shows the drop weight tower as well as the clamping system for the test specimens.

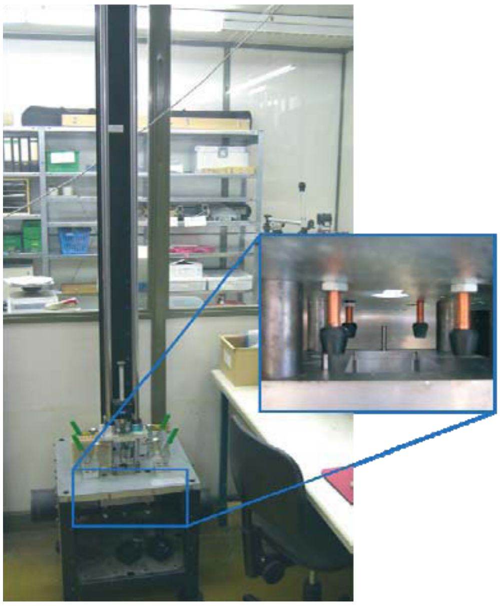


FIGURE 1. Drop weight tower

During the impact the contact force versus time is recorded by a load cell assembled at the impactor.

Figure 2 shows the contact force recorded during a low velocity impact with an impact energy of E = 25 J.

At a force of about 3.5 kN the measured curve has the first significant decrease. According to Schöppner [3] this represents the **D**amage **T**hreshold **L**oad (DTL). Here the first detectable laminate failures occurred. The further oscillation of the contact force up to its maximum load shows that there is additional damage in the laminate due to the impact.

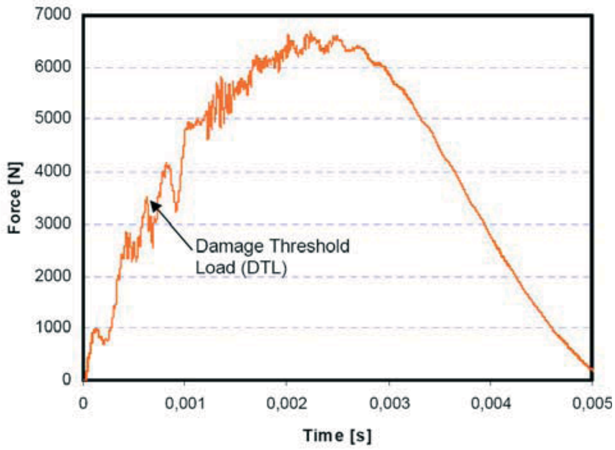


FIGURE 2. Contact force versus time during 40 Joule impact

2.2. Non Destructive Testing (NDT)

After impact the damage of the laminate can be evaluated by different NDT methods. It depends on the NDT method whether it is feasible to visualize all possible damages like broken fibres, matrix cracks or delaminations in the impacted laminate. As NDT method there is for example **C**omputer **T**omography (CT) or Ultrasound C-scan available.

CT gives explicit information about the laminate condition in each layer. It is a 3D method using X-rays for the inspection. By CT all defects can be evaluated, but it is a time consuming and expensive test method.

The ultrasound method gives integral information about the dimension and orientation of the damage in the impacted test sample. Ultrasound is currently the most popular one for non destructive evaluation of CFRP laminates in aerospace applications. In this work the ultrasound C-Scan method is used for the comparison of different preform architectures regarding the dimension of delaminations after impact.

2.2.1. Ultrasound C-Scan

In order to have another evaluation criterion beside the residual compression strength the ultrasound C-scan method was used in this campaign (see chapter seven).

Due to different impedances of air and solids water is applied as couple medium. By the water coupled ultrasound method in transmission mode different impedances in the laminate are detected. It is possible to visualize the impedance variation at a delaminated area graphically.

Figure 3 shows a 7x7 mm stitched carbon fibre test specimen after a 25 J and 40 J impact respectively. Depending on the impact energy the different dimensions of the delaminated areas can be seen. Beyond that the orientation of the defect can be visualized.

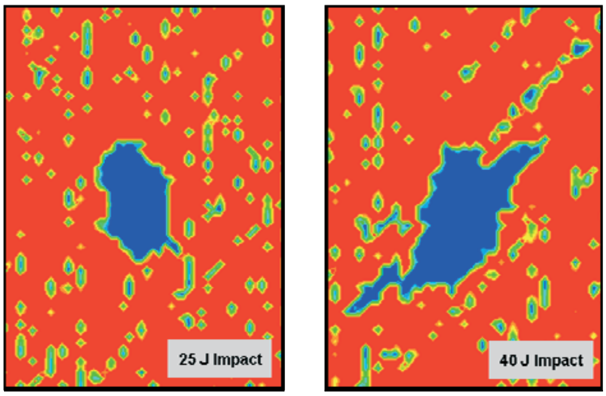


FIGURE 3. C-Scan of stitched carbon fibre samples after a 25 J and 40 J impact respectively

2.3. Determination of Residual Strength

As described in chapter one the residual compression strength is a measure for the damage tolerance of the tested material.

At the CAI-test the impacted specimen is compressed up to failure load. Figure 4 shows that the test samples are guided at the longitudinal sides. The guide tools are formed like a knife in order to minimize the friction between the tool and the test sample. A failure due to bending or a combined failure due to bending and compression stress can be avoided by this knife formed guide tools.

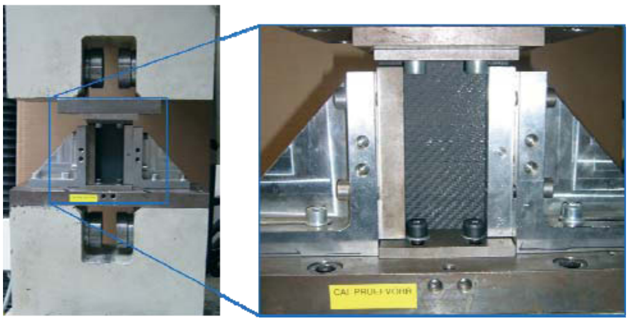


FIGURE 4. CAI-Test configuration

The CAI-tool is assembled to a standard test machine. In this measurement campaign a machine from “Schenk-Trebel” was used.

The testing machine closes with a velocity of v = 0.5 mm/min according to the test standards mentioned above.

Figure 5 illustrates that during the compression test the load-displacement diagram is recorded for the subsequent analysis of the maximum compression stress.

In order to evaluate the residual strength compared to the initial strength from each preform architecture several non impacted samples are tested, too.

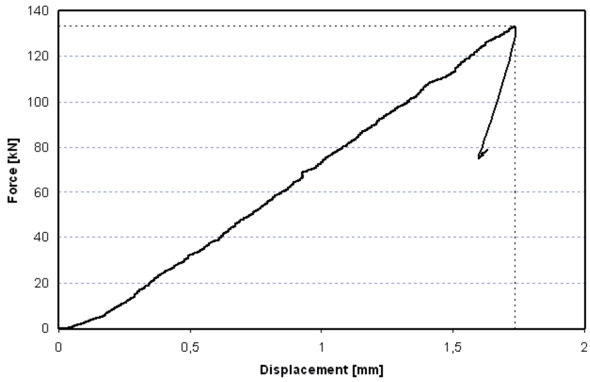


FIGURE 5. Load-displacement diagram of the CAI test

3. Z-REINFORCEMENT BY STITCHING

The introduction of fibres in the z-direction of a laminate increases the out-of-plane properties reasonably [4]. The single laminate layers are no more just bonded together by the matrix but also reinforced by the stitching yarn. Benefits are better damage tolerance, higher energy absorption and increased structural integrity.

Compared to other methods of z-reinforcement like e.g. the x-core technique, where cured carbon rods are pressed into a laminate, the two- and three-dimensional stitching technologies are the most flexible techniques in regard to component geometry, reinforcement material and process control.

In this work the tufting technology was used as stitching method. The stitching head is manipulated by a six axis industrial robot.

Tufting uses a single needle which penetrates the laminate and is pulled out again (compare figure 6). Due to the friction between the sewing thread and the laminate a loop remains within the material.

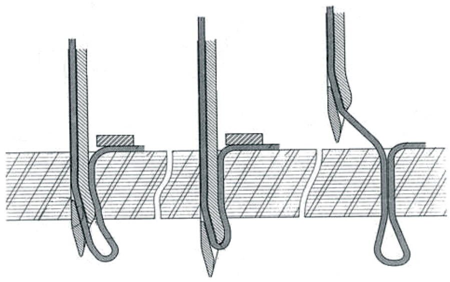


FIGURE 6. Tufting principle

In dry state this kind of stitching is not stable because there is no interlacing of the thread. During the impregnation and curing process the loops are bond to the laminate resulting in a structural z-reinforcement (compare figure 7).

For this work discussed here a Culimeta EC-9 68x3 S300 1383 (204 tex) e-glass stitching thread was used. The stitching patterns were 3x3 mm, 5x5 mm and 7x7 mm (stitch length x seam distance) with a loop length of 5 mm.

The seam quality was assured by logging the thread consumption ensuring sufficient loop length. The needle was a standard tufting needle with a rectangular cross section of 2 by 2 mm.

FIGURE 7. Tufting loops bonded to laminate after curing

4. TEST-MATRIX

The effects of different parameters on the damage tolerance were investigated in this project. For two different perform architectures the influence of the resin system and different stitch pattern were evaluated. As shown in figure 8 different levels of impact energy were applied on the several test samples.

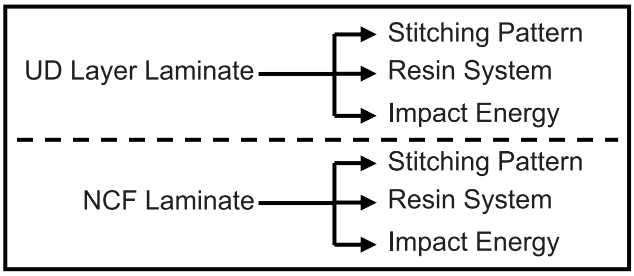


FIGURE 8. Parameter under investigation

Therefore all in all four parameters were varied during the experimental work package of this project - resin system, stitch pattern displacement, level of impact energy and the preform fibre architecture.

The preforms were infused with two epoxy resin systems in order to compare the influence of the matrix on the damage tolerance of stitched carbon fibre laminates as described above. The determined resin systems were RIM 235 from Hexion and LY 556 from Huntsman. For the infusion a **V**acuum **A**ssisted **R**esin **I**nfusion process (VARI) was used.

In order to vary the preform fibre architecture two different semi-finished products made of carbon fibre were used. It was a triaxial **N**on **C**rimp **F**abric (NCF) and a **u**ni**d**irectional (UD) layer laminate. The fibre orientations, the mass per area weight as well as the fibre specifications are shown in table 1.

	Orientation [°]	Material
UD	0/90	12k HTS, 800 tex Mass per area weight: 200 g/m^2
NCF	-45/0/+45	12k HTS, 800 tex Mass per area weight: 823 g/m^2

Table 1. Material configuration

The lay-up for the UD layer laminate was $[0°/90°]_{20S}$ and for the NCF $[-45°/0°/+45°]_{2S}$ to realize the thickness required in the test standard.

In the scope of this work only square stitch pattern were investigated. In table 2 the tested stitch pattern for the two semi-finished products are shown.

	Stitch Pattern		
UD	3x3	5x5	7x7
NCF	3x3	5x5	7x7

Table 2. Stitch pattern

The samples were impacted with two levels of energy; E_1 = 25 J and E_2 = 40 J. Beyond that as described in chapter 2.3 from each configuration non impacted specimens are tested for the determination of the initial strength.

For each preform and resin combination eight specimens were manufactured and tested. In total 96 test samples were used for this measurement campaign thus a qualitative as well as a quantitative conclusion regarding damage tolerance for different carbon composite materials combinations can be given.

5. SPECIMEN MANUFACTURING

The manufacturing process chain of the CAI specimens comprises the following steps:

As first blanks of 400 by 600 mm were cut out of the semi finished products and stacked according to the lay-up as described in chapter 4.

Then this lay-up was stitched fully automated on a 3D-stitching machine using the tufting technique with the different parameters for stitch length and seam distance corresponding to the test matrix shown above.

The resin impregnation was done with the vacuum assisted process (VARI) using either the resin system RIM 235 or LY 556.

After the impregnation the laminates were cured and tempered in a hot air oven according to the manufacturers' specifications.

Finally the CAI specimens were cut out of the cured laminates using a diamond saw with tolerances according to DIN EN 6038.

6. TESTING

After the manufacturing of the test samples, see chapter five, the specimen were investigated on their particular damage tolerance. Therefore each sample passed through the whole testing process chain described in chapter two.

After impacting the test samples with E_1 = 25 J and E_2 = 40 J were tested non-destructively by ultrasound subsequently. The ultrasound C-scans were analyzed in order to determine the size and orientation of the delaminated area inside of the carbon fibre laminate.

After the compression test the recorded load-displacement diagrams were used to calculate the residual compression strength of the tested materials.

Together with the data achieved by the ultrasound test and the residual compression strength it is possible to determine the damage tolerance of the tested material regarding stitch pattern, resin system, fibre orientation and preform architecture.

7. ANALYSIS OF DATA

The residual strength and the area of delamination due to the impact are the two aspects which are regarded for the analysis of the test results.

Stitching does not only increase the out-of-plain properties of a laminate but in the same step it can also decrease the in-plane properties due to disruptions of the ideally straight fibre orientation. The degree of in-plane properties loss depends strongly on the fibre architecture of the material [5], [6]. As showed in Figure 9 this effect is not significant in case of the two materials used in this study.

Only in the configuration of the LY 556 and +45/0/-45 NCF the influence of stitching density can be seen. The denser the stitching pattern the lower the in-plan properties.

The difference between the strength is less than 5,5%. For all other material combinations of the study this effect does basically not exist. Therefore the initial strength is not related to the stitching pattern in this measurement campaign.

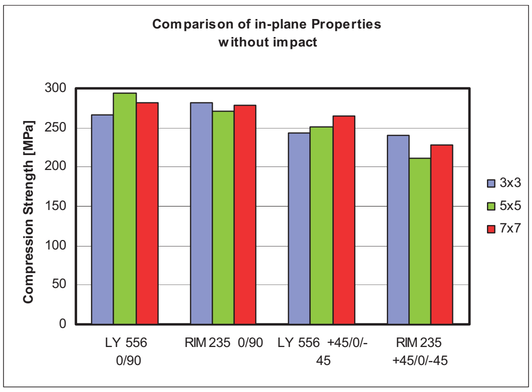


FIGURE 9.

7.1. Delamination area

To quantify the delaminated area of the laminate the C-scan images were first converted into black and white colour mode and afterwards the area was determined with standard digital image analysis software (compare Figure 10).

The small dark spots which can be seen in the left image are due to the stitching yarn. It is caused by the different impedances of the stitching thread and the carbon composite material[7].

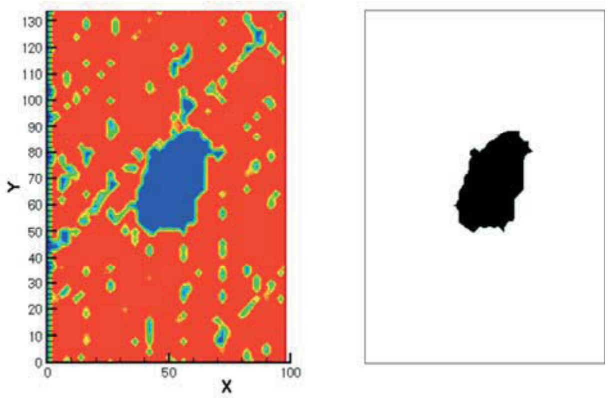


FIGURE 10. Determination of delamination area

The software calculated the percentage of the delamination related to the complete size of the image and the specimen respectively, which was identical for all C-scans.

As expected the damaged area of the laminate increases with increasing impact energy [8] and lesser stitching density thus lesser z-reinforcement [9], [10] in nearly all cases (compare Figure 12).

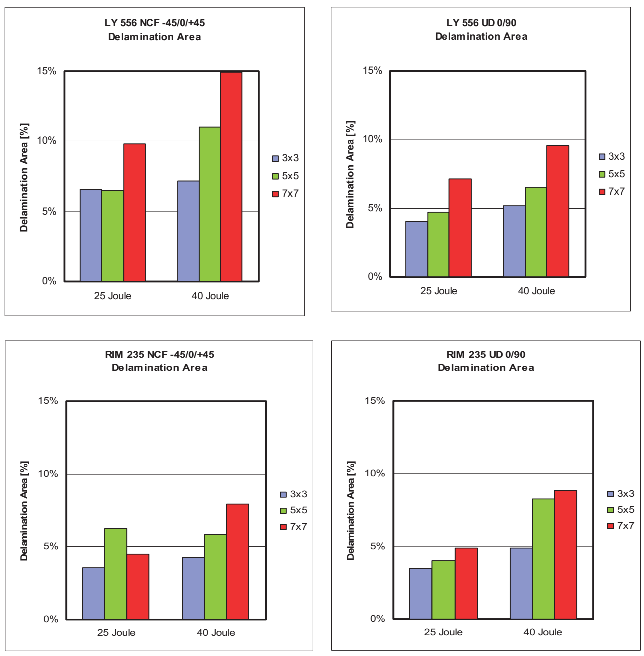


FIGURE 11. Delamination area

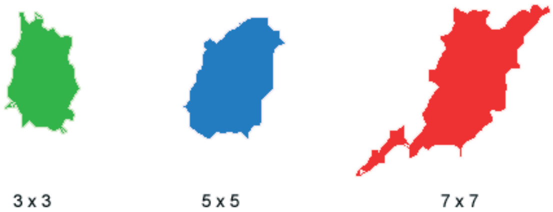


FIGURE 12: Comparison of delamination depending on stitching density with impact energy of 40 J

Only the average value of the specimens RIM 235, +45/0/-45 NCF, 5 x 5 with an impact energy of E_2 = 25 J are not in accordance with this trend and can be regarded as outliers.

In case of the specimens made of +45/0/-45 NCF those fabricated with the LY resin system show a considerably larger area of delamination than their counterparts made with the RIM system (compare figure 11, left).

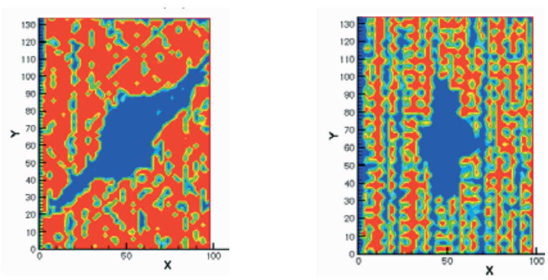
In contrast the samples made of 0/90 UD layer laminate the delamination areas are all nearly on the same level. There is no influence of the used resin system obvious (compare figure 11, right).

These facts state that the damage tolerance strongly depends on the fibre architecture of the preform material architecture. The influence of the resin system is on a lower order.

Beyond the delamination area the ultrasound C-scan images show that there is a relationship between the fibre angle of the preform and the delamination propagation as well.

Especially the samples which where impacted with the higher impact energy E_2 = 40 J show, that the shape of the delaminated area corresponds to the fibre architecture of the laminate. The damage shape in the +45/0/-45 NCF specimens is orientated along the +45 or -45 fibre orientation (compare figure 13 left).

In case of the 0/90 UD lay-up the shape of the delamination is mainly in the zero degree fibre direction. The delamination in 90° fibre direction is on a lower level (compare figure 13 right). At lower impact energy levels and / or higher stitching density the shape of the delamination area is roughly circular, see for example figure 3 left.



+45/0/-45 0/90

FIGURE 13. Delaminations following fibre orientation

7.2. Residual strength

Regarding the residual strength after impact a similar tendency can be observed as described in respect to the delamination area. Specimens with a dense stitching pattern show higher strength compared to those with lesser stitching density. Thus smaller delaminations results in higher residual strength (compare e.g. figure 14 top and figure 11).

The residual strength of the samples is comparable between the two resin systems. In case of the +45/0/-45 NCF material, specimens fabricated with the LY 556 resin system show in average 10% better properties than their RIM 235 counterparts.

This effect is not clearly visible in the case of the samples made of 0/90 UD layer laminate. Here the two resin systems show more or less the same damage tolerance performance in carbon composite applications.

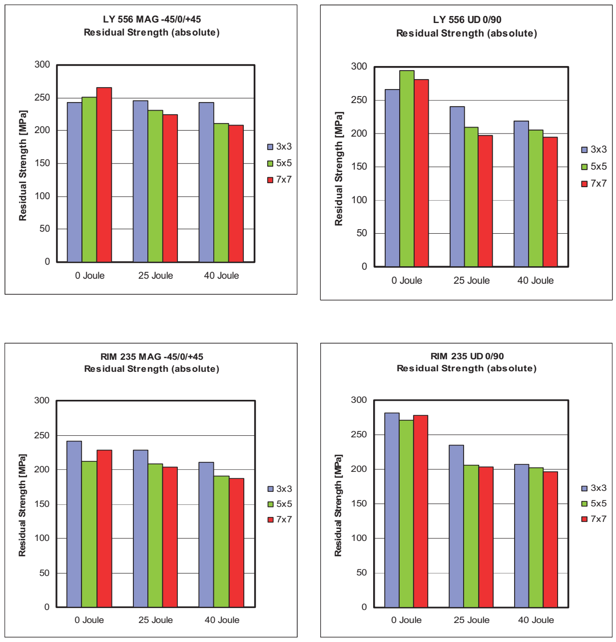
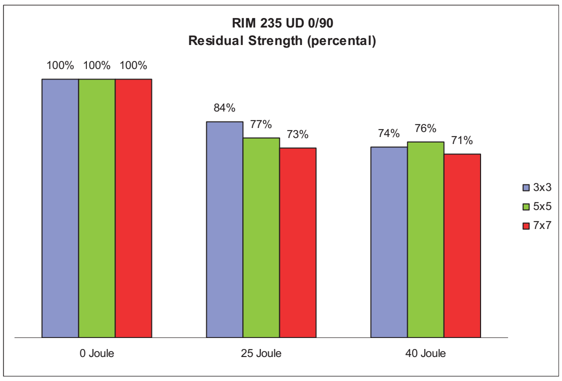


FIGURE 14. Residual strength

The reduction of the residual strength of the laminate depending on the impact energy is significantly higher for the UD layer laminate. This can be seen by comparing the two diagrams of figure 15 which show the residual strength of the impacted specimens in percentage of the not impacted ones (impact energy E_0 = 0 J).

The UD layer laminate specimens suffer a decrease of approximately 25% im comparison to around 10% in the case of the +45/0/-45 NCF laminate. Thus the latter ones fibre architecture shows a better damage tolerance. This effect is independent of the impact energy as well as of the stitch pattern.

The scenario with an impact energy of E_2 = 40J causes in the worst case a reduction of the residual compression strength of 29% for the UD layer laminate and only 17% for the +45/0/-45 NCF material. The best case values are 24% (UD layer laminate) and respectively 9% (+45/0/-45 NCF) for comparison.



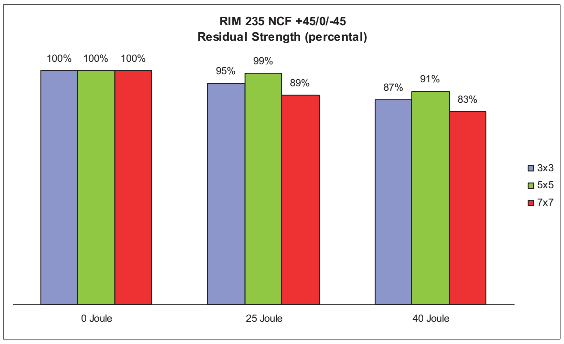


FIGURE 15. Reduction of residual strength due to impact

Therefore it can be seen that in contrast to the resin system the damage tolerance behaviour is strongly depend on the preform fibre architecture

8. INTERPRETATION OF DAMAGE TOLERANCE

It could be shown by the tests of this work that mainly four effects have an influence on the residual compression strength and the damage tolerance respectively. Those are the preform material architecture, the resin system, the stitching pattern and the orientation of the damage.

The variation of the stitching pattern has the largest influence on the damage tolerance. With a high amount of z-reinforcement the delamination area can be reduced and therefore the residual compression strength can be raised.

Additionally it was shown that the preform fibre architecture has also a large influence on the damage tolerant behaviour of carbon fibre reinforced composites. Due to the diverse fibre orientations in the laminates and their different singly ply weights other failure mechanism and therefore different damage tolerance behaviour can be observed.

Which resin system was used turned out to have a minor influence on the damage tolerance behaviour in comparison to the effect mentioned above. This is in accordance with Wagner [11]. The reason for the variation caused by the matrix can be seen in the different fracture toughness properties of the resin systems.

The influence of the damage orientation can be seen by comparing the two specimens shown in figure 13. Although the delaminate area and the crack length of the test sample made of +45/0/-45 NCF is larger, the residual strength is higher compared to the one of UD layer laminate sample. Obviously the crack orientation has an influence on the failure mechanism. In case of a compression loading it is important that there is a support for load carrying 0°-fibres. Thus fibre buckling can be avoided.

The large delamination of the +45/0/-45 NCF is orientated in 45° direction. Therefore the 0° fibres were less significant affected. The free unsupported length in compression direction is much smaller for this specimen compared to the UD layer laminate one. Here the unsupported length within the delamination area is approximately 30% longer.

9. SUMMARY

In the scope of this work two materials with different fibre architectures have been investigated on their damage behaviour. The parameters were two resin systems, three different stitching patterns as well as three impact energy levels.

It was shown that the variation of the stitching pattern has the largest influence on the damage tolerance behaviour. Higher amount of z-reinforcement meaning a dense stitching pattern leads to higher residual compression strength values.

Also the preform architecture has a significant influence. The performance reduction due to impact is higher in case of a UD layer laminate compared to the +45/0/-45 NCF material.

In regard to the resin system it was observed that their impact performance was nearly equal.

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