High Speed Impact Testing of Thermoplastic Composite Plates

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ABSTRACT

This paper presents the methodology and results for ballistic impact testing of thermoplastic composite materials. Ten different materials are investigated. The impact behavior of Aluminum 6082 is used as a reference to compare the results. The impact tests are performed with a gas cannon. Force – time, displacement – time as well as velocity data are recorded. Analytic suggestions for the calculation of the penetration speed of the materials are compared with measured results. It can be seen that it is possible to calculate the penetration speed within a certain percentage of the measured value. Also, the absorbed energies during the penetration process are compared. The results show that glass fiber composites have a better impact material behavior than carbon fiber-reinforced composites (CFRP). Thermoplastic matrix systems are a cheap option for composites but they do not have a significant better high speed impact and damage behavior than duroplastic resins.

INTRODUCTION

Conventional resp. standard duroplastic composite structures are known for their advantageous weight specific strength and stiffness. On the other hand, these materials are very sensitive in terms of transversal impact loads due to their brittle behavior. Impact loads are one of the dimensioning load cases for light weight structures within the aerospace industry (e.g. birdstrike, hailstrike). Similar questions can be found in other industries, like train- or automobile, too. Within this paper the behavior of thermoplastic composite materials under high speed impact loading is shown. Tests with an air pressure cannon are performed to obtain data and findings about the impact behavior of the investigated composites. Material samples are impacted at various speeds to perform tests with varying impact energies, which leads to various damage behavior. The aim is to obtain the speed and energy, at which a material sample perforates. These results (force – time, speeds, and energies) are compared and investigated, whether thermoplastics show a better ballistic impact behavior than duroplastic resins. The testing method and the final results are shown and explained within this paper.

For a better acceptance of composite materials in a lot of application areas it is important to reduce the costs of this material. A cost reduction can be achieved through the use of thermoplastics. Due to this fact the application area of thermoplastics should be expanded. An important application area for helicopters are the impact burdened parts. In addition the performed tests are very cost intensive. Due to this, a less cost intensive way to determine the perforation speed of composites is investigated, too.

The advantage of thermoplastic matrix systems in respect to duroplastic systems is the higher fracture toughness and ductility. This leads to the fact, that thermoplastics should be able to absorb more energy (Ref. 1). On the other hand, the material behavior is strain rate dependent with an increasing embrittlement at high impact velocities. Strong differences in the material behavior can be seen at low velocity impact tests (Ref. 2). Due to the inertia and the shockwave the physical behavior at high speed impacts is strongly different.

Godwin (Ref. 3) performed impact tests on thermoplastic composites. He detected that due to the increasing embrittlement thermoplastic composites do not have a better impact performance than duroplastic composites at high velocity impacts. Appelsved (Ref. 4) for example studied the material behavior under tension and compression. Nossol (Ref. 5) et al. investigated the dynamic behavior of thermoplastics with low energy impacts. Boccaccini (Ref. 6) determined, that the structural damage of impacts is local and due to this, the components keep some of their bearing capacity. Abrate (Ref. 7) gives a good overview about impact on composite structures. The ballistic impact behavior of new thermoplastic composites is investigated within this study and compared with duroplastic composites and aluminum.

Other advantages of thermoplastics are for example the easy use, easy storage, easy forming, easy welding and the possibility of recycling.

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IMPACT TESTING OF THERMOPLASTIC COMPOSITES

Theoretical Approaches for High Speed Impact Testing

Abrate (Ref. 7) gives two definitions of ballistic impacts. The first definition is, when the projectile perforates the sample, it is a ballistic impact. This is a vague definition. Therefore, the second one is used to define a ballistic impact within this paper. If the impact is stress wave – dominated, it can be called ballistic impact. He points out that a stress wave – dominated impact occurs for common epoxy matrix systems beyond approx. 10 - 20 m/s impact speed. All conducted tests are far beyond this level. Due to that fact the assumption is made that all performed tests are ballistic impacts.

Guoqi et al. (Ref. 8) perforated Kevlar – polyester laminates with high velocity and quasi – static impact tests. They received the following principal diagram, when they plot the force – displacement curve (Figure 1). This curve can be subdivided in four parts, marked in Figure 1. It is shown within this paper, whether performed tests have a similar expected behavior.

![Figure 1: "Load versus indentor displacement in static tests" (Ref. 7, 8)]

Materials

Duroplastic materials have a weakness under impact loads. The improvement of CFRP and its impact resistance as well as the reduction of material- and design costs would lead to a higher acceptance of this material in a lot of applications. A better impact performance can be reached with ductile fibers, nano matrix modifications and thermoplastic composite material. A better performance means that the material can withstand impact loads with a lower structural weight resp. can withstand loads despite an impact damage. The focus in this paper is on thermoplastic resin and its material behavior during high speed impact.

Different composite materials are tested. A series of tests is also performed with aluminum as a metallic reference. In total, 10 series are performed with 82 shots on different material samples. The investigated thermoplastic resin systems are “Polyetheretherketone” (PEEK) as well as “Polyamide 6” (PA6), with “FAB” referring to woven fabric and “UD” referring to unidirectional composites, respectively. Table 1 shows the tested sample materials. Wedekind (Ref. 9) shows that manufacturing conditions have a small influence on thermoplastic laminates within a certain range and are neglected within this study.

<table>
<thead>
<tr>
<th>Material</th>
<th>Number of performed tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al 6082</td>
</tr>
<tr>
<td>2</td>
<td>S2 – GF/EP FAB</td>
</tr>
<tr>
<td>3</td>
<td>CF / EP FAB</td>
</tr>
<tr>
<td>4</td>
<td>CF / EP UD</td>
</tr>
<tr>
<td>5</td>
<td>CF / PA6 UD</td>
</tr>
<tr>
<td>6</td>
<td>CF / PA6 FAB</td>
</tr>
<tr>
<td>7</td>
<td>CF / PA6 UD + mod</td>
</tr>
<tr>
<td>8</td>
<td>CF / PEEK</td>
</tr>
<tr>
<td>9</td>
<td>GF / PA6</td>
</tr>
<tr>
<td>10</td>
<td>CF / PA6 UD (thin)</td>
</tr>
</tbody>
</table>

The materials with the numbers 1, 5, 7 and 10 are used for pre – test studies. Within these studies, test shots were performed for calibration of the measurement systems like piezo elements and the light barrier as well as for adjustment of the high speed camera. All other test series are performed as full tests, with the adjusted measurement equipment.

The panels were fabricated by SGL Group and Airbus. The process is not further described within this paper. The average thickness of the tested samples is shown in Table 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Average Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Al 6082</td>
<td>2.56</td>
</tr>
<tr>
<td>2 – S2 – GF/EP FAB</td>
<td>2.15</td>
</tr>
<tr>
<td>3 – CF / EP FAB</td>
<td>2.57</td>
</tr>
<tr>
<td>4 – CF / EP UD</td>
<td>2.17</td>
</tr>
<tr>
<td>5 – CF / PA6 UD</td>
<td>2.53</td>
</tr>
<tr>
<td>6 – CF / PA6 FAB</td>
<td>2.35</td>
</tr>
<tr>
<td>7 – CF / PA6 UD + mod</td>
<td>2.68</td>
</tr>
<tr>
<td>8 – CF / PEEK</td>
<td>2.36</td>
</tr>
<tr>
<td>9 – GF / PA6</td>
<td>2.35</td>
</tr>
<tr>
<td>10 – CF / PA6 UD (thin)</td>
<td>2.42</td>
</tr>
</tbody>
</table>

Experimental investigations

The following tests are performed within the research project: Charpy impact tests, material damping behavior tests and impact- resp. damage resistance test. Charpy and damping tests are performed by Siemens AG and are not further described within this paper. The results of the Charpy impact tests are compared with the penetration speeds (resp. energies) of the ballistic impact tests.

For the impact tests a gas cannon is used. This test setup consists of three main parts. The air pressure tank, the
acceleration pipe and the sample holder. The velocity of the projectile is measured with a light barrier. The force is measured with four piezo elements, embattled behind the sample holder. Every single one can measure up to 20 kN. The signals are combined with a summation box and recorded with the software Catman Easy AP. The acceleration pipe as well as the sample holder are shown in Figure 2.

![Figure 2: Acceleration pipe and sample holder](image)

The impact tests are performed to gain knowledge about the material behavior under high speed resp. high energy ballistic impacts. For a comparability of the results, the setup is designed for testing standardized specimen. All specimens have a length of 300 mm and a width of 200 mm. Various thicknesses can be investigated. An inner and an outer wood frame are used to adjust the sample holder for the varying thicknesses of the samples. A marble, made of glass, is used as the projectile. It has a diameter of 35 mm and a weight of 55 g. The impact speeds vary between 40 – 120 m/s. This leads to impact energies between 44 J and 396 J. Thermal exposure is not considered within the performed tests.

The marbles are placed into a sabot for acceleration. The sabot is placed in the pipe inlet and accelerated with air pressure. The sabot is made out of PU foam. Different pressures lead to different velocities, which means varying impact loads and energies. The marble is separated from the sabot at the end of the acceleration pipe with an interceptor. Photocells measure the speed of the marble thus precisely giving the impact energy. A high speed camera is used to capture the impact as well as to measure the displacement of the projectile. This as well enables additional speed measurement for redundancy. The impact speed can be adjusted with the air pressure in the tank. A digital manometer is used for the adjustment. The sample clamping principle is taken according to previous work by Kim (Ref. 10). The projectile is shown in Figure 3. The characteristics of the test setup can be seen in Table 3.

![Figure 3: Impactor](image)

### Table 3. Characteristics of the air pressure cannon

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>English</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample length</td>
<td>0.984 ft</td>
<td>300 mm</td>
</tr>
<tr>
<td>Sample width</td>
<td>0.656 ft</td>
<td>200 mm</td>
</tr>
<tr>
<td>Cannon Length</td>
<td>14.4 ft</td>
<td>5.0 m</td>
</tr>
<tr>
<td>Cannon Height</td>
<td>4.92 ft</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Max Diameter Impactor</td>
<td>0.164 ft</td>
<td>50 mm</td>
</tr>
<tr>
<td>Max Speed</td>
<td>671.1 mph</td>
<td>300 m/s</td>
</tr>
</tbody>
</table>

For a detailed analysis of the test results the residual velocity is also needed. Within the performed tests it was not possible to measure the residual velocity if the projectile perforates the sample, due to the picture frame size of the high speed camera.

The test samples are fixed in a picture frame like target device on a massive steel frame. Between the target and the frame are piezo elements for force measurement. The data from four piezo elements is summated and illustrated in the following force – time diagrams. The different diagrams show the force – time behavior for aluminum, CFRP and glass fiber – reinforced plastics (GFRP) with duro – resp. thermoplastic matrix systems.

### TEST RESULTS AND DISCUSSION

#### Test Results

Force – time data are received. The different impact material behavior will be compared with one standard material, e.g. Aluminum 6082. Figure 4 shows the force – time curves for aluminum as well as CFRP and GFRP with epoxy resin. After 800 time steps a small deflection occurs. The pressured air and its suction effect generates this deflection. The deflection with negative values is produced by the wave through the material due to the impact. The diagram shows the typical and expected impact – and shock wave behavior. A further oscillation can be seen, but after 2000 time steps it can be neglected. It is clearly visible that the force maximum for carbon composites is about 50% of the aluminum maximum. The GFRP sample shows an impact behavior with a higher force peak.
A similar behavior can be seen in Figure 5. This diagram shows the force time behavior for composites, made out of glass – and carbon fibers, with thermoplastic resin.

Within Figure 6, the force – time behavior for aluminum and CFRP, independent from the matrix configuration, are compared. It can be seen that the matrix system (duro – or thermoplastics) does not have any influence on the impact behavior of CFRP within the performed tests.

On the other hand, Figure 7 includes the GFRP impact data. It can be seen that this material have a better impact performance compared to CFRP, independent from the matrix system.
Within all diagrams two different oscillations can be seen, a low and a high frequency oscillation. The low one comes from the oscillation of the sample holder itself. For further tests the sample holder will be stiffened to reduce this oscillation. The other oscillation is the high frequency one. This is the vibration of the sample itself.

Compared to the impact behavior of aluminum it can be said that the composite behavior is more brittle. After the impact, there is a small dent visible, and there are also cracks in the laminate. Impacts with a relative low energy show only small dents, the plastic deformation is low. But the damage on the non-impacted sample side (backside) is clearly visible in almost all tests.

Table 4 illustrates the top and bottom views of the perforated specimens. All shots were performed slightly above the perforation speed. The development of cracks seems independent from the fiber direction and type of material (UD, Fabric, Epoxy, PA6, PEEK). Only material 4 (CF EP UD) and the CF PA6 UD (thin) – (Number 10) show a different damage. Due to the fiber orientation of the first
and last layer (+45°) of CF EP UD, the damage seems really large. But the real penetration hole is in the middle of the plate. Only the last layer shows the large damage. All other materials have a similar crack length in horizontal and vertical direction. The material number 10 shows a large crack in horizontal direction. Whole areas are broken out of the sample. The whole damage is larger than the other penetration damages. To see further damage like delamination within the samples, an ultrasonic (C-scan) investigation has to be done.

Table 4: Penetrated specimens

<table>
<thead>
<tr>
<th>Material</th>
<th>Alu 6082</th>
<th>S2 Glas</th>
<th>CF EP FAB</th>
<th>CF EP UD</th>
<th>CF PA6 UD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (J)</td>
<td>300 J</td>
<td>216 J</td>
<td>114 J</td>
<td>127 J</td>
<td>151 J</td>
</tr>
</tbody>
</table>

Top view

<table>
<thead>
<tr>
<th>Material</th>
<th>CF PA6 FAB</th>
<th>CF PA6 UD mod</th>
<th>CF PEEK</th>
<th>GF PA6</th>
<th>CF PA6 UD / thin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (J)</td>
<td>161 J</td>
<td>193 J</td>
<td>149 J</td>
<td>317 J</td>
<td>132 J</td>
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</tbody>
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Top view

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Bottom view

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<th>CF PA6 UD mod</th>
<th>CF PEEK</th>
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Bottom view

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<th>CF PA6 FAB</th>
<th>CF PA6 UD mod</th>
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Bottom view
Force – Displacement

Figure 1 presents a simple, theoretical force – displacement behavior during impact. Figure 8 shows a measured force – displacement behavior of the CF PEEK material. The first area is a steady increase with the displacement. Small, local decreases could be indicators for a first damage within the material, e.g. matrix cracking. Another possible explanation is the stress wave propagation within the specimen. Due to the non – perfect impact into the middle of the plate, the four piezo sensors do not receive a signal at the same time. Due to that delay, fluctuations of the force are possible. This effect needs a further investigation at the used test setup. A force peak can be seen and after that, the force decreases. The described wave propagation can explain the second force peak. After that, the force decreases suddenly. Due to the fact that the measurement of the forces and displacements need a further investigation, further force – displacement behavior are not shown.

![Figure 8: Force – Displacement](image)

Comparison of penetration velocities

The speed, at which the impactor penetrates the test sample \( (V_p) \) can be estimated with the energy equivalence approach. The Charpy impact test results are needed for this approach. The speed can be calculated with this following formula:

\[
V_p = \sqrt{\frac{E_c}{E_{alu}}} \cdot V_{alu} \tag{1}
\]

\( E_c \) is the Charpy energy of the test sample material, \( E_{alu} \) is the Charpy energy of aluminum and \( V_{alu} \) is the measured perforation speed of aluminum.

On the other hand, there is a classic formulation to calculate the penetration speed, the FAA penetration equation (Ref. 11):

\[
v_{50} = \frac{\sqrt{2LCS \cdot t^2}}{m \cos^2 \Theta} \tag{2}
\]

\( L \) is the circumference of the impactor, \( C_s \) is an empirical value for the shear strength, \( t \) is the thickness of the specimen, \( m \) is the mass of the impactor and \( \Theta \) is the impact angle. This angle is assumed to be 0°.

These two analytic approaches are compared with the real measured penetration speed of the different materials. This is visualized in Figure 9. It can be seen that the first equation leads to good results compared with the measured velocities. Almost all values are within the fault measurement. The second equation has less good results. This comes from the fact that this conservative equation is valid for penetration of metallic components with an isotropic material behavior. For material 3, \( C_s \) was not determined.
It has to be pointed out that the performed tests are not fully statistically relevant due to the low number. The perforation speed $V_{50}$ is defined as that speed, at which 50% of the samples are perforated. But within the test series, the speed was determined once and was thereafter reduced. For first material tests it was important to determine one perforation speed and have a value to compare between the different layups and materials as well as to obtain the damage behavior for different impact energies.

As mentioned before, all tests are tracked with a high speed camera. All tests are evaluated. It is difficult to get the exact moment, when the impactor hits the specimen, due to the frame rate of the video. The videos are recorded with 15000 frames per second (fps). A higher frame rate is not possible, because the window area would be too small for a precise tracking of the impactor. Due to this fact, 15000 fps are used.

Another vagueness for tracking the way of the impactor is the zone, when the impactor disappears behind the frame of the sample holder. Automatic tracking software shows problems within this area. A spline interpolation is needed to adjust a curve in the area with the uncertain data. The disappearance of the impactor without penetration of the specimen can be seen in Figure 10.

![Figure 9: Comparison of penetration speeds](image-url)
Determination and comparison of absorbed energies

Abrate (Ref. 7) points out the following formula for calculation of the absorbed energy by the laminate:

$$ U_p = \frac{1}{2} m(v_i^2 - v_r^2) $$  \hspace{1cm} (3)

Up is the penetration energy, m the mass of the projectile, v_i the initial speed of the projectile and v_r the residual speed.

One difficulty was the measurement of the residual speed of the projectile after the perforation of the sample. For a first estimation, the last measurable speed with the high speed camera is assumed to be the residual speed. This indicates a systematic error in the measured values. They can only be used for comparison between the tests, not for comparison with other tests. The energy, absorbed by friction, is also neglected.

Figure 11 illustrates the absorbed energy during impact penetration, calculated with the formula mentioned above. As expected, GFRP and aluminum show the highest energy absorption values. The best CFRP material is carbon fiber with PA6 resin and a modification. All other materials have more or less the same energy absorption value.

The problem with the illustration in Figure 11 is that the thickness and the density of the material samples are neglected. Therefore, the values for the absorbed energies are divided by the thickness of the material samples. The new diagram can be seen in Figure 12. Independent from the matrix system, GFRP samples have the highest specific energy absorption. For S2 glass the specific energy absorption is 10% higher than that of aluminum, GF PA6 has 24% higher specific energy absorption. The best carbon fiber composite regarding energy absorption is the material number 7, CF PA6 unidirectional modified.

A way to evaluate the impact behavior in terms of lightweight design is to divide the measured, absorbed energies by the material density. The results are presented in Figure 13. It can be seen that with this point of view, the CF PA6 unidirectional modified material shows the best impact behavior. Glass fiber composites have a good behavior compared to aluminum, too.
**Figure 11:** Absorbed energy during penetration

**Figure 12:** Absorbed energy divided through sample thickness
Figure 13: Absorbed energy divided through material density

Aluminum as well as GFRP materials, independent of the matrix system, show the best impact behavior, when the absorbed and specific absorbed energies are compared. A promising material combination for strong impact resisting material would be aluminum and GFRP. Airbus is using such material combinations within the A380 airplane, for example. It is called GLARE.

APPLICATION OF RESULTS

Possible applications for helicopters can be seen in first sight for areas prone to impact damage where increased resistance compared to standard composites with thermoset resins would be an advantage. The canopy structure affected by bird strike is an example for these. Others examples can be engine inlet area or cowlings at upper deck structure as well. Similar to fixed wing aircraft door surrounding structures and cargo compartment area may point out a senseful area of application for newly developed thermoplastic composite systems with high impact tolerance.

CONCLUDING REMARKS

The use of thermoplastic composites can lead to a cost reduction compared to conventional epoxy based matrix systems and a wider acceptance of this material. High speed impact tests on thermoplastic composite materials are performed within this study to investigate the possible application of thermoplastic composites at impact burdened structures. Ballistic impact tests are performed with a gas cannon on material samples with 200 x 300 mm.

In conclusion it can be said that there is no difference in the ballistic impact behavior between thermo- and duroplastic composite materials. Thermoplastics are just as suitable as duroplastics for impact burdened structures.

It is shown that the maximum forces during high speed impact and the absorbed energies are independent from the matrix system. GFRP and CF PA6 modified have the highest specific energy absorption rates. A promising material combination with a good impact resistance would be aluminum with glass composites, also known as GLARE. With a thermoplastic matrix system, this material combination could lead to good impact behavior in critical areas around the helicopter and other transport systems.

The FAA penetration equation does not lead to good results for the estimation of the penetration speed for the tested materials. A theoretical approach via the measured Charpy energy shows good results for the perforation speed compared to the measured speeds. This approach needs a further investigation, because it could be a cost saving possibility to determine the perforation speed without extensive ballistic impact tests with a gas cannon.
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