# EXPERIMENTAL INVESTIGATIONS ON THE IMPACT BEHAVIOR OF WOVEN THERMOPLASTIC GLASS FIBER-REINFORCED LAMINATES

F. Schimmer[1], N. Motsch[1] and J. Hausmann[1]

[1]Institut für Verbundwerkstoffe GmbH, 67663 Kaiserslautern, Germany
Email: florian.schimmer@ivw.uni-kl.de, Web Page: http://www.ivw.uni-kl.de/

**Keywords:** Low velocity impact, barely visible impact damage, woven thermoplastic glass fiber-reinforced laminate, hot/wet testing

**Abstract**

This experimental study contributes to an enhanced understanding of damage mechanisms of thermoplastic laminates under impact loading. For this purpose, low velocity impact tests of quasi-isotropic woven glass fiber-reinforced polyamide 66 plates were performed under varying environmental conditions. The force-time characteristics show no damage threshold load for all specimens, which indicates the inhibition of pronounced delaminations. By means of backlight analyses, narrow circular-shaped damaged areas for dry and humid conditioned specimens are identified, whereas the damaged areas of the dry specimens are larger. In contrast, hot/wet specimens show elongated damaged areas with more distinctive matrix cracks and fiber breakage on the specimen surfaces. Since the polyamide matrix is loaded beyond its glass transition temperature in case of the hot/wet specimens, changed force-time characteristics and a significantly higher impactor indentation on the specimen surfaces are present.

## 1. Introduction

In contrast to superior in-plane properties of fiber-reinforced plastics (FRP), the through-the-thickness material behavior is mainly limited by the matrix properties. This leads to an enhanced susceptibility to impact loading perpendicular to the component surface. While metallic components show a distinct plasticity on their surface, damages of FRP mainly occur within the laminate. Thus, external visual inspections of impact events on FRP are only possible through skilled personnel. For the exact identification of impact damages, expensive and time-consuming non-destructive testing is necessary (e.g. ultrasonic analysis).

Structural damages of FRP structures in aviation industry are inevitable. They can occur during maintenance (e.g. tool drop, collision with vehicles) or during service (e.g. runway debris, bird strike, hail, burst tire, collision with vehicles, failure of rotating machinery). As a result of the lack of knowledge about the material's impact behavior and the poor external visibility of impact events, a damage tolerant design has been established for years in aviation industry. Guaranteeing safe flight conditions, at least between two scheduled maintenance intervals of an aircraft, a robust component design is necessary [1]. This design philosophy requires that all affected structural components sustain their design loads (ultimate load, UL) despite a pre-damaged state. These pre-damages, better known as Barely Visible Impact Damage (BVID), represent the minimum impact energy where a structural component has to sustain UL. The BVID energy threshold is not standardized. Depending on the aircraft manufacturer and the aviation safety authority, different criteria are applied. In most cases, a plastic indentation at the impact position (e.g. $t_{pl}$ = 0.3 mm) or the external impact visibility from a defined distance (e.g. $a$ = 1 m) are used [2].

In order to reduce impact damage, toughened epoxy resins are used as state of the art matrix material in aviation industry [1]. In recent years, few airframe structures have been manufactured with a thermoplastic matrix, aiming at cost reduction for material storage as well as for manufacturing, joining and recycling processes. In literature, opposing statements on the comparison of damage tolerance of thermoset and thermoplastic composites are found [3,4]. However, the same fail safe design limits are applied, since they are generally grouped into polymer matrix composites [5]. This is a consequence of an existing lack of understanding of damage patterns under impact loading, especially for thermoplastic composites. Consequently, this study aims at contributing to an improved understanding of damage mechanisms of thermoplastic laminates. Therefore, two conventional constituents, namely a woven glass fiber fabric and a thermoplastic polyamide matrix (GF-PA66 laminate), are used.

## 2. Test preparation

In order to guarantee maximum comparability of the test results, test preparation played a major role. Therefore, the same material batches as well as manufacturing and test procedures were applied. Since a polyamide matrix is generally known for its comparably high water absorption capability and low glass transition temperature, specimen moisture and specimen temperature are identified as key parameters for the evaluation of mechanical impact properties. Consequently, defined specimen moisture and temperature properties were set to represent different environmental conditions.

### 2.1. Materials

All specimens were cut out of plates manufactured in an autoclave process. Therefore, a twill weave glass fiber fabric of type HEXFORCE® 01202 1000 TF970 (HEXCEL), as well as a polyamide 66 film grade, ULTRAMID A34 (BASF SE), were stacked alternatingly. According to applying standards, a quasi-isotropic, symmetrical laminate lay-up was chosen. An overview of all relevant constituent and laminate properties is given in Table 1.

**Table 1:** Fiber, matrix and laminate properties (in-house measured properties are highlighted) [6].

| Fiber / fabric properties | | Matrix properties | |
|---|---|---|---|
| Fiber material: | E-Glass, 204 tex | Matrix material: | PA66 film |
| Architecture: | Twill weave, 2x2 | Film thickness: | **108.7 µm** |
| Areal weight: | 290 g/m$^2$ | | **156.6 µm** |
| Finish: | Silane, TF970 | | |
| **Laminate / plate properties** | | | |
| Laminate lay-up: | **$[(+45/-45)/(0/90)]_{4s}$** | | |
| Specimen thickness, $t$: | **3,48 ± 0,02 mm** | | |
| Specimen length, $l$: | **149.98 ± 0.29 mm** | | |
| Specimen width, $w$: | **100.02 ± 0.09 mm** | | |

### 2.2. Specimen preparation

In order to investigate the impact behavior as a function of the environmental conditions, all specimens were conditioned until reaching constant specimen masses. Overall, three different conditioning states – dry, humid and hot/wet – were chosen. Constant specimen masses are defined as a maximum mass deviation tolerance of 0.05 % within three consecutive measurements, whereas a time gap of at least 24 h between each measurement has to be respected. For the hot/wet conditioned specimens, the maximum mass deviation tolerance is defined at 0.1 % respectively. All specimens were conditioned at elevated temperatures in order to accelerate reaching moisture equilibrium. To avoid moisture absorption from ambient air of a conventional convection oven, the dry specimens were dehumidified by using a vacuum furnace. Additionally, the humid and hot/wet specimens were conditioned in a two-stage process, cf. Table 2.

**Table 2:** Conditioning parameters and realized test climates.

| **Notation (Abbr.)** | **Conditioning** | | | | **Test condition** | |
|---|---|---|---|---|---|---|
| | Equipment | Tempera-ture $T$ | Relative hu-midity $RH$ | Duration $t_{cond}$ | Tempera-ture $T$ | Relative hu-midity $RH$ |
| Dry (D) | Vacuum furnace | 50 °C | Vacuum | 647 h | 23 °C | 0 % |
| Humid (H) | Climate cabinet | 70 °C<br>70 °C | 62 %<br>50 % | 380 h<br>455 h | 23 °C | 50 % |
| Hot/wet (HW) | Climate cabinet | 70 °C<br>70 °C | 62 %<br>95 % | 380 h<br>574 h | 70 °C | 95 % |

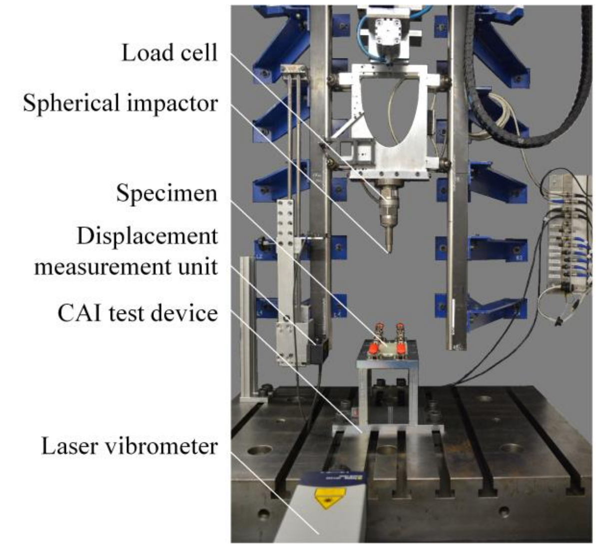
Due to the specimen wall thickness of about 3.5 mm, an accelerated specimen conditioning listed in Table 1 took more than one month until reaching constant masses. All water absorbing specimens (humid, hot/wet) showed a yellow surface discoloration in the course of time, cf. Figure 1.


**Figure 1:** Surface discoloration of the specimens (size: 150 mm x 100 mm) after 623 h of conditioning.

This yellowing and surface deterioration effect is known from literature, whereas a significant degradation of mechanical properties, especially of polyamide 66 as a thermoplastic matrix system, is not mentioned [7,8].

### 2.3. Experimental set-up

All specimens were tested at the in-house developed drop tower of the Institute of Composite Materials (IVW), cf. Figure 2. The test rig consists of a stiff frame with a guiding rail. The rail directs a carriage used as impact mass. For the impact tests, the carriage is equipped with a KISTLER load cell, type 9361B, with a maximum force of 60 kN for impact force measurement and a spherical impactor. The speed of the carriage is determined by an optical displacement measurement system, type M25L/100, MEL MIKROELEKTRONIK GMBH. The displacement measurement is based on the principle of laser triangulation. As a displacement measurement backup system, a laser vibrometer, type OFV-5000 / OFV-525, POLYTEC GMBH, is used. The plates are fixed according to DIN EN 6038 via four toggle clamps with a normal force of 1 kN per clamp. The clamping forces were approximately measured by using pressure sensitive films.




**Drop tower configuration**

| | |
|---|---|
| Carriage weight: | **4,79 kg** |
| Impact energies: | **9 J, 12 J, 20 J** |
| Spherical impactor diameter: | **16 mm** |
| Clamping force: | **1 kN / clamp** |
| Displacement measuring range: | **± 50 mm** |
| Size of base plate: | **0,6 m x 1,2 m** |

**Figure 2:** Left: Experimental set-up for low velocity impact tests. Right: Test rig configuration.

In order to maintain the realized test climates during impact testing, the dry and humid specimens were directly tested after removing them from the climate cabinet and cooling to room temperature. The hot/wet specimens were impacted at ambient air temperature as well since no temperature chamber is available. In order to minimize temperature and moisture losses when removing them from the climate cabinet at 70 °C and 95 % RH, preliminary handling tests with a portable convection oven were conducted. The most important results for maintaining hot/wet conditions during impact testing are:

- Moisture loss can be minimized by packing the specimens immediately into a low-density polyethylene (LDPE) pressure lock bag after removing them from the climate cabinet. The unpacking has to take place as close as possible before the impact test starts (in this case: $t_{\text{handling}} < 20$ seconds).
- The packed test specimens have to be stored briefly in a convection oven at 80°C in order to compensate for the temperature loss between the removal from the oven and the impact test. Water bowls in the oven are recommended in order to counteract the drying mechanisms of the oven. Thereby, a handling time of 30 seconds between specimen removal and impact event was appropriate.

By identifying these optimized handling times and procedures, the specimens were impacted at about 70 °C with an insignificant moisture loss. All impact tests were performed related to EN 6038 [2], whereby residual strength tests are not presented in this study. Overall 17 specimens were impacted at three different impact energies (9 J, 12 J, 20 J) and three different climates (D, H, HW). The humid specimens are used as a reference since it represents ambient air conditions.

## 3. Results

As a first step, the damaged specimens were visually examined since the GF-PA66 plates are semi-translucent. Each specimen shows a distinct imprint resulting from the spherical impactor geometry on the top surface (impacted side). The number of matrix cracks on this surface rises if the impact energy increases. At the lowest applied impact energy of 9 J, only the hot/wet specimen shows damages in the form of matrix cracks. Considering the bottom surface, the lower fabric layers push through the laminate accompanied with matrix cracks and fiber breakage. As in the case of the damages on the impacted side, only the hot/wet specimen is visually damaged at an impact energy of 9 J. The damages on the bottom side are also more distinctive if the impact energy increases. Regarding the visual damage extent as a function of the conditioning state at constant impact energy, e.g. at 20 J, the hot/wet specimens show the greatest extent compared to the dry and humid specimens. Little differences between the two last mentioned types of specimen are identifiable. The dry ones indicate some more matrix cracks on the top surface as well as a more distinctive damaged area in backlight analyses. By contrast, the push-through effect of the fabric layers on the bottom side is more severe for humid specimens, cf. Figure 3.

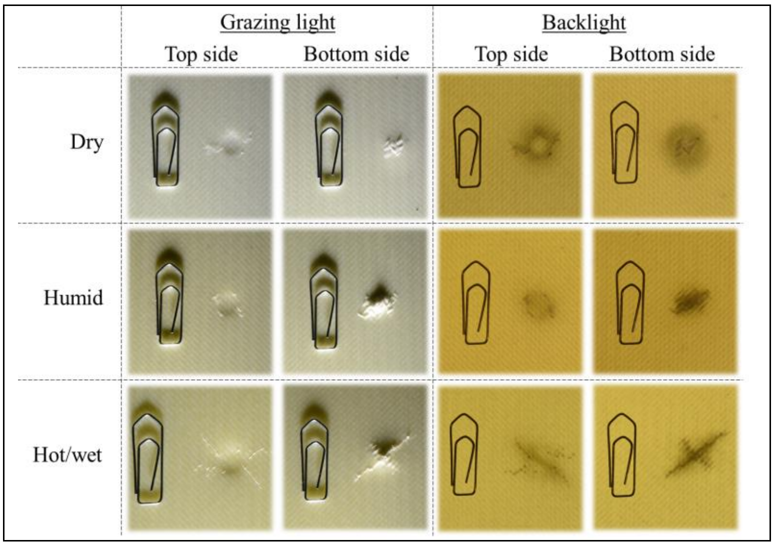



**Figure 3:** Comparison of visual surface damages in grazing light (left) and damaged areas by means of backlight analyses (right). All displayed specimens were impacted with an impact energy of 20 J.

For all specimens, a relatively narrow damaged area is evident, whereas a circular shape for the dry and humid specimens is visible via backlight analyses. Thereby, the damaged area of the dry specimens seems to be larger compared to the humid ones. This can be explained by the reduced moisture content of the dry specimens. Less moisture within the laminate provokes a more brittle damage behavior, which is mostly typical for thermoset materials. In contrast to the circular damage shape, the hot/wet specimens show elongated matrix cracks and fiber breakage according to the fiber orientation instead.

In general, this damage tolerant material behavior arises from an inhibition of delamination propagation, which is mainly ascribed to both laminate constituents. On the one hand, the thermoplastic matrix provides some plasticity, which redistributes inter-laminar shear stresses until the in-plane shear strength between the fabric layers is reached. This point describes the onset of distinct layer separation (delaminations), which is not identified by visual analyses. On the other hand, the fiber architecture of a single fabric layer causes energy dissipation via friction between the highly undulated fibers. Thus, at low impact energies, intra- and inter-laminar matrix cracks are mostly hindered to propagate along the plate's planar direction.

As a second step, the impactor indentation was measured 48 hours after the impact event using a white light profilometer. As supposed, the indentation of the impactor increases linearly if the impact energy increases, cf. Figure 4. This effect is independent of the conditioning state.

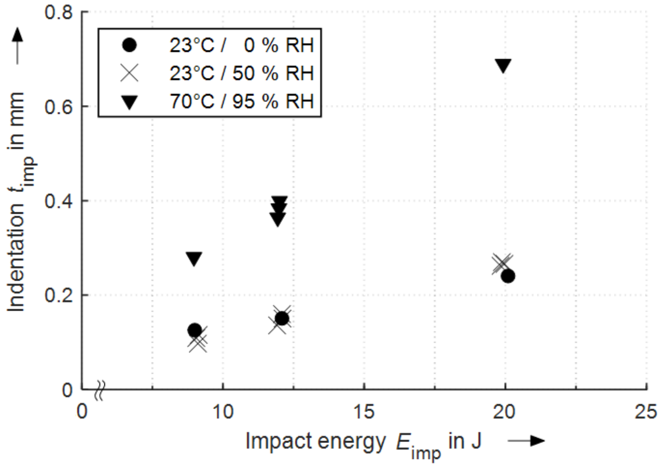



**Figure 4:** Impactor indentation $t_{imp}$ as a function of the impact energy $E_{imp}$.

According to the visual observations, no significant difference between the dry and humid specimens exists. As a consequence, a moderate moisture content change is acceptable for the indentation measurement of fiber-reinforced polyamide plates after impact. In contrast, the remaining indentation of the hot/wet specimens at constant impact energy is about 2.5 higher compared to the specimens tested at room temperature and moderate humidity. Consequently, the elevated temperature seems to play a major role for the damage behavior. However, the BVID energy threshold, defined in EN 6038 [2] as remaining indentation of 0.3 mm, is not reached for all specimens apart from the hot/wet specimens at 12 J and 20 J. In order to determine the BVID energy threshold for this quasi-isotropic woven GF-PA66 laminate, higher impact energies are necessary.

Regarding the force evolution as a function of the impact time, no initial damage onset point is detected for all specimens. This damage threshold load (DTL) is reached when first severe damages within the plate occur (usually delaminations). It is generally accompanied by a sudden load drop and a subsequently changed material behavior [9,10]. Figure 5 highlights three representative force-time curves of differently conditioned plates, which were impacted with an impact energy of 12 J.

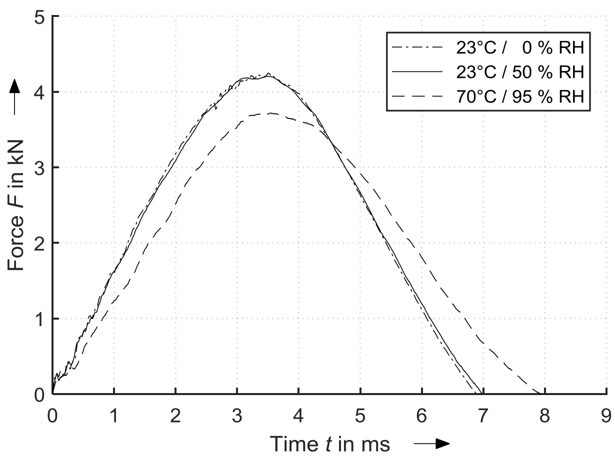



**Figure 5:** Exemplary force-time curves as a function of the specimen conditioning. All specimens were impacted with an impact energy of 12 J.

The missing initial damage force correlates with the visual analyses since no extensive delaminations and fiber breakage were stated. Especially delaminations are one of the main contributors to a sudden load drop because they substantially reduce the plate's bending stiffness. As they are not significantly present for the tested material, no damage onset point is identified.

The important influence of the specimen conditioning state also reflects in the force-time curves. Again, there is no difference between the dry and humid specimens. Consequently, surface yellowing dose not influence the response force and impact duration. Hence, it is just an optical surface change, which leads to the assumption that the long-term conditioning of the specimens at elevated temperatures does not initiate aging effects.

The impact duration and maximum impact force between dry and humid specimens are comparable. In contrast, the hot/wet specimens show a slightly changed material behavior, since reduced force increase and force decrease rates, as well as a lower maximum impact forces, are triggered, cf. Figure 5. The reduced impact forces and larger impactor indentations for hot/wet specimens can be explained by decreased matrix dominant properties of the laminate. Especially the transverse compression strength and out-of-plane shear strength are expected to be reduced, since the polyamide 66 matrix is impacted considerably above its glass transition temperature [11]. The mechanical property degradation is independent of the impact energy, whereas the impact of the specimen moisture content is minor compared to the specimen temperature, cf. Figure 6. Reduced matrix properties result in lower bending stiffness of the plate and with this, in longer impact durations compared to the dry and humid specimens, cf. Figure 5.

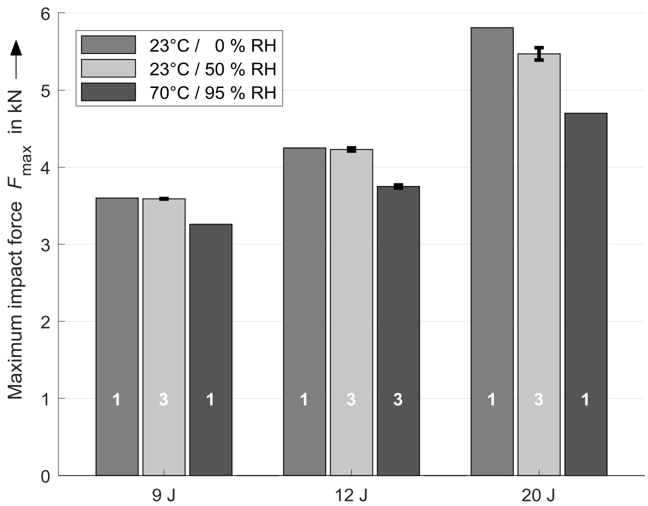



**Figure 6:** Maximum impact force (mean values) of all specimens as a function of the impact energy. The number of tested specimens is given within the bars, error bars are indicated when applicable (very little scatter).

## 3. Conclusions

The present paper investigated the impact behavior of woven glass fiber-reinforced polyamide plates under varying environmental conditions. Taking into account that humid conditioned specimens (23 °C, 50 % RH) were used as a reference, relevant findings are the following:

- The applied impact energies do not lead to pronounced delaminations within the material, which is confirmed by the absence of an initial DTL. Even the dry specimens with relatively low fracture toughness are characterized by a narrow damaged area. This effect is due to matrix plasticity and the wavy fiber architecture. In general, a high damage tolerance is expected for compression after impact tests.
- There is a linear dependence between the remaining impactor indentation and the applied impact energy. This correlation is independent of the specimen conditioning state. For hot/wet specimens, the indentation is significantly higher compared to dry and humid specimens.
- A reduced moisture content only has a moderate influence on the impact tolerance of woven GF-PA66 plates. In contrast, high temperatures and high moisture contents are crucial, since the glass transition temperature of the matrix is exceeded. This results in longer impact durations, lower maximum impact forces as well as lower force increase and force decrease rates.

Within the next steps, ultrasonic, thermography and CT analyses will be conducted in order to obtain a deeper understanding of the damage mechanisms within the thermoplastic material. Thereby, the results presented in this study will be substantiated. Besides, experimental investigations on further fiber-matrix combinations will be performed in order to study the influence of matrix toughness and fiber architecture on the damage tolerance.

**References**

[1] Breuer, Ulf Paul: Commercial Aircraft Composite Technology, 1st edition, Springer International Publishing Switzerland, 2016, ISBN: 978-3-319-31917-9

[2] EN 6038: Aerospace series – Fibre reinforced plastics – Test method – Determination of the compression strength after impact, European Norm, November 2015

[3] Vieille, Benoît; Casado, Victor Manuel; Bouvet, Christophe: About the impact behavior of woven-ply carbon fiber-reinforced thermoplastic- and thermosetting-composites: A comparative study, Composite Structures, Elsevier, 2013, vol. 101, pp. 9-21, https://doi.org/10.1016/j.compstruct.2013.01.025

[4] Nedzad, Hamed Yazdani; Auffray, Anthony; McCarty, Conor T., O'Higgins Ronan: Impact damage response of carbon fibre-reinforced aerospace composite panels, 20th International Conference on Composite Materials, Copenhagen, 19-24th July 2015

[5] Reid, S. R.; Zhou G.: Impact behaviour of fibre-reinforced composite materials and structures, 1st edition, Woodhead Publishing Ltd, 2000, ISBN: 1 85573 423 0

[6] HexForce® 01202 100 TF970: Product data sheet, Hexcel, March 2017

[7] Hellerich, Walter; Harsch, Günther; Baur, Erwin: Werkstoff-Führer Kunststoff – Eigenschaften - Prüfungen - Kennwerte. 10. Auflage, Carl Hanser Verlag, München 2010, ISBN: 978-3-446-42436-4

[8] Ehrenstein, Gottfried W.; Pongratz, Sonja: Beständigkeit von Kunststoffen, Band 1, Carl Hanser Verlag, München 2007, ISBN: 978-3-446-21851-2

[9] Abrate, Serge: Impact Engineering of Composite Structures, CISM Courses and Lectures, vol. 526, Springer Wien NewYork, 2011, ISBN: 978-3-7091-0522-1

[10] Cartié, D.D.R.; Irving P.E.: Effect of resin and fibre properties on impact and compression after impact performance of CFRP, Composites: Part A, Elsevier, 2001, vol. 33, issue 4, p. 483-493, https://doi.org/10.1016/S1359-835X(01)00141-5

[11] BASF SE: Ultramid® (PA) – Product Brochure, August 2013