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Influence of temperature and impact energy on low velocity impact damage severity in CFRP

Johann Körbelin*, Manuel Derra, Bodo Fiedler

Hamburg University of Technology, Institute of Polymers and Composites, Denickestraße 15, D-21073 Hamburg, Germany

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ABSTRACT

This study focuses on the effect of temperature and impact energy on the damage in CFRP under low velocity impact. Quasi-isotropic laminates with a thickness of 4.1 mm were impacted with energies between 8 and 21 J at temperatures ranging between 20 and 80 °C. The resulting damage was assessed using ultrasonic C-scans, radiography and confocal microscopy. The residual strength was evaluated utilizing compressive tests at 20 °C. It was found that delamination size is decreasing with increasing temperature. However, severe fibre failure on the impacted side occurs at elevated temperatures. This increases the visual damage detectability on the impacted side heavily while decreasing it on the opposite side. Nevertheless, the residual compressive strength is mainly dependent on the delamination area. Different impact energies can have the same effect on the residual strength, when impacted at different temperatures. As a result, visual damage severity does not correlate with the residual compressive strength.

1. Introduction

Carbon fibre reinforced plastics (CFRP) are widely used in the aerospace industry and lightweight application because of their outstanding properties in terms of stiffness and strength compared to density. However, due to their layered structure and therefore low out of plane strength and brittle behavior, a major concern with CFRP laminates is their low impact resistance. In contrast to metals, composites can absorb energy only through material damage and not via plastic deformation. Especially Low Velocity Impact (LVI) is of interest here, which often results in barely visible impact damage (BVID). These damages are difficult to detect during operation, but lead to a significant reduction in strength. Following the concept of "damage tolerance" structures must be designed in a way that still provides sufficient load capability with an BVID. In order to achieve this and make use of the lightweight construction potential of the material, a deep understanding of the damage caused by LVI and its factors of influence is required. Therefore this topic has been the object of considerable research and numerous studies dealt with the influence of impact energy on the damage in CFRP and the residual strength [1], however, questions still remain. Aircraft and composite structures in general are used in different climates and therefore various temperatures during operation. Still, a simple answer on how temperature is influencing the damage process cannot be given since different effects like matrix softening, stress relaxation, reduction of thermal stresses, etc. combine to influence the failure process. Therefore the influence of the temperature on LVI damage is of great interest and should be thoroughly investigated. Yet only few studies have dealt with the influence of temperature on the damage behavior of CFRP.

2. State of the art

Gómez-del Río et al. [2] examined the damage in CFRP, caused by LVI in temperatures between 20 and −150 °C. The resin system used had a nominal glass transition temperature (T_g) of 210 °C. Unidirectional, cross-ply, quasi-isotropic and woven-ply laminates with thicknesses varying between 1.6–2.2 mm and impact energies between 1 and 13 J were utilized. The specimens were fixed with a 60 mm diameter circular clamping. It was found that cooling the laminate has a similar effect as increasing the impact energy. But the larger extent of damage at lower temperatures is a result of a lower specific fracture energy of the epoxy matrix combined with increasing inter-laminar thermal stresses. With decreasing temperature larger matrix cracking, delamination extension and deeper indentation on the impact side and more severe fibre-matrix debonding and fibre fracture on the opposite face was observed. Survana et al. [3] investigated the influence of temperature on LVI impact damage at temperatures between 30 and 90 °C. The resin system had a 212 °C nominal T_g. Cross-ply $[0/90_2/0]_{2s}$ carbon

* Corresponding author.
E-mail address: johann.koerbelin@tuhh.de (J. Körbelin).

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fibre (CF)/epoxy laminates were impacted with an energy of 4.3 J, using a circular clamping fixture with a 36 mm diameter. The damage area showed a contrasting effect in comparison to cooling the laminate: The size of the damage area is reduced as the temperature increases. It is suggested that interlaminar fracture toughness, as obtained from low velocity impact tests, is strongly influenced by temperature, hence the larger extent of delaminations at low temperatures when observed in ultrasonic C-scan and μ computed tomography (CT) studies. The residual strength was assessed using three point bending tests. Due to the lower damage area the residual flexural strength increases with the temperature at which the specimen was impacted. Im et al. [4] investigated the influence of temperatures ranging from −30 to 120 °C on high-velocity impact damage in cross-ply CF/epoxy and CF/peek laminates. The CF/epoxy laminates have a nominal T_g of 130 °C. CF/epoxy laminates were cross-ply layups of $[0_6/90_6]$ and $[0_4/90_4]$. Impact damage was introduced via a 0.5 g steel ball and a circular clamping with a 150 mm diameter. Impact velocities ranged between 50 to 105 m/s and energies therefore between 0.625 and 2.7 J. It was found that the delamination area is increasing with decreasing temperature and that the delamination area per unit impact energy becomes larger at lower energies. Residual bending strength was investigated utilizing three point bending tests. The residual bending strength is increasing with increasing temperature for all CF/epoxy specimens. Aktaş et al. [5] investigated the residual compressive strength after LVI of quasi-isotropic and cross-ply glassfibre (GF)/epoxy laminates with 3 mm thickness. The resin system had a ca. 100 °C nominal T_g. The impact energy and the temperature at impaction were varied between 20–70 J and 20–100 °C. No detailed information on the clamping during impaction was given. The compressive tests were performed in a fixture according to ASTM D 7137 at room temperature. The damage shape showed a preferred orientation, the CAI-strength with the larger projected damage area in the load plane was lower over all temperatures. The maximum reduction of the CAI-strength was obtained at 100 °C while the minimum reduction was at 100 °C throughout all impact energies. It was found that the influence of temperature on damage size is higher for cross-ply laminates compared to quasi-isotropic laminates for the same energy level. Besides the residual compressive strength Aktaş et al. also [6] investigated the impact behavior of quasi-isotropic and cross-ply glass/epoxy laminates. Materials, layup and impaction were equal to the preliminary study. Impacts were performed at 20 °C, 60 °C and 100 °C. Plate thickness was ca. 3 mm and impact energies investigated were between 5 and 70 J. The study focuses on the effect of impact energy and temperature on the contact force development rather than the detailed damage morphology of the laminate. With increasing impact energy the maximum contact force increases rapidly up to thefirst fibre failure. The first fibre breaking limit is increasing with temperature. After the first fibre failure is reached the maximum contact force is increasing with impact energy and temperature. Up to the perforation threshold, the excessive energy rises by increasing the temperature, but the energy absorbing capability of the specimen is reduced with increasing temperature.

As the preliminary literature review revealed, the focus of studies looking at CF/epoxy laminates was mostly on rather thin, mostly cross laminates with a low amount of interfaces between fibre directions. The influence of increased temperature on the damage behavior of LVI in CFRP has, to the author's knowledge, not yet investigated. Therefore this study deals with the influence of temperature during LVI on the impact damage in quasi-isotropic laminates and its residual compressive strength.

3. Materials and experimental procedure

3.1. Material

Specimens were manufactured from a Hexcel© Hexply M21/35%/268/T800S prepreg system. The layup was a quasi-isotropic layup $[45/0/-45/90]_{2S}$ with a thickness of 4.08 mm, chosen according to ASTM D7136 M. The specimens were autoclave cured according to manufacturer's specifications, which results in a glass transition temperature of 203 °C. Every manufactured plate was inspected via ultrasonic C-scans for manufacturing flaws. The specimens were cut on a diamond blade saw and afterwards the edges were polished. For impact testing and determination of the residual strength the specimen dimensions were according to ASTM D7136 M 100·150 mm. To determine the undamaged compressive strength, specimens were prepared according to ASTM D3410 with the same layup. Specimen dimensions with 140 mm height, 25 mm width, 10 mm free gauge length and 2 mm thick GFRP tabs were selected. The dimensional tolerances of all specimens were within the tolerance specified in the according ASTM standard. All specimens were dried and stored in a controlled climate prior to testing.

3.2. Impact testing

The impact damage was introduced using a drop tower. The impactor nose had a semi-spherical nose with a diameter of 20 mm and was equipped with a load cell. The weight as well as the drop height varied depending on the impact energy. An overview of the characteristic values of the impact is shown in Table 1. The parameters of the impact process, such as mass and velocity, have been chosen to correspond to the characteristics of LVI-impacts defined by other studies, see Richardson et al. [1] and Sjoblom et al. [7]. The specimens were placed on an aluminium frame with a 75 · 125 mm cutout with 3 mm radius corners. The specimens were centred against metal pins as a positioning aid and were held in position by rubber-tipped toggle clamps with a load capacity of 1100 N. The boundary condition of this fixture is essentially simply supported.

Information about design temperatures and therefore temperatures of aircraft structures during ground or flight operation are sparse. Petersen et al. [8] performed numerical simulations of a CFRP wing box heated up by sun radiation at a high altitude airport. They encountered that maximum surface temperatures of the wing are between 68 and 110 °C during ground operation, depending on the color of the surface. Cooling of the wing during taxi and take-off led to reduced maximum temperatures between 63 and 87 °C. But even at airports, where the radiation is not as intense, similar temperatures are likely to be reached. One of the hottest airports worldwide is the Kuwait International Airport, which has reported max. temperatures of ca. 50 °C in June and July [9]. The height of the airport is close to sea level at 63 m.

Based on this data and the limitations of the electrical heated environmental chamber, temperatures chosen were 20 °C, 50 °C and 80 °C and therefore well below the T_g of the material used. The environmental chamber is not able to cool the temperature below the room temperature, which is kept at 20 °C. The temperature was monitored at the upper and lower surface of the specimen as well as the air temperature of the environmental chamber. The specimen was kept at the target temperature for 20 min before impacted. At least 6 specimens were impacted at each energy level and temperature.

The force data was recorded with a sample rate of 50 kHz. From this discrete force data the displacement of the impactor was calculated. Full contact between striker and specimen throughout the experiment is assumed. The displacement x may be obtained as:

Table 1
Test parameters of impact tests.

Energy [J]	Impactor Weight [kg]	Drop Height [mm]	Impact Velocity [$\frac{m}{s}$]
8	2.4	300	2.54
15	4.45	340	2.60
18	4.95	370	2.69
21	5.47	390	2.77