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

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Abstract

The present study deals with the effect of temperature and impact energy on the damage in CFRP subjected to low velocity impact. Quasi-isotropic laminates 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 drastically while decreasing it on the opposite side. Nevertheless, the residual compressive strength is mainly dependent on the delamination area. As a result, visual damage severity does not correlate with the residual compressive strength. Different impact energies can have the same effect on the residual strength, when impacted at different temperatures.

Keywords: Impact behaviour, Damage Tolerance, Delamination, Thermomechanical

1. Introduction

Carbon fibre reinforced plastics (CFRP) are widely used in the aerospace industry because of their 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 behaviour, a major concern with CFRP laminates is their low impact resistance. 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 should be thoroughly investigated. Yet only few studies have dealt with the influence of temperature on the damage behaviour of CFRP.
Gómez-del Río et al. [2] investigated the influence of low temperature on damage in CFRP and Survana et al. [3] at elevated temperature. They found that 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 could be observed. With increasing temperature a contrasting effect is obervable and the damage area is reduced. Other studies investigated the influence of temperature on

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high velocity impact [4] or investigated glassfibre/epoxy composites [5] [6].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. Therefore this study deals with the influence of temperature during LVI on the impact damage in quasi-isotropic laminates and its residual compressive strength.

2. Materials and experimental procedure

Information about design temperatures and therefore temperatures of aircraft structures during ground or flight operation are sparse. Petersen et al. [7] performed numerical simulations of a CFRP wing box heated up by sun radiation and found that the maximum surface temperatures during ground of the wing are between 68 and 110 °C. 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 [8]. Based on this data temperatures chosen were 20 °C, 50 °C and 80 °C and therefore well below the T_g of the material used. At least 6 specimens were impacted at each energy level and temperature. The impact damage was introduced using a drop tower. The impactor nose had a semi-spherical shape 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. All introduced impacts were low velocity impacts, as defined in [9][1]. A fixture according to ASTM 7136 M was used.

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

Table 1: Test parameters of impact tests

2.1. 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 to dimensions of $100 \cdot 150$ mm on a diamond blade saw and afterwards the edges were polished. The dimensional tolerances of all specimens were within the tolerance specified in ASTM 7136 M. All specimens were dried and stored in a controlled climate prior to testing.

2.2. Damage characterization

After impaction various non-descriptive test methods were used to assess the damage in the samples, in order to obtain the most complete picture of the damage. Ultrasonic C-scans were carried out and the projected delamination area was determined by the backwall echo. The image was converted into a binary picture using a threshold, which was kept constant for all pictures. The area was then determined by inverting the binary picture and summing up the area of all black pixels. The damage in the samples was also examined by confocal microscopy using an Alicona G4 microscope.
One sample of each temperature and energy was analyzed using radiography with a faxitron x-ray 43885 of Rohde & Schwarz. The radiograph was afterwards digitalized with a transmitted light scanner and then inverted in order to achieve better visibility of the damage.
The residual compressive strength tests were performed at 20 ° C with a Zwick Z400 universal testing machine using a fixture according to ASTM D7137. All compression tests were observed with a GOM Aramis M5 digital image correlation system to exclude unwanted bending of the specimens during the tests. The residual strength was calculated from the force-displacement data using:

$$\sigma_r = \frac{F_{max}}{b \cdot t} \qquad (1)$$

Where σ_r is the residual strength, F_{max} is the maximum force in the compression test, b the width of the specimen and t the thickness.

3. Results

Impact response showed no significant effect of temperature on the behavior of the specimens in the initial phase of the impact, as the initial stiffness of the specimen is similar. The maximum contact force, as shown in figure 1, is expected to be generally increasing with the impact energy. However, this is only the case up to 18 J. A temperature dependency of the maximum is only identifiable at 15 J. Here the highest impact force is encountered at room temperature, the lowest at 50 °C and then the contact force is increasing again at 80 °C.

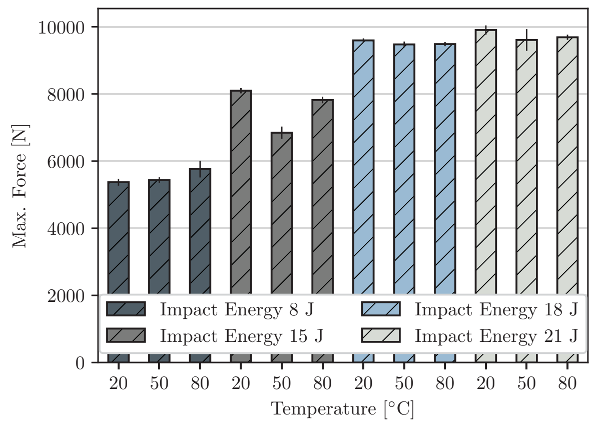


Figure 1: Maximum contact force at different energies and temperatures

Figure 2 displays the permanent deformation caused by the impactor. In general, it is evident that at higher temperatures the impact depths increase compared to the room temperature. Moreover, the highest permanent deformation is always at the highest temperature. Additionally, the projected area of the permanent rear bump was measured. Figure 3 shows that the outwards dented area is influenced by both temperature and impact energy, while there is no correlation with the indention depth shown in figure 2.

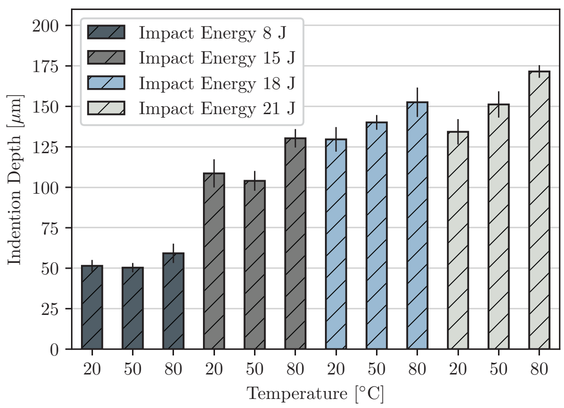


Figure 2: Permanent indention depth at different temperatures and impact energies

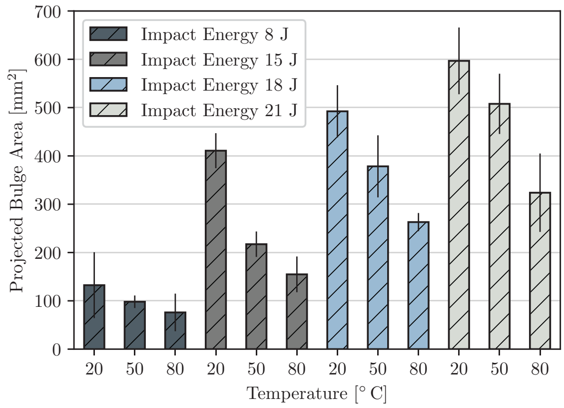


Figure 3: Projected area of rear bump at different temperatures and impact energies

On the microscope images, which were taken during surface scanning, a change in the appearance of the damage on the impacted side becomes evident. This is exemplary shown for specimens with 15 J impact energy in figure 4. At 20 °C two out of five specimens show fibre failure in the top layer. At higher temperatures all specimens show fibre failure on the top. In general it can be said that with increasing energy and temperature the amount of fibre breakage increases and furthermore the area in which fibre breakage occurs is much larger. However, temperature has a stronger effect than the impact energy.

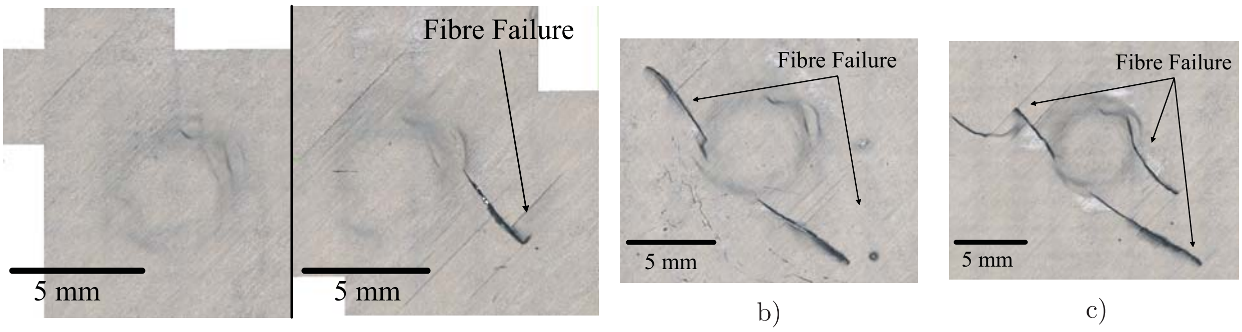


Figure 4: Microscopy picture of exemplary damage on the impact side at 15 J impact energy at 20 °C a), 50 °C b) and 80 °C b)

In the radiography pictures the change between failure modes, which became apparent in ultrasonic C-Scans and confocal microscopy, are visible at the same time. Figure 5 shows the change exemplary for impacts at 15 J impact energy. At 20 °C inter-fibre failure around the impact area is visible. At 50 °C this failure is drastically reduced, but with further temperature increase no further decrease takes place. However at 50 °C, as seen before, fibre failure appears and becomes more severe at 80 °C. Other impact energies exhibit similar behaviour. At 8 J fibre failure appears only at elevated temperatures and the damage area is generally smaller at equal temperatures. Impact damage with 18 J and 21 J show a significantly larger damaged aear.

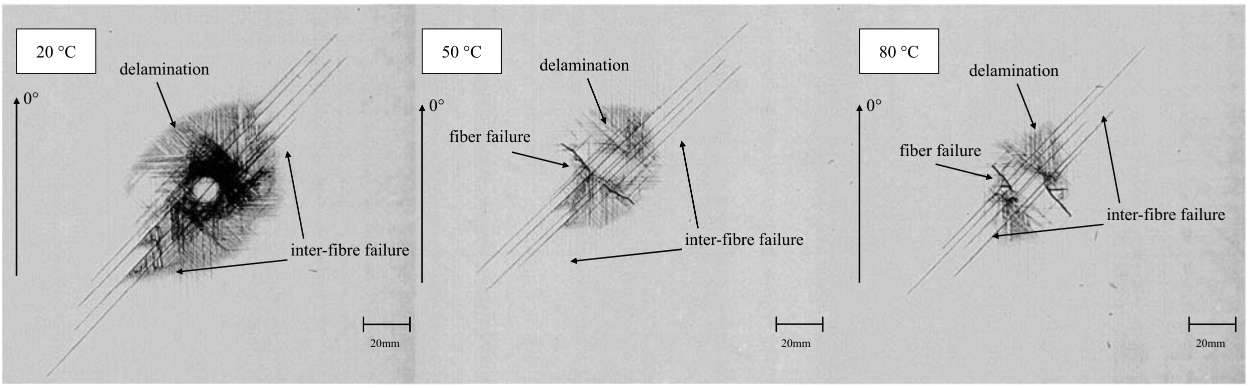


Figure 5: Radiographic image of the damage at 15 J and 20 °C, 50 °C and 80 °C

In figure 6 the residual strength for the different energies and temperatures is shown. All specimens impacted with 8 J impact energy showed no failure at the impact damage. That means they failed on the upper or lower side of the specimen and showed severe delamination at the load introduction area. Nevertheless, the residual strength increases with the impact temperature. The, compared to higher energies, higher scatter in data can be related to a more stability driven failure rather then defect driven.

All other specimens which were impacted above 8 J showed failure at the impact damage. At 15 J the residual strength is also increasing with the impact temperature. The fact that the temperature at 21 J impact energy shows no difference in residual strength has led to the addition of the 18 J impact energy test series.

4. Discussion

As the results have illustrated, damage in CFRP caused by LVI is changing with temperature: Delamination area and the amount of inter-fibre fractures decrease while fibre failure occurs at elevated temperatures as the temperature rises. The main reason for this shift is the change of mechanical properties of the polymeric matrix, which is significantly more sensitive to temperature than the fibre. With increasing temperature the epoxy matrix exhibits a lower fracture strength, modulus, yield point and a higher strain at breakage. The change in mechanical properties depends on the operation temperature compared to the T_g [10]. Nearly all mechanical properties of the composite are changing with the temperature, even at temperatures well below T_g. With increasing temperature the compressive modulus, strength and failure strain are decreasing [11]. The shear strength and modulus are decreasing and the failure strain increases [11] [12]. The inter-laminar shear strength (ILSS) declines considerably [12]. However, the tensile properties in fibre directions are nearly constant [13]. Callus [12] and Nettles [14] investigated the influence of temperature on the open hole compressive (OHC) strength and found that the strength and fracture strain are decreasing with rising temperature. The inter-laminar fracture toughness is also influenced by temperature. In mode I loading the initiation fracture energy release rate is slightly reduced, but the propagation energy release rate is increasing with temperature [15][16]. For mode II the energy release rates decrease with increasing temperature [17] [18]. The difference in thermal properties of fibre and matrix leads to orthotropic thermal expansion behaviour of a single ply. When the laminate is cooled from the curing temperature, internal stresses occur due to the constrained contraction by adjacent plies. These internal thermal stresses are decreasing with increasing temperature up to a temperature close to the curing temperature. However, all these various influences do not change linearly but non-linearly and combine to influence the failure behavior. Complex loads on the composite are applied during impact loading: e. g. crushing load of the impactor and compressive, tensile and strong inter-laminar shear loads due to bending. These conditions yield in a strong influence of temperature on the damage and failure under impact load.

The delamination surface is particularly sensitive to temperature changes, which can be seen in figure 6 as well as in the radiographic pictures, see figure 5. For example, at 15 J impact energy the delamination area decreases from 475 mm^2 to 285 mm^2 which is roughly a reduction of 40 % when the temperature rises by 30 °C. This reduction in delamination area is accompanied with a higher residual strength. At first glance this seems to be a positive development, especially when looking at figure 6. Here the projected delamination area and the according residual compressive strength are shown. It can be seen that the delamination area is corresponding with the residual compressive strength. This is similar compared with the findings of Survana et al. [3], who encountered a correlation of delamination area to residual bending strength. Due to the sensitivity of the delamination area to temperature, different combinations of temperature and impact energy can lead to the approximately same projected delamination area. Impacts with 15 J at 20 °C, 18 J at 50°C and 21 J at 50 °C exhibit roughly the same projected delamination area. Therefore the delamination surface in the laminate cannot be linked to the impact energy without considering the temperature.

The radiographic, see figure 5, and microscopic, see figures 4, examinations show a clear change in failure modes as fibre failure becomes more apparent and severe which, to the best of the author's knowledge, has never been identified during investigations of the influence of temperature on the development of damage in CFRP under impact load. Only the top layer exhibits fibre failure, as a result of the highest compressive loads due to bending during impaction. Fibre breakage occurs at the edge of the impactor, where the greatest bending and high local loads act. The higher the temperature, the more the fibre fracture expands from the impact point, see for example figure 4. Due to the decreasing shear modulus and shear yield point of the matrix the compressive strength of the composite is reduced and fibre breakage due to out of plane fibre-microbuckling occurs at lower load levels [11][17]. These observations are in line with the results of Gómez-del Río et al. [2], who encountered fibre fractures on the non-impacted side of the laminate when cooling the laminate. The fibre fractures absorb a lot of energy [19], which means that less energy is available for other failure types. This, the more ductile matrix behavior and the reduction of inter-laminar stresses

are probably accountable for the reduction of delamination area, despite the reduction in mode II fracture energy release rate with increasing temperature. This means that the influence of the resin fracture toughness is reduced at elevated temperatures. Matrix softening is also accountable for the change in permanent indention depth, see figure 2. Also in this case different energy/temperature combinations exhibit similar indention depths, for example impacts with 15 J at 80°C, 18 J at 20°C and 21 J at 20°C.
The occuring damage modes during impaction are strongly influenced by the fixture. The fixture used in this study is, as mentioned, basically simply supported. It therefore allows for relatively unconstrained bending during impaction. A fixture where the specimen is fixed at the edges, would exhibit a different kind of failure.

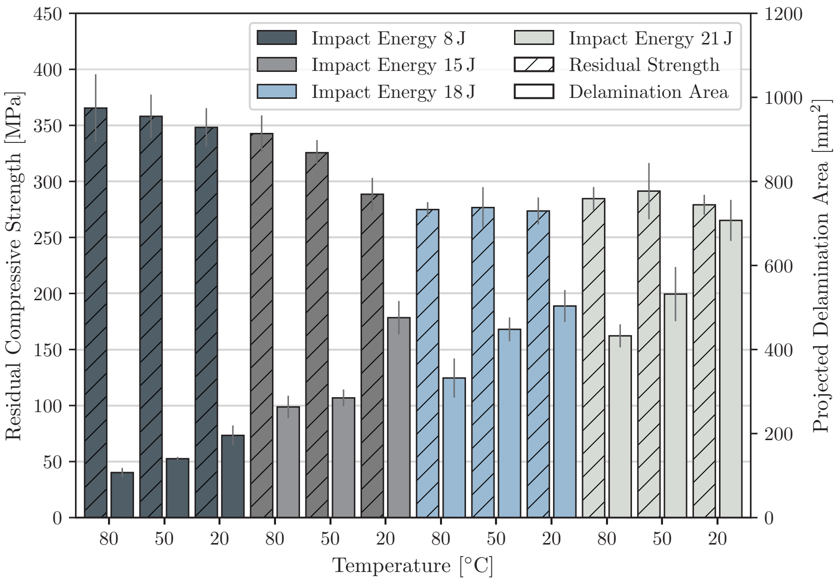
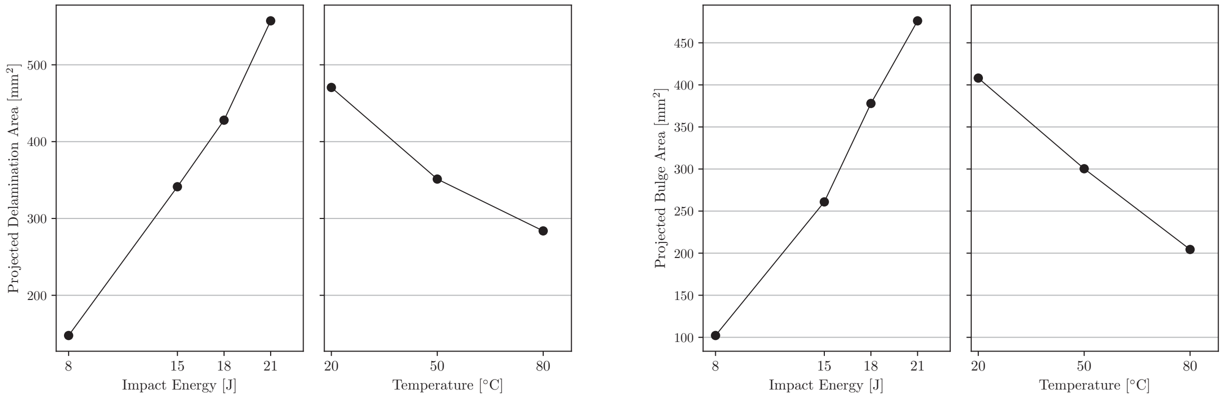


Figure 6: Comparison between delamination area and residual compressive strength

Due to the change in failure modes, it becomes clear that visual inspection is not sufficient to assess the damage severity of impact damage. A frequently used characteristic value for assessing impact damage is the indention depth, which is often associated with impact energy [20]. But when comparing figure 2 and 6 it can be seen that the residual strength cannot be judged by the indention depth. E. g. impacts at 15 J/80 °C and 21 J/50 °C have the same indention depths. The optical discernibility of impact damage increases when fibre fractures occur on the impacted side, but no conclusions can be drawn about the residual compressive strength. Rather the opposite is the case: A damage caused by the same impact energy at a different temperature which favors fibre failure exhibits a higher residual compressive strength. This could change for the case when the compressive loading occurs at elevated temperatures; here the fibre breakage could play a more important role in influencing the damage. The main effect diagram in figure 4 displays the effect of temperature and impact energy on the projected delamination area and the projected bulge area. It can be seen that the sensitivity to the influences is similar for both types of measurement.

In figure 6 the projected delamination area, obtained from the ultrasonic C-scans, and the residual compressive strength are shown. Here the lack of influence of temperature at higher impact energies on the residual strength becomes more apparent. For delamination areas greater than 332 mm^2 there is no significant change in the residual strength. This is due to the fixture used in the compression test. This impact damage is already at the critical size to initiate failure early. Therefore larger delamination areas show no significant change in residual strength. This behavior can probably be avoided with a larger specimen size. A further reduction in residual strength is only to be expected when significantly more damage due to higher impact energy can be observed. Without consideration of the temperature, the impact energy



a) b)

Figure 7: Main effect diagrams for the effect of temperature and impact energy on the projected delamination area (a)) and projected bulge area (b))

is therefore not a reliable parameter to determine the delamination area in this experiment, since different temperature/energy combinations can result in the same delamination area. The encountered fibre failure could influence the compressive residual strength at elevated temperatures or other residual strengths, e.g. for laminates under shear or tensile loading.

5. Conclusion

The present study illustrates that temperature as a variable is introducing more uncertainties to the assessment of damage as a result of LVI. At elevated temperatures fibre breakage occurs on the impacted side. Accordingly the delamination area is reduced. This increases the visual damage detectability on the impacted side heavily while decreasing it on the opposite side. However, residual compressive strength is mainly dependent on the delamination area. Therefore the damage resulting from significantly different impact energies can have the same effect on the residual compressive strength when impacted at different temperatures. As a result, visual damage severity does not correlate with the residual compressive strength. But the influence of the occurring fibre breakage on other residual strengths, such as tensile strength, is probably significant.

6. Acknowledgement

This work was carried out with funding from the German Research Foundation (DFG) within the project number FI 688/5-1. This financial support is gratefully acknowledged.

References

[1] M. Richardson, M. J. Wisheart, Review of low-velocity impact properties of composite materials, Composites Part A: Applied Science and Manufacturing 27 (12) (1996) 1123–1131. doi:10.1016/1359-835X(96)00074-7.

[2] T. Gomez-del Rio, R. Zaera, E. Barbero, C. Navarro, Damage in cfrps due to low velocity impact at low temperature, Composites Part B: Engineering 36 (1) (2005) 41–50. doi:10.1016/j.compositesb.2004.04.003.

[3] R. Suvarna, V. Arumugam, D. J. Bull, A. R. Chambers, C. Santulli, Effect of temperature on low velocity impact damage and post-impact flexural strength of cfrp assessed using ultrasonic c-scan and micro-focus computed tomography, Composites Part B: Engineering 66 (2014) 58–64. doi:10.1016/j.compositesb.2014.04.028.

[4] K.-H. Im, C.-S. Cha, S.-K. Kim, I.-Y. Yang, Effects of temperature on impact damages in cfrp composite laminates, Composites Part B: Engineering 32 (8) (2001) 669–682. doi:10.1016/S1359-8368(01)00046-4.

[5] M. Aktaş, R. Karakuzu, Y. Arman, Compression-after impact behavior of laminated composite plates subjected to low velocity impact in high temperatures, Composite Structures 89 (1) (2009) 77–82. doi:10.1016/j.compstruct.2008.07.002.

[6] M. Aktas, R. Karakuzu, B. M. Icten, Impact behavior of glass/epoxy laminated composite plates at high temperatures, Journal of Composite Materials 44 (19) (2010) 2289–2299. doi:10.1177/0021998310369576.

[7] D. Petersen, R. Rolfes, R. Zimmermann, Thermo-mechanical design aspects for primary composite structures of large transport aircraft, Aerospace Science and Technology 5 (2) (2001) 135–146. doi:10.1016/S1270-9638(00)01089-0.

[8] H. A. Nasrallah, E. Nieplova, E. Ramadan, Warm season extreme temperature events in kuwait, Journal of Arid Environments 56 (2) (2004) 357–371. doi:10.1016/S0140-1963(03)00007-7.

[9] P. O. Sjoblom, J. T. Hartness, T. M. Cordell, On low-velocity impact testing of composite materials, Journal of Composite Materials 22 (1).

[10] B. Fiedler, T. Hobbiebrunken, M. Hojo, K.Schulte (Eds.), Influence of stress state and temperature on the strength of epoxy resins, 2005.

[11] C. Soutis, D. Turkmen, Moisture and temperature effects of the compressive failure of cfrp unidirectional laminates, Journal of Composite Materials (31).

[12] P. J. Callus, France-australia technical arrangement ta 1/99 – work package 1: Study of the equivalence of hot/dry and hot/wet testing (2005).

[13] O. Allix, Modelling and identification of temperature-dependent mechanical behaviour of the elementary ply in carbon/epoxy laminates, Composites Science and Technology 56 (7) (1996) 883–888. doi:10.1016/0266-3538(96)00036-X.

[14] A. Nettles, Hot/wet open hole compression strength of carbon/epoxy laminates for launch vehicle applications (NASA/TM—2009–215900).

[15] Y. T. H.S. Kim, Wen Xue Wang, Effects of temperature and stacking sequence on the mode i interlaminar fracture behavior of composite laminates, Key Engineering Materials 183-187 (2000) 815–820. doi:10.4028/www.scientific.net/KEM.183-187.815.

[16] W. Zhao, Mode i delamination fracture characterization of polymeric composites under elevated temperature, Dissertations, Syracuse University (May, 2011).

[17] K. D. Cowley, P. W. Beaumont, The interlaminar and intralaminar fracture toughness of carbon-fibre/polymer composites: The effect of temperature, Composites Science and Technology 57 (11) (1997) 1433–1444. doi:10.1016/S0266-3538(97)00047-X.

[18] A. J. Russell, K. N. Street, Moisture and temperature effects on the mode i and mode ii interlaminar fracture of graphite/epoxy composites, Key Engineering Materials 37 (1989) 199–208. doi:10.4028/www.scientific.net/KEM.37.199.

[19] M. J. Laffan, S. T. Pinho, P. Robinson, L. Iannucci, A. J. McMillan, Measurement of the fracture toughness associated with the longitudinal fibre compressive failure mode of laminated composites, Composites Part A: Applied Science and Manufacturing 43 (11) (2012) 1930–1938. doi:10.1016/j.compositesa.2012.04.009.

[20] E. Panettieri, D. Fanteria, M. Montemurro, C. Froustey, Low-velocity impact tests on carbon/epoxy composite laminates: A benchmark study, Composites Part B: Engineering 107 (2016) 9–21. doi:10.1016/j.compositesb.2016.09.057.