EFFECT OF IMPACT DAMAGE ON THE COMPRESSION FATIGUE PERFORMANCE OF GLASS AND CARBON FIBRE REINFORCED COMPOSITES

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1. Introduction

The use of structural adhesives and composite materials for example in aircraft, wind energy, automotive or marine industry requires highly durable and reliable materials. Many fibre reinforced composites show excellent fatigue strength to weight ratios [1], but are also sensitive to localized impact loadings [2-3]. Considering the operational lifetimes of 20 years and a number of loading cycles from 10^8 to 10^9 for example in wind turbine rotor blades [4] the combined impact and fatigue performance of fibre reinforced structural materials is an important issue. Impact damage may occur during operation as well as during manufacturing, transport or maintenance of fibre reinforced composite parts.
Therefore the fracture mechanics and fatigue properties of the materials used have to be investigated and optimized. One approach to improve the interlaminar fracture toughness of composites and their impact damage resistance can be the use of new resin systems. Especially for wind turbine rotor blades the dynamic long term stability and fatigue damage tolerance plays an important role.

2. Experimental

This study focuses on the post-impact compression performance of glass and carbon fibre reinforced composites under static as well as under dynamic loading. The investigation of two different fibre and matrix materials allows to reveal some basic structure-properties-relationships which have to be considered when comparing the Compression After Impact (CAI) behaviour of different composite materials.

2.1. Materials

Matrix systems used were a two part standard epoxy/amine infusion resin EPR L 1100 + EPH 294 (‘EP‘) and a thermosetting polyurethane formulation from Henkel AG & Co. KGaA (‘PUR‘). Glass fibre reinforced laminates were made from biaxial SAERTEX Non Crimp Fabric (NCF) (E-Glass) with an areal weight of 672 g/m^2. The carbon fibre reinforcement was a NCF NC2 0/90-300-1270 with 300 g/m^2 from WELA.

2.2. Processing and sample preparation

The quasiisotropic glass and carbon fibre reinforced laminates were manufactured by VARTM-process. Laminate stacking sequence of the glass fibre NCF`s was $[+45/-45/0/90]_{2s}$, while the lower areal weight of the carbon fibre NCF required a $[+45/-45/0/90]_{3s}$ layup to obtain the same laminate thickness of 3.85 mm. This corresponds in both cases -GFRP and CRFP laminates- to fibre volume contents of about 55 %. The pre-cut 400 mm x 400 mm dry textiles were placed in an aluminum RTM-tool, which is afterwards clamped together and heated in a hydraulic hot press. The clamping force of the hot press is set to match exactly the post injection pressure of 5 bar to ensure homogenous laminate thickness. Before injection, the two-part resin systems were stirred in a laboratory mixer and degassed after being homogenously mixed. After injection, the mould was heated up by the press and kept at 90 °C for four hours to cure the laminates. Quality assurance was done by visual inspection for the GFRP laminates and with ultrasonic c-scans for the CFRP laminates. The impact specimens were cut out from the laminates with a circular diamond saw. The aspect ratio of the specimens was according to [5] but in consideration of a maximum force of 55 kN of the servohydraulic testing machine the length and width of the specimen edges were scaled down to 90 mm and 60 mm, respectively.

2.3. Impact testing

Epoxy and polyurethane matrix based fibre reinforced laminates are subjected to low velocity impacts with different impact energies. For impact testing the specimens were clamped into a fixture designed for their geometry. Three steel pins ensure that the specimens are reproducibly placed in the fixture and centered above a 45 mm diameter window [6] in the lower metal plate of the fixture (Fig. 1).

Figure 1: Impact support and lower part of the clamping fixture

A constant clamping force is applied to the specimen by the upper rubber-padded part of the fixture [7]. The low velocity impacts were performed using a 3 kg impactor with a 16 mm diameter hemispherical tip [5, 8], equipped with a piezo force measurement device. Since according to [5] and [8] the impactor weight was held constant, the variation of the impact energy, respectively the kinetic energy of the impactor in the moment of first contact with the sample, was set by its drop height. To prevent secondary strikes the impactor was automatically captured on its rebound from the sample. For each impact energy a series of five samples was investigated. After impact loading the delamination damages of the tested specimens were investigated. Images of their delaminated areas were obtained by ultrasonic c-scans in case of CFRP; for the glass fibre reinforced laminates the delaminated areas were evaluated optically. ImageJ software was used to quantify the delamination areas of the specimens.

2.4. Static testing

Static compression tests were conducted in a universal testing machine Zwick 1485 with a fixture designed for static as well as dynamic testing of the 90 mm x 60 mm sample geometry (Fig. 2).

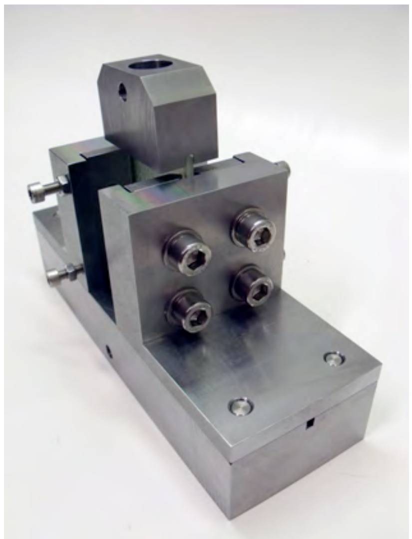

Figure 2: CAI testing fixture

For each impact energy level a series of five specimens was tested to determine the residual static compression strength after impact (CAI). Testing conditions were 23 °C and 50 % relative humidity. Crosshead speed of the testing machine was 0.5 mm/min according to AITM 1.0010 [5] and can also be found in literature [9, 10].

2.5. Fatigue testing

Fatigue testing was carried out in a servohydraulic testing machine IPLH50K from Instron Schenk under ambient laboratory conditions. From the residual static compression strengths the upper load spectrum limits for fatigue testing are derived. Run outs were defined for specimens which underwent $2 \cdot 10^6$ load cycles without failure. The compression-compression fatigue tests were performed at 5 Hz with a constant amplitude sinusoidal loading and a stress ratio of $R = 10$.

3. Results and Discussion

3.1. Impact damage

At low impact energies the extent of damage in the GFRP laminates is dominated by the matrix system used. Fig. 3 shows that the epoxy based glass fibre reinforced laminates at impact energies of 10 J and 20 J have much bigger delaminated areas in comparison to the GFRP laminates based on the polyurethane matrix system. At higher impact energies the differences between both matrix materials are less pronounced, since more fibre fracture takes place in the impact location. Especially at low impact energies the damage characteristics of GFRP laminates seem to be strongly affected by the matrix properties. This is in accordance with the higher interlaminar as well as neat resin fracture toughness of the polyurethane system (results not shown here). Moreover, the polyurethane matrix exhibits a better adhesion to the glass fibres used in this investigation.

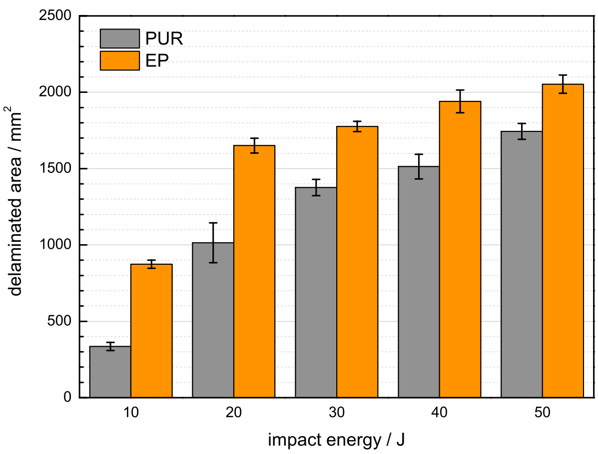

Figure 3: Delaminated areas of polyurethane (PUR) and epoxy (EP) based glass fibre reinforced laminates after different impact loadings

Comparison of specimens with almost the same delaminated areas reveals that an impact energy of 50 J is needed for the polyurethane composite to obtain the same size of delaminated area as a 20 J impact would cause in the epoxy laminate (Fig. 3).

During an impact the entire energy of the impactor is not entirely absorbed by the composite. There are mainly two energy terms: The absorbed energy, which is almost completely dissipated in the composite in terms of creating damage [7] and the elastically stored energy, which lets the impactor rebound from the sample. As can be seen from Fig. 4 and Fig. 5, there is not a general correlation between the dissipated damage-energy and the delaminated area actually developed from. In fact there is a strong dependency on the materials used and their compositions. Delaminated areas are indeed the most common way to characterize the damage of composites, but are only a suitable tool when comparing materials with comparable damage characteristics.

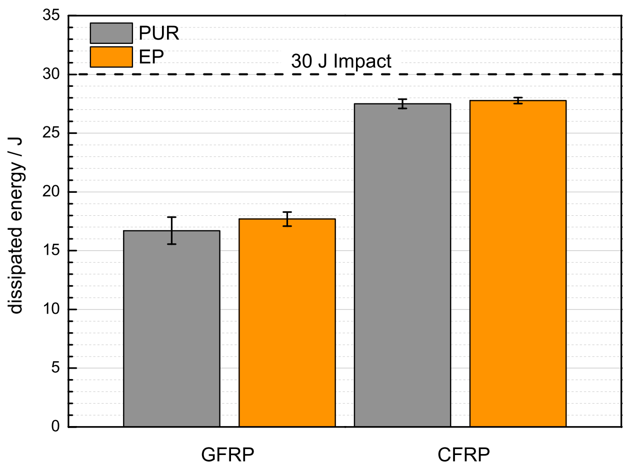

Figure 4: Dissipated energies in the polyurethane and epoxy based glass (GFRP) and carbon (CFRP) fibre reinforced composites at 30 J impacts

Another way to characterize impact damage would be the investigation of the damaged volume. But since the damaged volume is hardly to access and to define, an energy-based approach may be a suitable complementary tool to quantify the damage extent in different composite materials more precisely.

Fig. 4 shows the dissipated energy in GFRP and CFRP laminates at 30 J impacts. Around 58 % of the impact energy is dissipated due to fibre and matrix damage in the GFRP laminates. Impact loading of CFRP laminates with 30 J releases around 93 % of the impact energy within the composite to damage the material. Although the CFPR laminates are absorbing a much higher fraction of the impact energy, the resulting delaminated areas are smaller in comparison to the GFRP laminates (Fig. 5). This indicates the different peculiarities of the failure mechanisms in GFRP and CPRP laminates.

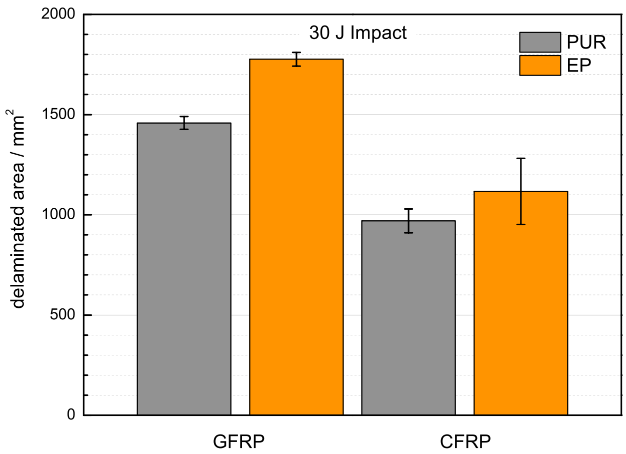

Figure 5: Delaminated areas of the polyurethane and epoxy based glass (GFRP) and carbon (CFRP) fibre reinforced composites after 30 J impacts

The glass fibres have much higher strain to failure than carbon fibres and therefore the GFRP laminates respond to impact loading more elastically than CFRP laminates do. This also corresponds to the observation that impact damage in GFRP laminates spreads more widely in the laminate plane, while the CFRP impact damages are more localized around the impact point and show deeper indentations as well as a higher tendency to penetrate the material. Due to the low strain to failure of the carbon fibres the fibre breakage seems to be much more relevant for CFRP composites and leads also to severe damage propagation perpendicular to the laminate plane. In GFRP composites the higher strain to failure of the glass fibres leads to a higher contribution of the matrix properties to the overall impact damage behaviour. Therefore the use of the improved polyurethane matrix system significantly reduces the delaminations in GFRP composites, while this matrix effects are less visible for CFRP (Fig. 5). In each case, GFRP and CFRP respectively, the absorbed energies for epoxy and polyurethane based composites are equal (Fig. 4). The higher interlaminar fracture toughness of the polyurethane system therefore results in less delaminated areas at the same amount of absorbed energy (Fig. 5, Fig.4).

3.2. Static compression testing

The residual static compression strengths after impact (CAI) of the GFRP composites strongly reflect -as a function of impact energy- their delamination behaviour (Fig. 3, Fig. 6).
At same impact energies the residual compression strengths of the polyurethane GFRP laminates are around 1.5 to 1.6 times higher compared to the standard epoxy GFRP system (Fig. 6), mainly due to the smaller delaminated areas. But even comparing GFRP epoxy and polyurethane specimens with similar damage (epoxy: 20 J, polyurethane: 50 J, Fig. 3) the polyurethane matrix system shows around 1.3 times higher residual compression strength (Fig. 6). Furthermore, even the lowest CAI value of the polyurethane GFRP system (Fig. 6, 50 J) is above the highest residual compression strength of the epoxy system (Fig. 6, 10 J). This leads to the conclusion that for GFRP the better fibre matrix interaction as well as the increased matrix toughness of the polyurethane system significantly enhances the damage resistance and damage tolerance compared to the standard epoxy system.

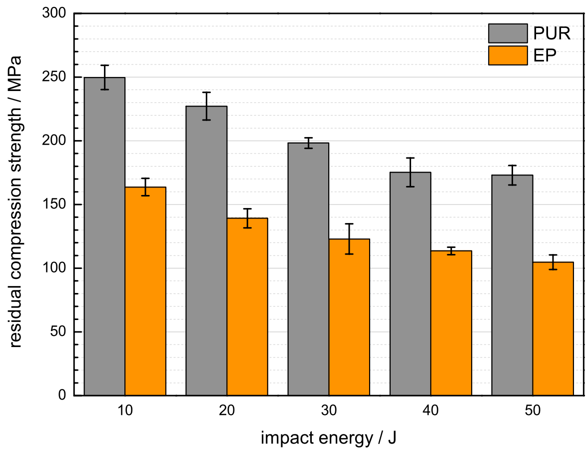

Figure 6: Residual static compression strengths of polyurethane (PUR) and epoxy (EP) based glass fibre reinforced laminates after different impact loadings

The residual compression strengths after 30 J impacts on the GFRP and CFRP laminates reflect also the different damage mechanisms in these materials (Fig. 7). The glass fibre reinforced polyurethane shows the highest residual compression strength because of the elastic response of its glass fibre reinforcement in combination with the good damage resistance of the polyurethane matrix. In the case of carbon fibre reinforced polyurethane the amount of absorbed energy is much higher (Fig. 4), which indicates more extensive material damage. The use of the standard epoxy system in the GFRP composites leads -compared to polyurethane- to a higher decrease in the residual compression strength than in the CFRP laminates. In the GFRP`s under investigation the matrix properties contribute more to the overall CAI performance than in the CFRP laminates. So the CAI performance of a composite material is strongly dependent on its components, their interaction, the amount of absorbed energy and, of course, its compression strength.

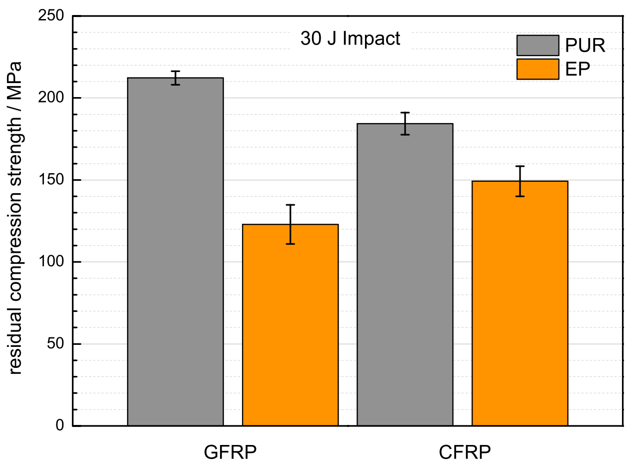

Figure 7: Residual compression strengths of the polyurethane and epoxy based glass (GFRP) and carbon (CFRP) fibre reinforced composites after 30 J impacts

3.3. Compression fatigue

Compression S/N curves were derived from glass and carbon fibre reinforced laminates subjected to 30 J impacts (Fig. 8). The polyurethane based laminates exhibit the best fatigue performance in accordance with the quasistatic properties. In combination with the carbon fibre reinforcement the polyurethane matrix shows a slightly better dynamic damage tolerance for high numbers of load cycles compared to the glass fibre reinforcement, though the quasistatic residual compression strength of the CFRP is slightly lower. The very similar S/N curves of the polyurethane based GFRP and CFRP laminates can be considered as a result of two different main material characteristics: on the one hand the high fraction of elastically reflected energy of the GFRP laminates and on the other hand the high compression strength of CFRP`s.

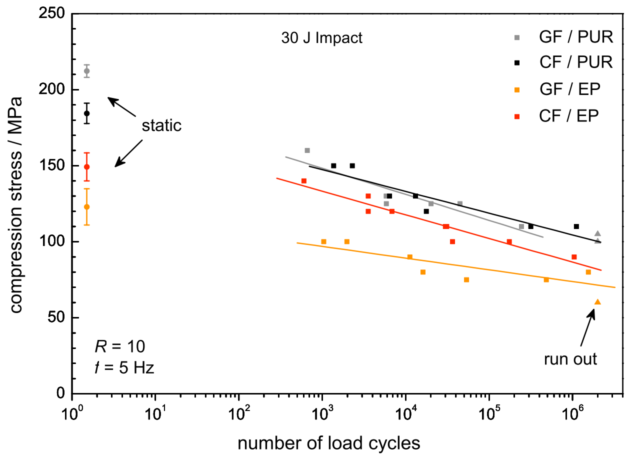

Figure 8: Compression S/N curves of glass and carbon fibre reinforced polyurethane and epoxy after 30 J impact loading

The bearable fatigue loads of the carbon fibre reinforced epoxy laminates are found to be on a lower compression stress level than the polyurethane based ones. But the decrease in fatigue strength -when switching from polyurethane to epoxy matrix- is less pronounced than under static testing conditions. Thanks to good the fibre properties the combination of the brittle epoxy system and carbon fibre results in intermediate fatigue properties, while the glass fibre reinforced epoxy shows the lowest residual compression strength in static as well as under dynamic testing. In this investigation the glass fibre reinforced standard epoxy represents the material with the lowest damage resistance in terms of delaminated areas. The shallow slope of the epoxy-glass S/N curve implies a less critical fatigue damage growth but on a much lower level compared to the other investigated materials.

4. Conclusion

The use of the polyurethane matrix system significantly improved the damage resistance and damage tolerance of glass fibre reinforced composites within the investigated impact energy range from 10 J to 50 J, compared to a standard epoxy reference resin. Under dynamic loading after 30 J impact the thermosetting polyurethane showed its superior fatigue performance particularly in combination with glass fibres. In the carbon fibre reinforced composites the polyurethane matrix improves the damage resistance and damage tolerance as well, but not in the dimensions observed as in combination with glass fibres. Possible reasons for this behaviour can be the higher amount of fibre breakage in the CFRP laminates during impact loading and therefore the lower influence of the matrix properties on the overall CAI performance. At impact energies of 30 J the static residual compression strengths are dominated by the matrix system used, while under dynamic compression after impact testing the good mechanical properties of the carbon fibres become more visible. Glass fibre reinforced polyurethane has the highest static residual compression strength while the combination of polyurethane and carbon fibre seems to be best in fatigue properties.

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