INFLUENCE OF IMPACT DAMAGE ON THE FATIGUE BEHAVIOUR OF LARGE SCALE COMPOSITES

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Keywords: Glass fibre reinforced polymers, Damage mechanisms, Defects, Multiaxial loading

ABSTRACT

Defects in composite structures like impact damages have a major influence on the fatigue behaviour. These defects may occur during lifetime of composite parts and lead to delaminations between adjacent layers with different fibre orientations and to matrix cracks within these layers.

We investigated the relationship between impact damage and fatigue lifetime. Specimens made of a glass fibre non-crimp fabric (NCF) were produced by vacuum assisted resin transfer moulding (VARTM). Impact damage was introduced using a drop weight with a hemispherical head and a canon. Two types of specimens were used: coupons with dimensions of 250 mm x 30 mm and a stringer-panel with the dimensions of about 1000 mm x 1000 mm. The panel was tested in a hexapod test rig applying multiaxial loads. In comparison, the obtained results from the coupon tests can be transferred to larger scale composite structures.

In coupon tests, it was purposed to characterise the damage development in fatigue of fibre reinforced polymers as a function of impact damage, lifetime and stress ratio as precise as possible. Therefore, the stiffness degradation during fatigue due to matrix cracks, delaminations, fibre failure and temperature development of the specimens was plotted vs. the number of load cycles. In interrupted fatigue tests at defined numbers of load cycles the influence of defects on the matrix crack development was determined and correlated with the stiffness degradation. Furthermore, thermoelastic stress analysis was performed during the interrupted tests in order to determine the stress concentrations in the area of the impact damage. The coupons were tested under fatigue loading using a stress ratio of R=1 (tension-compression) and R=10 (compression-compression).

1 INTRODUCTION

Composite materials find increasing application in technical structures, mainly aircraft, as rotor blades for windmills, and in general engineering applications. However, the design guides and the presently existing failure criteria do lead to an insufficient use of their strength potential. While an intense use of textile structures for composite materials, with their sophisticated fibre architecture in the textile reinforcement, their design is still extremely conservative. This is due to a lack of understanding of the three dimensional stress state inside composite materials. It is therefore evident to investigate composite materials under multiaxial loading conditions.

To ensure the service of a component over a long period, it is necessary to exactly know the material-specific fatigue behaviour after impact damage, also known as post-impact fatigue (PIF) [1,2].

Under cyclic loading in tension and compression, the damage behaviour of FRP is a combination of different damage mechanisms like matrix cracks, fibre–matrix deboning, delamination and fibre fracture. All the observed types of damage cause stiffness degradation of the composite before ultimate failure [3,4]. At tensile fatigue loading the different damage mechanisms can be classified in three phases of damage accumulation [5,6]. Phase I is characterised by inter fibre crack initiation and crack growth, which leads to a strong increase of the matrix crack density in the transverse layers and resulting in a decrease in stiffness. In phase II the characteristic damage state (CDS) characterized by a saturation of transverse cracks is reached [4]. In parallel delaminations start to form at the intersection of transverse matrix cracks and adjacent layers, though the decrease in material stiffness is slow.
Delamination growth and stress redistribution accelerate the degradation process in phase III causing fibre fracture and steep decrease of residual stiffness, yielding to the final failure [5,7,8]. Under compressive fatigue loading the composites did not show the three phases of composites degradation and only a small initial loss in stiffness mainly caused by longitudinal matrix cracks [9,10] occur.

In the case of tensile and compressive loads are applied to the FRP a faster degradation and earlier final failure at comparable stress levels [10,11] is observed. Damage caused by an impact can have a negative effect on the fatigue performance of FRP. Generally, the failure mode of impact damage is extensive, including matrix cracks, delaminations and fibre fracture [12].

With regard to this background, the objective is to evaluate the influence of impact damage on the fatigue behaviour and lifetime of GFRP by mechanical testing of standard coupons as well as larger structures.

2 MATERIAL AND EXPERIMENTAL PROCEDURE

2.1. Material

The FRPs consist of two glass fibre non crimp fabrics (GF-NCF) made of the roving OC 111A from Owens Corning infiltrated with epoxy resin Epikote MGS RIM 135 and curing agent Epikure MGS RIMH 137 (Momentive) by vacuum assisted resin transfer moulding (VARTM), cured for 48h at 30°C. The laminates consist of eight plies \([0°-45°90°45°]\), with a fibre volume content of 34.3% ± 3%. Each ply orientation has different quantities in the laminate: \([0°:49%,-45°:23%,90°:5%,\)
45°:23%\]. The mechanical properties of matrix and fibres are given in [9]. Aluminium/GFRP end tabs were attached to ensure homogenous load introduction. Specimens with dimensions of 250 mm x 30 mm x 3 mm were cut with a diamond saw in 0° direction of the GF-NCF, which is the main reinforcement direction. To avoid edge delamination, the specimen edges were polished with siliconcarbid sandpaper. After specimen preparation a post-curing of 15h at 80°C was performed to obtain a glass transition temperature of about 86°C. The specimens were then stored at standard conditions of 23°C and 50% humidity for at least one week until testing to reduce internal stresses, as proposed by Schürmann [13].

The test panels consist of the same material as the coupon specimens. The panels were designed by IFL Braunschweig and manufactured at ILK Dresden.

2.2 Cyclic loading, coupon test

The coupons tests were performed with a test frequency of 4 Hz on a servo-hydraulic test machine. The stress ratio was \(R = -1\) which is tension and compression loading. In total, six stress – life – curves (S/N-curves) with different levels of impact energy were determined. All specimens were loaded stress-controlled with a sinusoidal load until macroscopic failure. An anti-buckling device consisting of two aluminium halves, placed on both sides of the specimens was used to avoid global buckling. To reduce friction between the anti-buckling device and specimen the aluminium was covered with a polytetrafluoroethylene (PTFE) foil. A slot in the anti-buckling device allowed local buckling as recommended by Matondang and Schütz [14], strain measurements with a laser extensometer and observation of the specimen with NDT techniques. The stiffness variation is used as an indicator for material degradation \(D = 1-E/E0\). Specimens without impact damage were tested without any interruptions until final failure. Cyclic loading of all other specimens was interrupted after 50 cycles to introduce an impact damage. To obtain detailed data about the fatigue behaviour, some impacted specimens were tested in repeatedly interrupted fatigue tests after defined numbers of cycles for application of NDT methods optical scan.

2.3. Introducing impact damage to coupons

Specimens were removed from the fatigue test machine to introduce impact damage with a drop weight having a semi hemispherical head and a diameter of 20 mm. The mass of the impactor was constantly \(m = 1.3\) kg. To obtain different energy levels the drop height was changed. Investigated impact energies were 1.02 J, 1.91 J, 2.55 J, 3.19 J, 3.95 J and 5.1 J, according to the initial potential energy of the impactor, no dissipation was taken into account. All introduced impacts were low
velocity impacts (LVI) as defined in [15–17]. Specimens were clamped pneumatically between rubberised steel bearings with a hole underneath the specimen. The diameter of the hole underneath was 25 mm and the hole in the upper clamping was 40 mm. Ensured by a spacer, the impact was introduced exactly in the centre of the specimens. All impacts were introduced after 50 fatigue load cycles in order to simulate an impact damage of the structure during lifetime where material degradation had already taken place. After impacting, specimens were tested in the servo hydraulic testing machine as described above.

![Figure 1: Optical scan of specimen preloaded at ±140MPa for 50 cycles and 5.1J impact.](image1)

2.3 Cyclic loading of stringer panel and impact

The hexapod testing machine is a unique set up. Figure 2 shows a schematic of the hexapod. It is possible to perform all types of torsion, shear and normal loads and to combine these. It enables to test composite structures under realistic (multiaxial) loading conditions at high frequencies. Multiaxial testing involves the controlled use of numerous hydraulic cylinders, working continuously but separately controlled. For a hexapod six hydraulic cylinders have to work together. The stringer-reinforced test panel is located between the rig (yellow) and the load cell (black). In detail the set up allows a single force up to 500kN and single torque of 40kNm. The displacements and corresponding angles are in combination ±150 mm (max. ±300 mm) and ± 5° (max. ± 12°), respectively. The dynamic capabilities are a max. speed of 1m/sec, an acceleration up to 6 g and a test frequency of max 30 Hz.

![Figure 2: Test setup of the hexapod.](image2)
The applied load for the present test campaign is a combination of tension-compression load of $F_{x,\text{mean}}=22.5\text{kN}$ and $F_{x,\text{amp}}=57.5\text{kN}$ in phase with the shear of $F_{y,\text{mean}}=13\text{kN}$ and $F_{y,\text{amp}}=33\text{kN}$. The test frequency was $1\text{Hz}$. Figure 3 illustrates the applied loading conditions. The impacted area in the central part of the panel was investigated by a digital image correlation system (DIC) to achieve information about the local deformation during loading.

Before starting the fatigue tests, the impact damage was introduced into the panel by shooting a plastic (POM) bullet of $20\text{mm}$ in diameter onto the center of the panel. The air gun had $8\text{bar}$ pressure leading to achieve an impact energy of $14\text{J}$.

3 RESULTS & DISCUSSION

3.1 Coupon tests and critical impact energy

More than $86\%$ of the impacted specimens failed directly in the area of the impact damage. The decrease of the fatigue life with increasing impact energy is depending on the fatigue load level. At low load levels, rather high impact energy levels result in a considerable loss of fatigue lifetime, while at higher load levels small impacts already lead to a significant decrease in fatigue lifetime. Thus, the fatigue life is reduced by an impact, but it depends on the impact energy and the fatigue load level in mechanical testing. It seems that for each load level there is a distinctive difference concerning the influence of the impact energy on the fatigue life. One possibility to describe this phenomenon could be the definition of a critical impact energy level. If it is exceeded the fatigue life strongly decreases. The amount is dependent on the applied load level. Fig. 5 shows the correlation of fatigue life and
impact energy. The mean values and the standard deviation of the number of cycles to failure, based on a log-normal distribution, are shown for each load level. For each of the three investigated load levels a unique relation between the samples’ fatigue life and impact energy was obtained. The specific critical impact energy level ranges from 2.55 J to 3.19 J at a stress level of ±125 MPa and from 1.91 J to 2.55 J at ±140 MPa and is below 1.91 J at ±152 MPa, respectively.

![Figure 5: Mean values of cycles to failure plotted against impact energy and fitted by Boltzmann regression to visualise the change of fatigue life caused by impact damage.](image)

### 3.2 Stiffness and Damage Evolution of the Stringer Panel

The delaminated area in the test panel has not grown after 50,000 load cycles (Fig. 6). However, the number of interfibre cracks increased. The damage evolution is very similar to the behaviour of the coupon specimens under uniaxial load. Furthermore, the delaminated areas do not show a specific deflection in thickness of the panel (z-direction), marked in red in Fig. 7.

![Figure 6: Panel with impact damage after 50000 load cycles](image)
Figure 7: DIC Measurement displacement in z-direction.

At each load cycle, the secant modulus was recorded. The degradation of the panel show a moderate decrease in stiffness versus life time. After 50,000 load cycles the panel failed during the compressive portion of the loading (Fig. 8).

Figure 8: a) Stiffness evolution in 0°-fibre direction; the circle represents final failure of the panel; b) Final failure of the panel during compressive load cycle (N=50,000).

9 CONCLUSIONS

There is a specific and critical impact energy causing a dramatic decrease of fatigue life. For the tested material a unique critical value of impact energy exists, which is dependent on the stress level. However, no lateral growth of delamination area was found for the coupon tests as well as for the test panel, but the growth of interfibre cracks was intensive next the impacted area.

ACKNOWLEDGEMENTS

The authors are grateful to the German Research Foundation (DFG) for supporting this work as part of the project SCHU 926/16-2 within PAK267. Special thanks to Prof. P. Horst from, ILF TU Braunschweig, GER, for the design of the test panel and Prof. M. Gude from ILK, TU Dresden, GER, for its manufacturing. Results are partly published in Composites Science and Technology 102 (2014) 28–34.
REFERENCES


