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Damage monitoring in polymer matrix structures

K. SCHULTE

Polymer Composites Group, Technical University, Hamburg-Harburg, 21073 Hamburg, Germany

ABSTRACT

The variation of the mechanical stiffness during fatigue loading has been shown to be an important qualitative and quantitative damage analogue. A correlation between stiffness reduction and the development of the various types of damage, such as intra- and interply cracking, delamination growth or fibre fracture, has been made by various authors. In this paper, the in situ detection of the temperature increase during fatigue loading together with the measurement of the variation of the electrical resistivity is reported. Both techniques promise to be valuable analogues to monitor damage development.

INTRODUCTION

Fatigue failure in metals is known to consist of crack initiation and growth. Crack initiation starts with dislocation movement. Submicrocracks are then formed at slip bands. They subsequently grow and coalesce to form a crack of detectable size (short crack to complete the crack initiation process. This is then followed by the growth of a single crack until final rupture. The period of crack initiation and submicrocrack growth covers most of the fatigue life.

In composite laminates the fatigue process is characterized by the initiation and multiplication rather than propagation of cracks. Crack initiation in composites takes place very early in fatigue life and coincides with the first ply failure, i.e., the first cracking of the weakest ply. While in metals, crack growth accelerates during fatigue, the crack multiplication in composites decelerates, resulting in the uncontrolled final rupture of the composite, also called the "sudden death" [1].

The similarities between the fatigue mechanisms suggest, one might borrow from the well developed metals technology. The differences, however, point out the need to develop a specific methodology suitable for composites.

Composite materials offer substantial improvements over metals for application to structures subjected to fatigue loading. Their characteristic response to fatigue, however, is substantially different from that of metals. Whereas in metals damage development under cyclic loading exhibits one failure mode, which is the initiation and propagation of one single crack, composites exhibit a combination of different failure modes, which is the initiation and multiplication (and not growth) of cracks, including transverse, longitudinal and angle ply cracking in the matrix along fibres (inter ply cracks), delaminations (intra ply cracks), fibre fracture and interface debonding.

In this paper it is tried to review three different techniques to continuously monitor damage development, which is accompanied by different damage mechanisms.

STIFFNESS REDUCTION

During fatigue cycling, stiffness reduction can be used as an analogue to monitor damage development. Its change can be related directly to stress redistributions which can be expected, if internal damage occurs in composite laminates [2-4]. A typical stiffness reduction curve for the cross-ply laminate with continuous fibres is shown in Fig. 1a. The shape of the curve suggests three regions of interest: an initiation region (stage I) with a rapid stiffness reduction of 2-5 per cent, an intermediate region (stage II), in which additional 1-5 per cent stiffness reduction occurs in an approximately linear fashion, and a final region (stage III), in which stiffness reduction occurs in abrupt steps ending in specimen fracture. A very similar behaviour in stiffness reduction due to tension fatigue loading can be observed for the cross-ply laminate with aligned short carbon fibres (Fig. 1b). In the woven fabric (Fig. 1c) the initial stiffness reduction (stage I) in early fatigue life is followed by a region with a gradual reduction (stage II). In contrast to the cross-ply laminates with continuous and short carbon fibres, final fracture did not initiate abruptly (sudden death behaviour) with the last 10 per cent of fatigue life; after about 50 per cent of the fatigue life a further pronounced decrease in stiffness occurred, leading by a stepwise reduction to fracture of the test coupons (stage III) [5].

Fig. 1 Normalized stiffness reduction (E/E_0) versus fatigue life.
a) Continuous fibres
b) Aligned short fibres
c) Eight-shaft satin fabric

EFFECT OF THERMAL HEATING

Under cyclic loading conditions, when performed at high frequencies of about 10 Hz, an internal generation of heat leads to an increase in specimen temperature. Polymer materials show an internal heating due to cyclic loading. Therefore a temperature variation can as well be used to monitor damage [6-9]. During fatigue loading of a composite material the heat generation can mainly be related to the matrix material used, its viscoelastic behaviour, internal friction and the amount of crosslinking. The type of fibre, its volume

fraction and orientation and the stacking sequence in a composite laminate additionally effect matrix loading and therefore heat generation. In addition to the materials aspects, conditions as shape of sample, test frequency and load level influence the amount of heating. However, also under static loading conditions a temperature variation of a material can occur [10]. In 1851 Thomson (Lord Kelvin) [11, 12] showed the proportionality between the load change applied and the resulting temperature variation for an isotropic material under adiabatic elastic deformation and uniaxial stress where

$$T = -\alpha_1 T_0 \Delta\sigma / c \rho$$

α_1	K ⁻¹	= linear coefficient of thermal expansion
T_0	K	= ambient temperature
c	kJ K ⁻¹ m ⁻³	= specific heat capacity
ρ	g/cm ³	= specific density
$\Delta\sigma$	N/mm ²	= stress change
ΔT	K	= temperature change

The above equation describes, the so called "Thermoelastic Effect". The amount of temperature change of a certain volume element depends on the change of the sum of principal stresses, on its material factors and on the ambient temperature. For an isotropic material with a positive coefficient of thermal expansion uniaxial tensile stresses lead to a decrease in temperature.

In Fig. 2 are shown the results from a cross-ply laminate, containing 0°- and 90°-plies. The fibres in the 90°-plies hinder transverse deformation. They are under compressive load and their temperature change is negative. In addition, the matrix in the 90°-plies is under tensile loading, leading for the matrix, which has a positive thermal expansion coefficient, to a cooling down.

Both these effects superimpose the temperature increase in the 0°-plies, and the result is a cooling down of the entire specimen. At higher stresses, with the initiation of transverse cracks [13] in the 90°-plies, the stresses in the 90°-plies are locally released and a load transfer from the 90°-plies into the neighbouring 0°-

Fig. 2: Tensile test of a cross-ply laminate. Variation of strain and specimen temperature.

plies occurs. With increasing number of cracks the temperature increase due to loading of the 0°-plies becomes more and more dominant (the curve of temperature change goes through a minimum) and at high stresses the temperature increase can be measured. Viscoelastic deformations at the transverse crack tips possibly contribute to the temperature increase.

In Fig. 3 is shown the temperature development in a cross-ply test piece. A temperature increase due to dissipation can be observed at the beginning of the test. Later the temperature remains constant. This has two reasons:

- Each specimen has, depending on load level, frequency, stacking sequence and constituents a stable temperature level [6].
- A damaged specimen has, if a constant damage state is reached, a higher stable temperature level as an undamaged one [6].

For the present test, where the result is shown in Fig. 3, a constant damage state means, that in early load history (during the first load cycles) transverse cracks initiate in the 90° -plies, which are also responsible for the slight stiffness reduction observed at the beginning of the test. Later the number of transverse cracks, the stiffness reduction and the specimen temperature remain constant.

In the case of continuous damage growth, which will be observed at higher fatigue load levels, also a continuous increase in specimen temperature is measured. Fig. 4a shows the temperature change for four different tests. All tests were performed until specimen rupture occurred. A continuous temperature increase can be observed throughout the tests. This corresponds with the parallel observation of the

Fig. 3: Fatigue test of a cross-ply laminate at a low load level. Stiffness reduction, development of transverse cracks and temperature change are plotted versus the number of load cycles. Specimen did not fail. Number of transverse cracks taken from x-ray radiographs.

Fig. 4: Fatigue test of cross-ply laminates at high load levels. All specimens run to failure.
 a) Temperature change versus number of load cycles.
 b) development of transverse cracks versus number of load cycles. Number of transverse cracks taken from x-ray radiographs.

transverse crack development (Fig. 4b), where the number of cracks increases with increasing load cycles, and, the higher the cyclic load level the more transverse cracks are formed.

The variation of specimen temperature can be used, as well, as a damage analogue for composite materials. Increasing specimen temperature is a result of increasing (matrix) damage.

EFFECT OF VARIATION OF ELECTRICAL RESISTIVITY

In the case of a usual metal sample the conductivity is essentially the same for any direction of current flow through the sample. In CFRP samples the conductivity is not homogeneous and depends on the orientation of the fibres. The specific resistivity for carbon fibres ($1500 \times 10^{-8} \Omega\text{m}$) is much higher than that for metals (i.e. aluminium = $2.5 \times 10^{-8} \Omega\text{m}$). The high specific electrical resistivity of the epoxy matrix used is to be seen as an insulator. The electrical resistivity measurement records mainly fibre breakage in form of a change in electrical resistivity [14]. The current-conducting carbon fibres lead to a certain electrical resistivity of the entire laminate, which mainly depends on the volume fraction and the stacking sequence of the laminate.

Fracture of single carbon fibres can be expected in cfrp laminates under static loading [13]. The observation of fibre fracture is, in general, not possible during a load test except when fibres split off the specimen surface and can be seen with the naked eye. However, the variation in electrical resistivity during static loading is a clear indicator of fibre fracture, as seen from Fig. 5, which shows the stress-strain curve of a unidirectional specimen $[0_g]$ together with the variation of electrical resistivity with laminate strain.

Fig. 5 Tensile test of a unidirectional laminate, showing the stress/strain curve and dependent electrical resistivity of a cfrp specimen [14].

The electrical resistivity first increases approximately linearly with increasing fibre strain. This increase in resistivity, R , is expected, because

$$R = \frac{\rho \cdot l}{A}$$

with ρ = specific electrical resistivity, l = current path length and A = conductor section. The length l , increases under load and A decreases. After about 0.7% strain the electrical resistivity no longer varies linearly. This can be related to fibre fracture. Above 1.2% strain the electrical resistivity rises in stepwise fashion to higher values. This can be directly related to fibre fracture. The fibre fracture is partly indicated - but with a much lower resolution - in the stress-strain curve.

The electrical resistivity method, however, cannot only indicate strain and fibre fracture, but also delaminations, one of the most pronounced damage mechanism, can be detected. In Fig. 6 is shown the result of a tensile test on a unidirectional specimen consisting of 5 plies [15]. The third ply (center ply) was cut through. During initial loading linear elastic deformation occurs, following Hook's law, with a linear increase in electrical resistivity. In the cutted third ply shear stresses transfer the loads from one ply end to the other through the matrix and neighbouring intact plies. When the shear stress exceeds the matrix properties a delamination initiates, and a plateau is formed in the stress-strain curve. Subsequently the electrical resistivity increases. Only when the delamination growth has come to an end, that is when the third (center)ply is completely separated from the neighbouring plies, a further increase in the stress-strain curve and electrical resistivity can be observed.

Fig. 6: Tensile test of a unidirectional laminate. Center ply was cut through stress-strain curve and dependent variation of electrical resistivity; both indicating delamination growth [15].

In Fig. 7 is shown the result of a fatigue test on a $[0_2, 90_2, 0_2, 90_2]_s$ cross-ply laminate [14]. Specimen temperature, stiffness reduction (normalized secant modulus) and electrical resistivity were simultaneously measured and correlated with fatigue life. During the test, the maximum load in a fatigue cycle was increased in stepwise fashion. Fig. 7 suggests the following:

- The electrical resistivity increases, but at each load step the resistivity jumps to a higher level.
- During the test, a continuous increase in temperature, dependent on frequency and maximum load level, can be observed.
- The high stiffness reduction at the beginning of the fatigue test can be related to transverse crack development in the 90° -plies, which is strongly related to the temperature increase.
- At the end of the fatigue test, approaching final failure, a strong stiffness reduction is again observed, accompanied by a rapid temperature increase. The resistivity jumps in steps to higher levels, which indicates that load bearing 0° -fibres have failed. The onset of final failure is then initiated.

It was shown in previous papers that the final reduction in stiffness can be related to the failure of a single fibre or even bundles of fibres [5].

The method of monitoring the electrical resistivity is thus an appropriate non-destructive in-situ technique to monitor damage development and especially to investigate fibre fracture.

Fig. 7: Variation of secant modulus, temperature and electrical resistivity during cyclic loading (% of fatigue life) of a cross-ply laminate [13].

CONCLUSION

The measurement of the temperature variation can be used to get information about the internal damage situation in a carbon fibre reinforced plastic laminate. It can especially be used in fatigue tests as a damage analogue. The measurement of the variation of the electrical resistivity in a carbon fibre reinforced plastic laminate should be applied in combination with temperature measurements, because the resistivity of the fibres decreases with increasing temperature. It is an appropriate method for continuously monitoring the damage of a cfrp component.

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