1 Introduction
Carbon fibres are primarily used in lightweight structures because of their excellent mechanical properties. More and more, the known electrical properties of carbon fibres become of interest for smart composites [1].

For the following investigation electric isolated ex-PAN carbon fibre rovings (Toray T300B 1K) are used as piezoresistive embedded sensors. In previous papers it has been shown that these carbon fibre sensors (CFS) can be used as strain sensors [2, 3].

The objective of this paper is the monitoring of microcracks in continuous fibre reinforced plastics. Based on experimental results a fundamental study is performed using analytical and numerical simulation methods.

CFS applied to composite pressure vessels are investigated to verify their usability as monitoring sensors.

2 Experimental Characterization
Carbon fibres are used as sensor elements. The piezoresistivity, the influence of a single crack and multicrocking are investigated in tension tests.

All tests are carried out using specimens made of unidirectional glass fibre reinforced laminates (GFRP) to avoid a short circuit with the embedded CFS. The GFRP specimens are made of the HexPly NVE 913/28%/192/EC9756 or EC9673 prepreg system. Both contain the same resin system and glass fibres with similar mechanical properties. Consequently, there are no differences between these two prepreg systems in the following experiments and simulations. The laminates are cured by means of a vacuum bag and a hot press for 1.5 hours at 120°C and 7 bar.

The change of electrical resistance of the CFS is measured by means of Wheatstone half bridges. Unloaded specimens of the same kind with CFS, positioned next to the loaded specimens, enable compensation of temperature effects. The CFS endings are metal-coated to provide an electrical connection to the half bridge circuits. The feeding voltage of the amplifier (HBM MGCplus ML801/AP815i and Spider 8-30) is 1.0 and 2.5 V.

2.1 Carbon fibre as sensor element
In [2] it has been shown, that the piezoresistivity of the CFS can be described by the following equation:

\[
\frac{dR}{R_0} = \varepsilon (1 + 2\nu) + \frac{d\rho}{\rho} = k \cdot \varepsilon, \quad (1)
\]

\(k\) strain sensitivity,
\(R_0\) initial electrical resistance,
\(dR\) change of the electrical resistance,
\(\varepsilon\) strain,
\(\nu\) Poisson ratio,
\(\rho\) specific electrical resistance.

For the experimental characterization, specific tension specimens of GFRP laminates with embedded CFS [2] are used. For specimen type #1 (Fig. 1) the CFS is embedded in an area of constant extensional stiffness resulting in homogeneous strain level subjected to tension load. This specimen is used to determine the strain sensitivity \(k\) for different specimen layups.

Due to the fact that the metal-coated endings of the CFS are possibly damaged at strain levels higher
than 2.500 µm/m, the specimen type #2 (Fig 2) provides a load relieving area A. The metal-coated endings are positioned in this load relieving area A, where extended tabs with additional reinforcements are placed. These tabs relieve the strain level at the area A compared to the strain level at the testing area B. Therefore specimen type #2 (Fig 2) is used for investigations of the sensor behaviour at higher strain levels. All CFS are embedded in a single 0° layer at the symmetry plane of the specimens.

The CFS measure the strain along the total sensor length. The integral strain measurement can be defined by:

\[
\frac{\Delta R}{R_0} = \frac{k}{l} \int_0^l \varepsilon(x) dx ,
\]

(2)

\( l \) fibre length,
\( R_0 \) initial electrical resistance,
\( \Delta R \) change of the electrical resistance,
\( x \) fibre direction.

Therefore the change of resistance of sensor fibres along \( m \) areas with different extensional stiffnesses can be described by:

\[
\left( \frac{\Delta R}{R} \right)_l = \sum_{j=1}^m \left( \frac{\Delta R}{R} \right)_{l,j},
\]

(3)

\( l \) fibre length,
\( m \) number of areas with different extensional stiffnesses.

With the aid of equation (2) and \( \varepsilon_j = (F / C_j) \) the electrical resistance of a CFS embedded along the areas with different extensional stiffnesses \( C_j \) can be calculated by:

\[
\left( \frac{\Delta R}{R} \right)_l = \sum_{j=1}^m l_j k_j \frac{F}{C_j},
\]

(4)

\( F \) tension force,
\( C_j \) extensional stiffness of area \( j \).

For the specimen type #2 equation (4) results in:

\[
\left( \frac{\Delta R}{R} \right)_{\text{CFS}} = \left( \frac{l_A}{l_{\text{CFS}}} k_A \frac{F}{C_{A}} \right) + \left( \frac{l_B}{l_{\text{CFS}}} k_B \frac{F}{C_{B}} \right),
\]

(5)

\( l_A \) load relieving area,
\( l_B \) testing area,
\( l_A \) CFS length in area A,
\( l_B \) CFS length in area B,
\( l_{\text{CFS}} \) total CFS length.

2.2 Test series

Static and cycling tension tests are performed with a constant testing speed of 0.6 to 7.0 mm/min. For the cycling tests each specimen is loaded five times at each load level. After this the load level is increased. For each specimen 5 to 10 steps are applied ranging from 10 % to 80 % of the ultimate tension load. Tab. 1 specifies the dimensions of the used tensile specimens.

2.2.1 Piezoresistivity

Two tension tests are performed, one at low strain levels with specimen type #1 and one at high strain levels with specimen type #2. The layup of unidirectional layers [0]_s used in the specimens enables the investigation of the CFS behaviour without the influence of any cracks.

Fig. 3 shows the change of resistance \( \Delta R/R \) of the embedded CFS in specimen type #1 with the strain level \( \varepsilon \) (measured by strain gauge). In total, there are nine CFS in three specimens tested. The specimens are loaded and unloaded five times up to a strain level of 1 070 µm/m. The determined strain sensitivity \( k \) has an arithmetic average of 1,727 with a standard deviation of 0,014.

The tests at strain levels higher than 2 500 µm/m with the specimen type #2 show a linear piezoresistivity up to the strain level of 8 000 µm/m (Fig. 4). This linear behaviour up to high strain levels is a basic prerequisite to use CFS as a strain sensor and for crack monitoring.

2.2.2 Single crack

For crack monitoring by means of CFS it is essential to know the influence of a single crack on the CFS signal. For this purpose, a specific specimen is developed with a similar concept to TCT-specimens (transverse crack tension) and to the specimen type #2 (Fig. 5). The layup is [0/0°/0°/0°/0°] at the testing area and the CFS are embedded in the
symmetry plane. The layers, which are termed “0°”, are cut through all at the same place.

In the beginning of the test, both ends of the cut layers are bonded together by resin. At an average stress of 93.1 MPa this bonding fails and a single crack is formed. An average change of 122 μΩ/Ω at ΔR/R = 3 300 μΩ/Ω is detected for the embedded CFS. Fig. 6 shows exemplarily for one specimen the crack initiation at the stress level of 91.3 MPa and the change of 138 μΩ/Ω at 134 MPa. No influence of the presence of CFS on the stress level resulting in the crack initiation could be observed. Fig. 7 shows the behaviour of one CFS in a cycling test with increasing stress levels. The global strain is measured by an extensometer, which is positioned in an area not influenced by the crack. The influence of the crack on the CFS signal increases with increasing stress level. The presence of the single crack leads at a stress level of 178 MPa to a change of 350 μΩ/Ω at ΔR/R = 5 000 μΩ/Ω.

At strain levels measured by the extensometer higher than 4 000 μm/m, disproportionately high changes of resistance are measured at the load cycle with a maximum stress level of 223 MPa. Fractures of filaments of the CFS near the tip of the single crack could be verified by means of microscopic inspection.

2.2.3 Multicracking

The influence of microcracks on the CFS-signal is investigated by means of transverse cracks in 90° layers subjected by tension load. Therefore two different laminates consisting of 0° and 90° layers ([0/90] and [90/0]) are used to analyse multicracking in static and cycling tension test. The load is increased until transverse cracks in the 90° layers are initiated and the crack density reaches a constant value. The crack density, the resulting stiffness loss of the specimen, the sensor signal and the acoustic emission energy are used for characterization. The crack density is determined by light transmission and by counting the number of cracks in the specimens (Fig. 8).

At the time the first transverse cracks are initiated and become visible at the laminate [0/900/900/0], the first significant acoustic emissions (AE) are detected, the strain signal of the strain gauge and the resistance of the CFS increase (Fig. 9 and 10). High signal levels up to 40 000 μΩ/Ω are measured by the CFS at a crack density of 1.0 mm-1. Fig. 9 indicates that the CFS signal correlates to the increasing crack density.

The AE signals are recorded using four wide band SE-sensors with a band-pass filter ranging from 20 kHz to 1 MHz, an acquisition rate of 10 MS/s and a 20 or 40 dB preamplification. The signals are detected with a threshold based triggering. More details of the experimental setup, the used pattern recognition and results can be found in [4, 5].

Tab. 2 summarizes the pattern recognition results of GFRP specimens [0/900/900/0] for static and cycling tension tests. The AE-onset takes place at the same stress level for specimens with and without embedded CFS. The analyses of the AE signals by pattern recognition allow the relation of acoustic emission energies to different failures.

The biggest energy fraction can be attributed to matrix cracking, which can be verified by means of microscopic inspection of transverse cracks in the 90° layers (Fig. 11). Another major energy fraction relates to interface failure, which appears at transverse cracks as well. A significantly smaller energy fraction belongs to acoustic emissions which are correlated to single fibre breaking.

Fig. 11 shows a micrograph for the GFRP specimen [0/900/900/0] after static tension test with a maximum stress of 215 MPa. In the symmetry plane the embedded CFS is visible and the transverse cracks in the 90° layers are identifiable. In addition, fractures of single filaments of the CFS at two transverse crack tips are visible.

The test procedure is repeated with the laminate [90/0/900]. Using this setup, the transverse cracks initiated in the 90° layers are lying outside. In summary the same behaviour of the CFS can be observed at crack initiations and at increasing crack density. Furthermore fractured filaments of the CFS at the crack tips are observed at specimen, which are loaded to 80 % of their ultimate tension strength.

3 Simulation of the interaction between microcracks and the CFS

Shear-Lag-Analysys [6, 7] and a detailed finite element modelling are applied to simulate the global stiffness loss of the laminate and the local effects near to the crack tip on the CFS.

For all simulations it is assumed that the transverse cracks extend over the total width and the total
thickness of the 90° plies. The path of these cracks is perpendicular to the adjacent 0° plies and parallel to the yz-plane. The distance between adjacent cracks is constant and the crack surfaces are stress free. Fig. 12 shows a typical 0°/90° laminate with these assumptions. The crack distance is described by the parameter a.

3.1 Shear-Lag-Analysis

One possibility to investigate transverse cracks in laminates is provided by the analytical approach of Shear-Lag-Analysis. In this paper, the one dimensional analysis of Garret and Bailey [6] and its refinement by Nairn et al. [7] are used. In laminates [0°/90°/0°] (Fig. 12) the load in the cracked 90° plies is transferred to the adjacent undamaged 0° plies. The additional stress $\Delta \sigma(x)$ transferred from the 90° plies to the 0° plies is given by [7]:

$$\Delta \sigma(x) = e_c \frac{E_{90}t_{90}}{t_{90}} \frac{\cosh\left(\frac{a - x}{2}\phi\right)}{\cosh\left(\frac{a}{2}\phi\right)} ,$$

(6)

where

$$\phi^2 = \frac{Gz_{900}E_c(t_{90} + t_{0°})}{E_{900}E_{0°}t_{0°}^2} ,$$

$x$ distance from the crack,

$e_c$ strain at the undamaged laminate,

$E$ Young’s modulus,

$G$ shear modulus,

$t$ thickness,

$a$ distance between two adjacent cracks,

$(.)_c$ composite (entire ply group),

$(.)_{90°}$ 90° ply group,

$(.)_{0°}$ 0° ply group.

The additional stress in the load-bearing 0° plies results in an increase of local strain and in a global stiffness loss of the laminate. The strain $e_{90°}(x)$ at the 0° plies can be calculated by Equation (6) and

$$e_{90°}(x) = (\Delta \sigma(x) + \sigma_{90°,c})/E_{90°}.$$

$\sigma_{90°,c}$ and $e_c$ are the stress and strain of the 0° plies in the zone in which there is no influence of any transverse cracks. Fig. 13 shows the calculated strain ratio $e_{90°}(x)/e_c$ as a function of the distance from the crack (variable x) and the thickness of the 90° plies (2 $t_{90}$). Tab. 3 specifies the employed material constants.

The global stiffness reduction depends on the crack density $\delta$ and can be expressed by:

$$\frac{E_c(\delta)}{E_c} = \left(1 + \frac{2E_{90}t_{90}}{E_{0°}t_{0°}} \tanh\left(\frac{\phi}{2\delta}\right)\right)^{-1},$$

(7)

$\delta$ crack density.

3.2 Numerical analysis

Finite element method (FEM) is used to investigate the strain distribution in the presence of transverse cracks. The effect of increasing crack density on the stiffness reduction and on the signal of the embedded carbon fibre sensor is analysed. In [8] 2D and 3D analyses were compared. The results showed no significant differences. In this paper, 2D models in generalized plane stress are used for the numerical analysis.

Due to symmetry the investigation is performed with quarter elementary cells (Fig. 14). The displacements of the nodes of all 0° layers at the position $x = 0$ are fixed. The tension load $F_c$ is applied by equal displacements at all nodes with $x = \frac{a}{2}$. Tab. 4 specifies the material properties for the numerical analysis.

Fig. 15 shows the strain distribution of the 0° layer for the laminate [0°/90°/0°/90°] with the embedded CFS as a function of the distance $x$ from the transverse cracks. The analysis is performed having the transverse cracks in the two 90° ply groups on opposite sides. $e(x)_{90°,CFS}$ is defined as the strain of the elements of the 0° ply, while $e(x)_{CFS}$ is the strain of the elements of the 0° ply including the interface to the adjacent 90° ply. Due to the integral strain measurement method the CFS measures this strain distribution and the global stiffness loss along its fibre length.

The maximum local strain levels at the crack tips are $e(x)_{90°,CFS} = 0.0181$ and $e(x)_{0°,CFS}$, interface $= 0.0205$ at an applied strain of $e_c = 0.008$. These strain levels are above the ultimate strain $e_{90°,ultimate} = 0.015$ of the Toray T300B carbon fibres used in the CFS.

The effects of increasing crack density are investigated by a variable length $a/2$ of the quarter elementary cells. Fig. 16 shows the stiffness reduction depending on the crack density. The
stiffness reduction is determined by Shear-Lag-Analysis and FEM. Moreover, the theoretical maximum stiffness reduction \( E_{\text{redmax}} \) is calculated, which assumes a stiffness of zero for the 90° ply groups. The difference of 8.4% between the results of the Shear-Lag-Analysis and the results of the FEM can be explained by the simplifications applied for the one dimensional analysis. Nevertheless, the similar curves of the stiffness reductions as a function of transverse crack density allow the use of an approximate function based on Equation (7), where the laminate parameters are substituted by two parameters \( \alpha \) and \( \beta \):

\[
E_c(\delta) = \left(1 + \alpha \delta \tanh \left( \frac{\beta}{\delta} \right) \right)^{-1},
\]  

\( \alpha, \beta \) laminate-dependent parameters.

Using the example of the laminate \([0/90°/0/90°/0]_6\) in Fig. 14 the laminate parameters \( \alpha = 0.71 \) \( \beta = 1.544 \) are determined by means of least-squares method (Fig 16).

3.3 Fracture mechanic analysis

The fundamental approach of fracture mechanics [9] is used to analyse transverse cracks in fibre-reinforced plastics by:

\[
G = \frac{d\Pi}{dA},
\]

\( G \) energy release rate,

\( \Pi \) potential energy,

\( A \) crack area.

Transverse cracks develop in laminates when the energy release rate \( G_n \) reaches the critical value, the so-called critical energy release rate \( G_{mc} \) [7, 10].

Cycling tension tests with increasing load levels are typically applied for the characterization of fracture mechanic properties of composites [11]. The procedure applied in the present paper is illustrated by Fig. 17. The specimens are loaded and unloaded five times at each load level. At each load level \( i \) the fifth cycle is transferred to a load-displacement diagram.

The energy release rate of cycling loads \( \Delta G_n \) can be calculated with \( \Pi_{i,i+1} \) as released strain energy, which is described by the area of the load-displacement diagram (Fig. 17):

\[
\Delta G_{m;i,i+1} = \frac{\Pi_{i,i+1}}{A_{i,i+1}} = \frac{1}{2} \left( \frac{F_i}{A_{i,i+1}} \right) \left( F_i \right)_{i+1}, \quad (10)
\]

\( \Delta G \) energy release rate for cycling loads,

\( s_i \) maximum displacement of cycling load level \( i \),

\( F_i \) maximum force of cycling load level \( i \).

The released strain energy is calculated by the change of the electrical resistance of CFS using the load cycle \( i \) and \( i+1 \). Thus the energy release rate is calculated by:

\[
\Delta G_{m;i,i+1} = \frac{1}{2} \left( \frac{\Delta R}{R} \right)_{i+1} \left( \frac{\Delta R}{R} \right)_{i+1} \left( \frac{F_i}{A_{i,i+1}} \right), \quad (11)
\]

where

\[
\left( \frac{\Delta R}{R} \right)_i = k \frac{s_i}{l_{CFS}},
\]

\( G_n \) energy release rate for transverse cracks,

\( F_i \) maximum load of cycle \( i \).

Using this calculation the sensor monitors the stable crack growth.

4 Comparison of experimental and simulated results

The experimental and numerical investigations described above have shown that the CFS measure the stiffness reduction caused by the increasing crack density of the laminates (Fig. 18 and 19). Fig. 18 shows a comparison of experimental results of cycling loads and calculations for the laminate \([0/90°/0/90°/0]_6\) (specimen G5). At the load cycle with the maximum stress of 123 MPa the differences between the measured (“test data”) and the calculated CFS-sIGNALS (“Shear-Lag-Analysis”, “FEM”) is less than 10 %.

This coincides with the negligible AE-signals (no crack initiation). During the next load cycle with the maximum stress of 154 MPa, the crack density \( \delta \) increased up to 0.68 mm\(^{-1}\). The crack formations result in a significant stiffness loss of 35 %, which becomes apparent in the calculated and measured change of CFS-signals of 2 500 \( \mu \Omega \Omega \). At the latter load cycles
with increasing stresses, the calculated maximum stiffness loss is reached. Further increasing strain levels at the crack tip $> 1500 \, \mu m/m$ (Fig. 15) can cause damage of single filaments of the CFS (Fig. 11) resulting in high signal levels. Fig. 19 shows the same comparison for static loads (specimen G6). Again the stiffness loss is measured by the means of CFS which is confirmed by the analysis. At higher crack density of $0.66 \, mm^{-1}$ and a stress level above $148 \, MPa$ the cracks cause disproportionate CFS-signals. The calculated energy release rate $[7]$ is compared with the test results (Fig. 20). Equation (8) with the laminate-dependent parameters $\alpha = 2.3$ and $\beta = 0.68$ are used to calculate the energy release rate by means of [7]. The accurate determination of the crack density at low stress levels is difficult and leads to a major difference between measured and calculated curves at the crack density of $0.03 \, mm^{-1}$. Despite this, the curves are similar up to the crack density of $0.43 \, mm^{-1}$.

Fig. 21 shows the summation of the released energy per crack area measured for the single load cycles. The single curve progressions are similar up to the load level at which a crack density of $0.43 \, mm^{-1}$ is reached, and damage of the CFS occurs. Thus it became apparent that this way of monitoring crack afflicted laminates is possible.

5 Applications

The industrial application of CFS as monitoring sensors is investigated for composite pressure vessels. Static and cycling loadings are applied up to pressure levels of $700 \, bar$, for pressure vessel types 2 (metal liner with circumferential fibre reinforcement) and 3 (metal liner with axial and circumferential fibre reinforcement). The sensors, CFS and strain gauges (HBM LI66), are embedded during the winding process of the vessel type 2 (Fig. 22). For cycling loads the pressure rises from $15 \, bar$ up to $495 \, bar$ and afterwards is released to $15 \, bar$ (Fig. 23). At each hundredth load cycle, measurements of 14 load cycles are performed. Fig. 23 shows the arithmetic mean of the measured differences of the minimum and maximum signals at these 14 load cycles. At a constant pressure level and circumferential strain of $2 \, 177 \, \mu m/m$, a constant change of electrical resistance of $3 \, 667 \, \mu \Omega/\Omega$ at the CFS is measured. No cracks are observed nor are any irregularities detected at the measured signals. Fig. 24 shows test results of a pressure vessel (type 3) with CFS and strain gauges. The sensors are applied on the surface of the vessel. The loading test is performed as an autofrettage process with the maximum pressure level of $700 \, bar$. Above the pressure level of $314.8 \, bar$ are deviations of the measured signals of CFS and the strain gauges visible. These deviations up to $50 \, \mu \Omega/\Omega$ bar are more easily observed as the first derivatives of the CFS and strain gauge signals (Fig. 25). As is usually the case for vessels type 3 during an autofrettage process, these deviations can be caused by transverse crack initiations in the axial fibre reinforcements.

6 Conclusions

In this paper carbon fibres are used as sensors for strain measurements and crack monitoring. A good correlation between the signal of embedded CFS and the transverse crack density is found to describe the stiffness reduction and the energy release rate. The investigation is performed on specimens and pressure vessels. Experimental as well as analytical and numerical analyses are performed. It has been shown that a signal change of $1171 \, \mu \Omega/\Omega$ correlates with an energy release rate of $1198 \, J/m^2$. Due to the integral strain measurement method of the CFS the monitoring of the crack density is possible. When the local strain level at the crack tips exceeds the ultimate strain of the filaments, the fractured filaments result in disproportionate CFS-signals. Fracture mechanic analysis is applied to characterize transverse cracks and the damage propagation in the laminates. It is shown that strain measurements and crack monitoring are possible by means of CFS, to ensure safe operations of composite structures over their life time.

Acknowledgments

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Fig. 1. Specimen type #1.

Fig. 2. Specimen type #2.

Test series Piezoresistive $<200 \mu m/m$ Piezoresistive $\geq50 \mu m/m$ Single-crack Multicracking Multicracking

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>#1</th>
<th>#2</th>
<th>#2</th>
<th>#2</th>
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<td>40</td>
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<td>$[0_4]$</td>
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<td>$[0/90_8/0/90_8/0]$</td>
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<td>Number of CFS per specimen</td>
<td>3</td>
<td>3</td>
<td>3</td>
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Tab. 1. Specifications of tensile specimens (*: with cut layers).

Fig. 3. Tension test of GFRP specimen $[0_8]$ with embedded CFS and specimen type #1.

Fig. 4. Tension test of GFRP specimen $[0_8]$ with embedded CFS and specimen type #2.

Fig. 5. GFRP specimen $[0/0^*/0/0^*/0]_8$ with strain gauge and three embedded CFS ($0^*$: cut layers, single crack).
Fig. 6. Tension test of GFRP specimen [0/0°/0/0°/0] at a stress of 134 MPa (0°: cut layers, single crack).

Fig. 7. Tension test with increasing stress level of GFRP specimen [0/0°/0/0°/0] (0°: cut layers, single crack).

Fig. 8. GFRP specimen [90°/0/90°] with strain gauge and two embedded CFS.

Fig. 9. Static tension test of GFRP specimen [0/90°/0/90°/0] (specimen G6).

Fig. 10. Cycling tension test of GFRP specimen [0/90°/0/90°/0] (specimen G5).

Tab. 2. Pattern recognition results of GFRP specimen [0/90°/0/90°/0] in tension tests.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>G1</th>
<th>G2</th>
<th>G6</th>
<th>G3</th>
<th>G4</th>
<th>G5</th>
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<td>3</td>
<td>0</td>
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<td>125</td>
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<td>67.5</td>
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<td>Energy fraction interface failure [%]</td>
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<td>5.1</td>
<td>31.6</td>
<td>19.3</td>
<td>10.5</td>
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<td>0.9</td>
<td>0.2</td>
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Fig. 11. Micrograph for the GFRP specimen [0/90°/0/90°/0] after static tension test with the maximum stress of 215 MPa.

Fig. 12. 0°/90° laminate with transverse cracks.

| $E_{0°}$ [MPa] | 16.500 |
| $E_{90°}$ [MPa] | 43.500 |
| $G_{0°,90°}$ [MPa] | 3.500 |
| $t_0$ [mm] | 0.125 |

Tab. 3. Material constants of the GFRP laminate used for the Shear-Lag-Analysis.

Fig. 13. Influence of the distance from the crack (variable $x$) and the thickness of the 90° plies (2 $t_{90°}$) on the strain ratio $\varepsilon_{0°}(x)/\varepsilon_c$ (crack distance $a = \infty$).

Fig. 14. 0°/90° laminate with embedded CFS in the symmetry 0° ply (0°, CFS), transverse cracks and the quarter model.

<table>
<thead>
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<th>Layer</th>
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<th>(0°, CFS)</th>
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<td>44 250</td>
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<td>14 500</td>
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<tr>
<td>$G_{0°,90°}$ [MPa]</td>
<td>3 500</td>
<td>4 500</td>
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<tr>
<td>$G_{0°,90°}$ [MPa]</td>
<td>4 500</td>
<td>3 500</td>
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<td>$\nu_{0°,90°}$</td>
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<td>$\nu_{0°,90°}$</td>
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Tab. 4. Material properties for FEM.
Fig. 15. Strain of the embedded carbon fibre sensor determined by FEM.

Fig. 16. Stiffness reduction depending on the crack density, determined by Shear-Lag-Analysis and FEM for GFRP [0/90\(^\circ/0/90\(^\circ)]\) with CFS.

Fig. 17. Cycling tension test with increasing load levels.

Fig. 18. Comparison of experimental results of cycling loads and calculation for the laminate [0/90\(^\circ/0/90\(^\circ)]\) (specimen G5).

Fig. 19. Comparison of experimental results of static loads and calculation for the laminate [0/90\(^\circ/0/90\(^\circ)]\) (specimen G6).

Fig. 20. Comparison of energy release rate depending on the crack density of the laminate [90\(^\circ/0/90\(^\circ)]\).
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Fig. 21. Summation of the released energy per crack area depending on the crack density of the laminate [90°/0/90°].

Fig. 22. Embedding of the CFS and the strain gauge during the winding process of a vessel.

Fig. 23. Cycling pressure test of a pressure vessel (type 2) with embedded CFS and strain gauge.

Fig. 24. Autofrettage process of a pressure vessel (type 3) with embedded CFS and strain gauge.

Fig. 25. First derivatives of the CFS and strain gauge signals at the autofrettage process of a pressure vessel (type 3).

References


