INTERLAMINAR PHOTOELASTIC HEALTH MONITORING OF ADHESIVE JOINTS AND COMPOSITE STRUCTURES FOR EXTENDED ENDURANCE STRENGTH (InterPHACE)

Ch. Taudt[1*], U. Gieland[2], H. Klose[2], T. Baselt[1], P. Hartmann[1]

[1]*Leupold-Institut für Angewandte Naturwissenschaften (LIAN)*
[2]*Institut für Produktionstechnik (IfP)*
Westsächsische Hochschule Zwickau, University of Applied Sciences, Dr.-Friedrichs-Ring 2a, DE-08056 Zwickau
**christopher.taudt@fh-zwickau.de*

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Abstract

In this work a novel approach to monitor the structural health of composite systems based on the photoelastic properties of prevalent matrix polymers (e.g. epoxy resins) is presented. The Structural Health Monitoring technique is designed to detect impacts and arising, barely visible damages i.e. delamination directly at the interface of different materials.

As a starting point diverse cured epoxy resins are investigated in view of interdependencies between curing parameters and stress optical properties. Based on elementary experiments important parameters like the signal character, sensitivity and the metering range are investigated. With the knowledge of the basic capabilities of the approach a signal interpretation model is developed. Finally the developed model is tested in dynamic experiments and further concepts for the advanced development of the presented SHM approach are expressed and discussed.

1 Introduction

As demands for lightweight, energy efficient and secure systems in aerospace, automotive and civil applications as well as multi-material design advances, so called Structural Health Monitoring (SHM) techniques become increasingly important. A critical and therefore observable area in e.g. composites is the interfacial zone where fiber and matrix are bonded together. Internal stresses and uncertainties due to production constraints as well as in-service damage primarily appear and proceed in this zone.

Especially with regard to rather complex structures designed with fiber reinforced polymers (FRPs) appropriate sensor techniques based on the piezoelectric effect, acoustic emission, fiber optics and electric resistance have been under intense investigation over the past decade, [1]. They are capable of the accurate determination of constraints including deformation, stress, impacts and defects, [2-9].

In order to overcome problems of scalability and complexity this work aims to present an alternative SHM approach for interfacial zones in polymer based multi material systems. An optical material property which is load dependent and existent in polymers is stress birefringence. While the mechanisms of stress influenced polarization behavior is broadly used in experimental mechanics as photoelasticity, only little work was done on polarimetric in-situ sensing, [10, 11]. As these kinds of sensors use optical fibers attached or integrated in systems the scope of this work is to directly utilize the polarization sensitive behavior of the common polymers used in FRPs. By testing diversely cured epoxy resins a basic comprehension of the different characteristics under static loading situations should be obtained. Progressing from that the formulation of a simple and significant signal analysis is forced. In contrast to common methods the stress induced change in polarization should be determined rather by the time derived detection of different states of polarization (SOP) than by absolute values. A common method to quantify stress in birefringent media is the measurement of phase shift between the two polarized components of light propagating through this media. With the knowledge of the materials stress optical coefficient absolute stresses can be calculated at every point of interest within the model. Although this method is suitable for the exact stress estimation in solid bodies, problems emerge with the implementation as to interfacial health monitoring technique. Since locally uneven material conditions may occur, it can be useful to measure relative changes in stress instead of absolute values. Therefore the occurrence of fast SOP changes can be seen as an indicator for unusual stress peaks e.g. due to impacts, which can be critical for the health of the interfacial zone.

Following up the proposed signal interpretation model was applied and studied under laboratory conditions in various dynamic experiments. A basic laminated system is not only used to study the signal interpretation under impact load but to show the advantages of the proposed SHM method. Apart from the simplicity in design these are the high sensor integration, the wide application possibilities and self-adjusting sensitivity. In addition it should be noted that the sensors have not be fabricated externally as part of the structure becomes sensitive and the dimensions of a sensor are only limited by the components dimension which should be monitored.

2 Materials and initial (static) tests

In order to evaluate the stress optical characteristics of common composite matrices, quasi static measurements were planned and executed. For this purpose two epoxy resins with different curing parameters and therefore different mechanical properties could be selected, Tab. 1.

type	**hardness HB** $\left[\frac{N}{mm^2}\right]$	**elastic modulus** $\left[\frac{N}{mm^2}\right]$	**Curing**
casting resin	3.37	3300	cold / room temperature
laminating resin	186.20	4500	hot

Table 1. Mechanical properties of the investigated epoxy samples

The materials represent two points in a range of possible materials with reasonable differences between them. As described in theory epoxy resins should show only relatively low birefringence and nearly zero relaxation behavior as they are considered to have energy elastic material properties, [12, 13]. As soon as materials show partially entropy elastic characteristics, birefringence increases significantly and considerable relaxation behavior becomes visible. The latter is primarily present in soft materials, like rubber, as its cause is relative deformations of larger molecular structures instead of displacement changes in between atomic bonds as in energy elastic materials. The following experiments were conducted necessary in order to get knowledge of the mechanisms dominant in the two materials and its implications on an intended sensor system.

For this purpose Ref. [14] for standard compression tests of polymers was used as a basis. Additionally appropriate optical components for birefringent measurements were attached, Fig. 1.

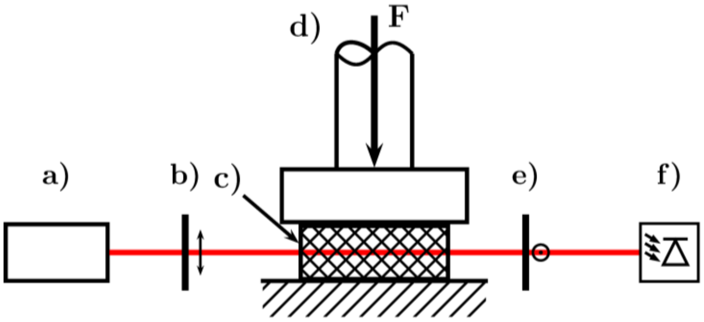

Figure 1. Experimental setup for static measurements with a) laser (635 nm), b) polarizer, c) epoxy sample, d) loading device, e) analyzer and f) photo detector

The applied components as a) laser, b) (dicroidic) polarizer, e) analyzer as well as f) photo detector enable the detection of changes in the polarization state through the c) sample under d) load. The determination of absolute stress values was not scheduled in this setup as a relation between hard and soft sample should primarily be investigated.

The tests have been carried out using a universal testing machine at a speed of 2mm/min up to 1 MPa of compressive stress in the sample and a wavelength of 635 nm, Fig. 2 a).

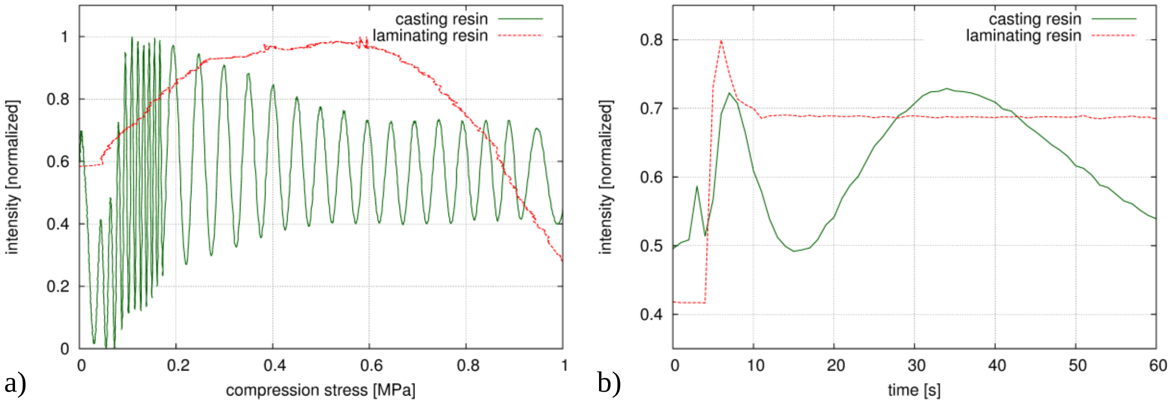

Figure 2. Results of the static measurements with a) change of polarization over load rise and b) relaxation behavior over time

It becomes clear that the difference in hardness relates to significant differences in polarization changes caused by compressive load in both materials. This applies to both scale and slope characteristics. The unique slope progression in the casting resin was detectable in all investigated samples. A further visual investigation revealed internal stresses in this sample series which may be caused by curing effects especially at the edges of the mold. It is likely that these internal stresses affect the behavior of the samples under load and cause a characteristic behavior especially up to 0.2 MPa as visible in the plotted data.

While in the softer material changes of the SOP happen at a fast rate the contrast applies to the relaxation behavior, Fig. 2 b). Both materials show clearly visible relaxation but the scale increases significantly in softer materials. This is possibly associated with the occurrence of different deformation models for the two materials. It is likely that the casting resin shows a major part of entropy elastic behavior while the laminating resin is mainly dominated by energy elastic behavior.

3 Signal interpretation model

In the manufacturing of parts made of FRPs slight temperature gradients in curing as well as other production uncertainties will lead to locally uneven internal stress distributions. As shown in the initial experiments different curing parameters can lead to significant different signals. In consequence this will lead to difficult signal interpretation of possible sensor data. An additional aspect to be considered is that one of the main reasons for interfacial destruction and crack growth are stress peaks within short time scales caused for example by impact loads, [15]. Taking these loads situations as well as the specific stress optical characteristics of some polymers into account an acquisition of relevant measurement signals could be developed by considering the following aspects during sensor design:

- detection of relative and time dependent instead of absolute changes in stress
- measurement sensitivity specific to material properties at the point of interest
- preference of line/area measurements instead of point sensors
- detection of any polarimetric changes independent from its source

In contrast to the measurement of absolute stress values the detection of load changes in relation to time becomes the main task. As the fast change in load caused by impact relates to an equally fast change in the SOP, the system can be founded on that time resolved detection of polarization states. The additional derivation of the obtained signal will magnify the recognition of relevant load situations, Fig. 3.

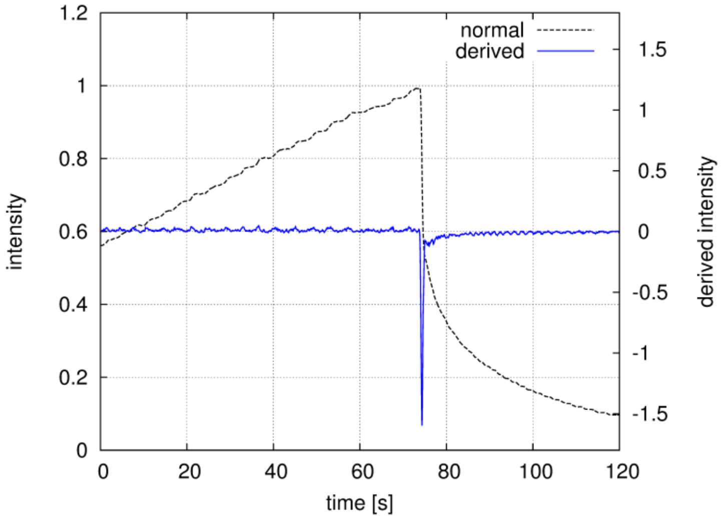

Figure 3. Development of signal interpretation through derivation of obtained changes in SOP

This method prioritizes the fast change in signal as it is typical for impact loads and simultaneously oppresses slower load changes. Therefore normal working loads or material relaxation are not overlaying on the critical sensor information. In effect, multiple measurement information can be acquired through amplitude and time analysis of both normal and derived signal. Consequently this model allows the separation of different load situations and enables the examination of both static and dynamic material behavior independently.

Amplitude and frequency of the resulting data represents the amount of load rise and the loading rhythm respectively. These parameters can easily be taken as input for structural life predictions as described in literature, [16].

4 Impact testing

In order to test the above stated signal interpretation model dynamic measurements i.e. impact tests on a simplified interface model consisting of two bonded aluminum panels were carried out. The experimental setup is slightly evolved from the static experiments with c) & f) quarter-wave plates to prevent extermination of signal information and a vertical tube to accommodate an e) impactor sphere, Fig. 4.

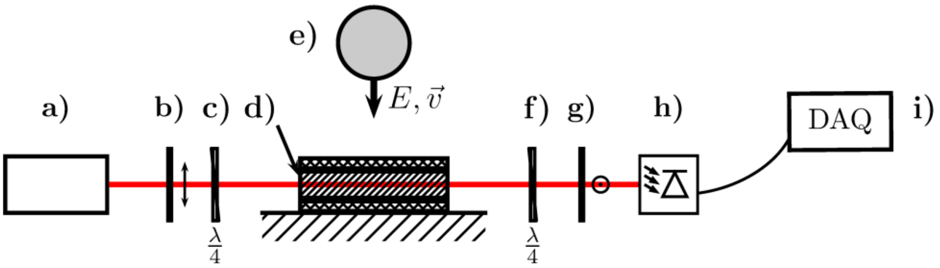

Figure 4. Experimental setup for dynamic measurements with a) light source, b) polarizer, c) & f) quarter-wave plate, d) sample (consisting of aluminum panels and epoxy adhesive), e) impactor, g) analyzer, h) photo detector and i) data acquisition unit

Using samples of 4 mm thickness (2 mm epoxy adhesive, 2 x 1 mm aluminum panels) the impacts where carried out at low velocity of 2 m/s and under different energy levels (50 - 200 mJ). As a result, characteristic plots for the polarization change due to impact stress could be obtained and analyzed with the signal interpretation model, Fig 5.

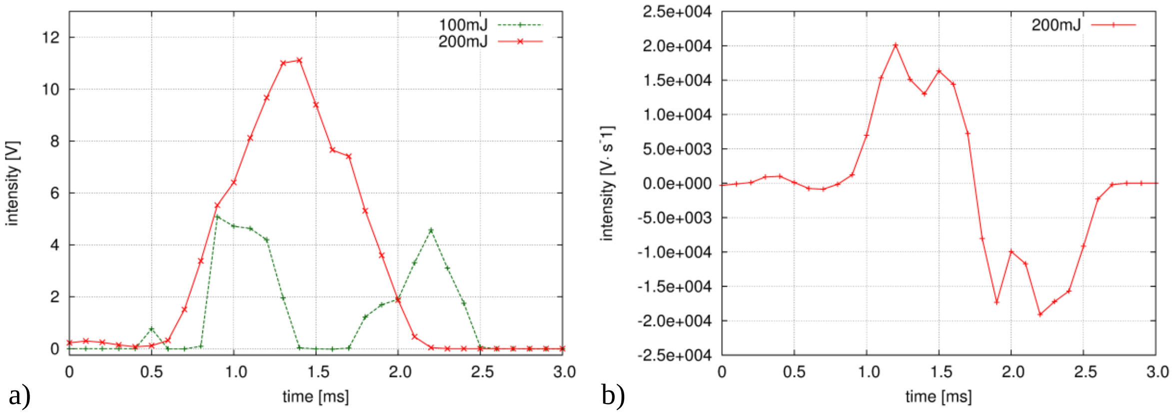

Figure 5. Results of the dynamic measurements with a) change of polarization over time and b) first derivative of the obtained signal

In the data depicted it becomes visible that the time period where load rise and fall happens can be rather short but are nearly the same for different impact energies. In contradiction to the equality in time, the character of the polarization change is significantly for both investigated energies. While the slope progression for 200 mJ is similar to the assumptions made before, the slope for 100 mJ shows not only considerable lower intensities but an unexpected double peak in polarization change where the 200 mJ sample showed only a single one. As these effects occurred in multiple samples and at energy levels of 50 mJ as well, a separate discussion and comparison with the results obtained by numerical calculations was performed in [17].

Nevertheless the method of deriving the signal as a function of time shows a clear signal structure, which possibly can be approximated as a square wave signal. In result an elementary and comparable event representation emerges which can be used for impact triggering, structural life predictions and the like.

Additionally to the event notification it may be desirable to get an impression of the strength of an impact in a real world application. For that purpose it is contemplated to use integrating area based sensors instead of point sensor and the comparison of multiple sensors on demand. Another approach to qualify the health of the structure will be the comparison of current and historical data. By just analyzing time progressing signal changes in amplitude and frequency, the obtained data is reduced to a minimum with the effect of saving time, data broadcasting bandwidth and complexity of the system as a whole.

5 Summary

In conclusion it could be shown that stress optical behavior of common epoxy matrix materials is strongly dependent on its curing parameters and therefore of the state of internal stresses. With regard to an appropriate health monitoring technique for polymer based fiber composites a signal interpretation model was developed which takes these facts into account. The model is focused on the time resolved detection in changes of the state of polarization which are caused by peak load situations like impacts.

Further experiments could be used to determine the dynamical characteristics of the proposed health monitoring technique incorporating the developed interpretation model. The results showed good applicability and informative value of the interpreted measurement data.

In order to record the behavior systematically and at different impact energies as well as under different sample configurations, further investigations are due to be carried out. One of the main goals of the ongoing experimental work is the integration and application of the proposed health monitoring technique to the level of interfaces in fiber reinforced plastics as shown in a preliminary concept, Fig. 6.

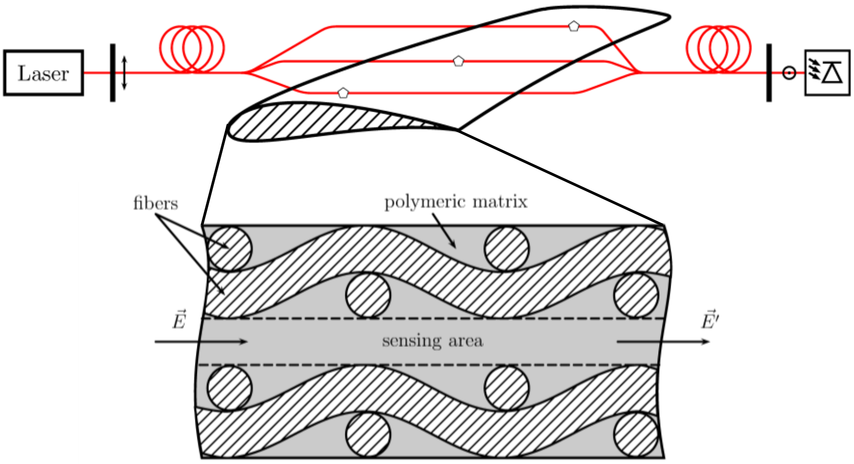

Figure 6. Overall and detailed concept of integrated polarimetric health monitoring in FRP

Possible applications for the polarimetric in-situ health monitoring technique cover a wide range within technologies where polymers are used for structural purposes. In particular systems with fiber reinforce polymers, structural adhesives and bulk polymers could benefit from it. In contrast to fiber optic sensors it could be considered to implement the in-situ polarimetric technique in applications where the integration of fibers is technically difficult, impossible (e.g. seals) or economically not reasonable.

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