In-Situ Impact Monitoring of Polymer-Based Multi Material Systems by Stress Optical Analysis

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ABSTRACT

One of the recent developments in construction and design over the past years is the combination of various materials in order to take advantage of their specific benefits. In context of this approach polymer based bonding and laminating techniques play a significant role. As for efficiency, scalability and safety reasons it is vital to monitor and maintain the health of the material interfaces.

This paper presents a novel health monitoring technique which is based on the stress optical behaviour of polymers in these systems (e.g. matrices, adhesives). In contrast to existing sensing methods it aims to detect relative changes in the state of polarisation. Therefore, a prioritized task is the detection of impact loads due to the fact that they are a common reason for interface damages like delamination.

Based on the knowledge of stress optical performance and signal character of polymers a signal interpretation strategy is developed. With respect to the basic capabilities of the proposed monitoring principle an experimental setup for the application and measurement of impact loads was established. In a range of test cases with bonded panels the in-situ sensing properties under different impact energies could be studied. Following up work was concentrated on the development of a finite element model of the previous experiments with respect to the stress distribution during the impact situation under varying conditions. A final discussion takes the obtained results into account to formulate the quality and performance of the bespoken health monitoring technique including an outlook on possible applications.

INTRODUCTION

The on-going demand for lightweight, energy efficient and secure systems in aerospace, automotive and civil applications has driven design paradigms towards the use of multi material approaches, [1]. The choice and combination of materials with specific strengths, like in fibre reinforced plastics (FRPs), enables the design of highly optimized material systems. It also draws new challenges towards testing, evaluation and monitoring of these rather complex structures.

Especially so called Structural Health Monitoring (SHM) techniques have been under intense investigation in recent years, [2]. With sensors based on techniques like

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the piezoelectric effect, acoustic emission, fibre optics and electric resistance most constraints including deformation, stress, impacts and defects are detectable, [3-10]. However SHM lacks of acceptance and implementation on a larger scale because it partially fails to meet user demands like, [11]:

- high structural integration
- reliability over life span
- scalability (number of sensors at low price)
- significance of measurement information
- simplicity in infrastructure

Although most of the named sensor principles are very accurate in measurement, manufacturing and implementation is complex. Furthermore, it should be considered that some sensor systems run well on a lab scale but suffer from difficulties on an industrial scale. Taking this into account, some work was done on much simpler sensing technologies like polarimetric fibre optical sensing for example by *Murukeshan et al.*, [12]. Similar to photoelasticity the change in polarisation state of an optical fibre due to stress induced birefringence is used to measure the load present. Apart from static load measurements it is also possible to detect peek loads which are especially critical in laminated structures.

In this paper we present a health monitoring technique, which is based on the polarimetric approach but uses the specific material present in a certain structure (i.e. matrix material or adhesive) instead of an optical fibre. The advantages of this approach are the following:

- wide range of possible applications
- self-adjusting sensitivity (initially and over lifetime)
- scalable sensor dimensions (only limited by part structural dimensions)
- no sensor fabrication required
- high sensor integration

In consideration of multi material systems one should note, that the interfacial zone of two materials is the weakest and most critical area of the system. Production uncertainties, cracks and (high) internal stresses are likely to occur primarily in this region, [13]. Evaluation and monitoring of this zone is therefore desirable.

A common method to quantify stress in birefringent media is the measurement of phase shift between the two polarised 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. The formation of the interfacial zone is influenced by a variety of constraints. This possibly leads to locally uneven stress distributions. Subsequently it can be useful to measure relative changes in stress instead of absolute values. A second important factor is the character of critical loading situations. Critical stress either occurs in form of impacts i.e. fast load rises or as high frequency load oscillations. Detecting these situations necessitates both relative and time resolved measurement, [11].

Following these requirements it is considered to analyse the polarisation affected signal in an alternative manner. Instead of comparing the initial and the manipulated signal it is proposed to just examine the latter. In case of the above mentioned stress situations this will automatically lead to a significant change in the initial state of polarisation (SOP). Therefore the derivation of the signal will reveal fast changes of the SOP as distinct amplitude values, Figure 1.

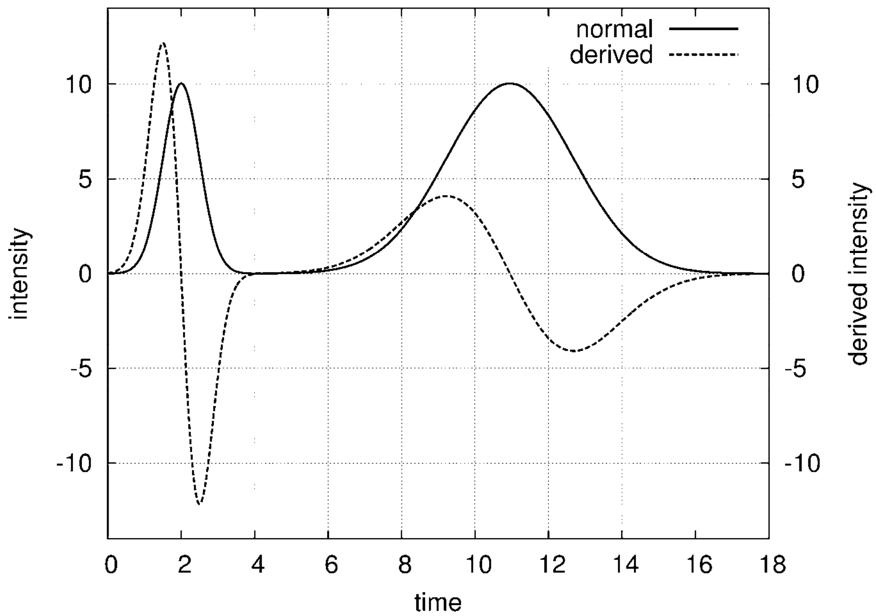

Figure 1. Schematic signal and its derivative with one relatively fast changing and one slow changing level.

Making use of this method prioritises the fast change in signal as it is typical for impact loads and simultaneously oppresses slower load changes like normal working loads or material relaxation. According to this, 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 behaviour independently.

In conclusion of these theoretical considerations it can be stated that important impact parameters can be described through derivations of the signal. 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 [14]. While the curve progression was set to be sinusoidal in theory it is necessary to analyse experimental data in order to record the real signal character during impact.

EXPERIMENTAL SETUP AND RESULTS

By means of the above stated signal interpretation model, impact properties of a polymeric based laminate (aluminium panels bonded with epoxy) were tested under laboratory conditions. Therefore an adequate experimental setup for low velocity impact test (LVI; $\vec{v} \approx 2\, m/s$) was established, Figure 2. The basic components such as a) light source, b) & g) polariser, c) & f) quarter-wave plate, h) detector and i) data acquisition are equivalent to standard stress optical setups, [15].

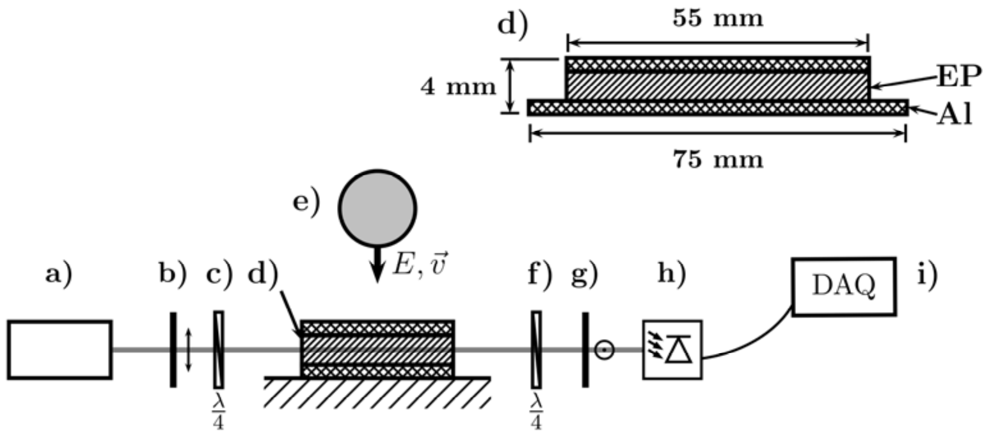

Figure 2. Experimental setup with a) light source, b) & g) polariser, c) & f) quarter-wave plate, d) sample consisting of aluminium panels (AL) and epoxy adhesive (EP), e) impactor, h) detector and i) data acquisition.

Additionally, a tube was fitted above the d) sample in order to apply different impact loads by dropping a e) sphere from appropriate heights. The measurements were carried out at impact energy levels of 50, 100 and 200 mJ, respectively. Aluminium panels of 1 mm thickness were bonded using an epoxy adherent. The adhesive thickness of 2 mm was generated between the aluminium panels. The data obtained show a characteristic progression for individual impact energies, Figure 3.

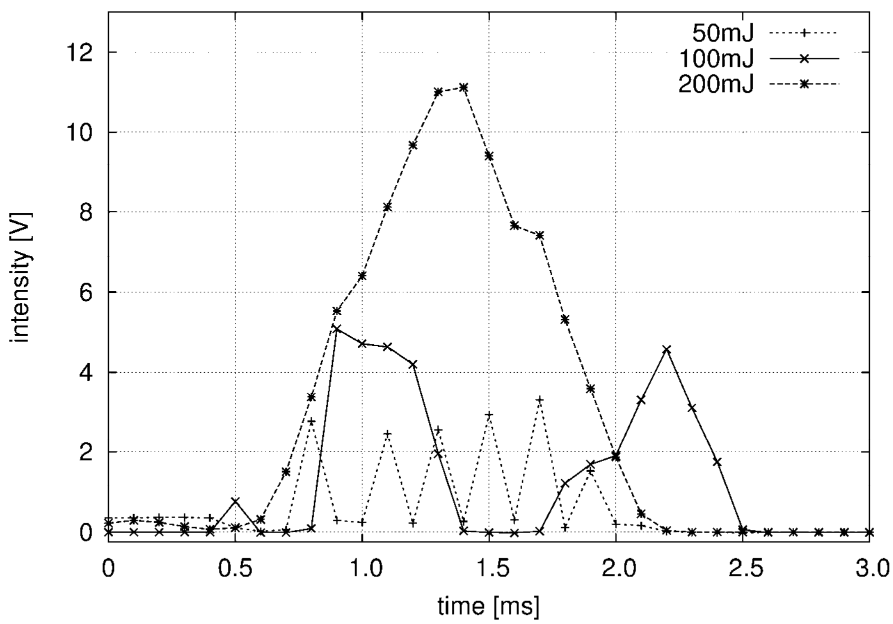

Figure 3. Exemplary experimental results at different impact energies.

As depicted, the data observed in the experiments show differences to the signal character assumed in the theoretical considerations. While the initial assumption was that the wave shape has sinusoidal character, the real wave shapes differ from that and are distinctive for the corresponding impact energies. Whereas impacts with relatively low energies such as 50 mJ show multiple signal oscillations during the impact event, higher loads show significantly less signal changes. The absolute signal amplitudes tend to be dependent on the impact energy in most cases. In order to proof this statistically more experiments are conducted necessary as the standard deviations are relatively high, Table 1. The reason may lies in the diverse stress structure of every sample as already discussed in the first part of this work.

Table 1. Comparison of characteristic impact parameters.

	time constant [ms]	**amplitude [V]**	**frequency [Hz]**
50mJ	2.00 ± 0.08	5.50 ± 1.34	4356.03 ± 28.60
100mJ	2.03 ± 0.17	9.26 ± 1.83	896.21 ± 73.29
200mJ	3.05 ± 0.85	8.75 ± 2.92	277.84 ± 23.74

As for the interpretation of the signal oscillations specifically at lower energy impacts it is assumed that they originate from vibrations of the sample caused by the impactor. Potentially stress peaks arise from these vibrations propagating through the sample likewise lamb waves, [11].

With regard to the time constants associated to one impact it becomes obvious that they are apparently equal throughout all energy levels, Table 1. In theory this should not be possible. It indicates that, like in case of the described oscillations, other effects play a role. This behaviour has to be investigated in future works.

Based on the above discussed data the first derivative was calculated, Figure 4.

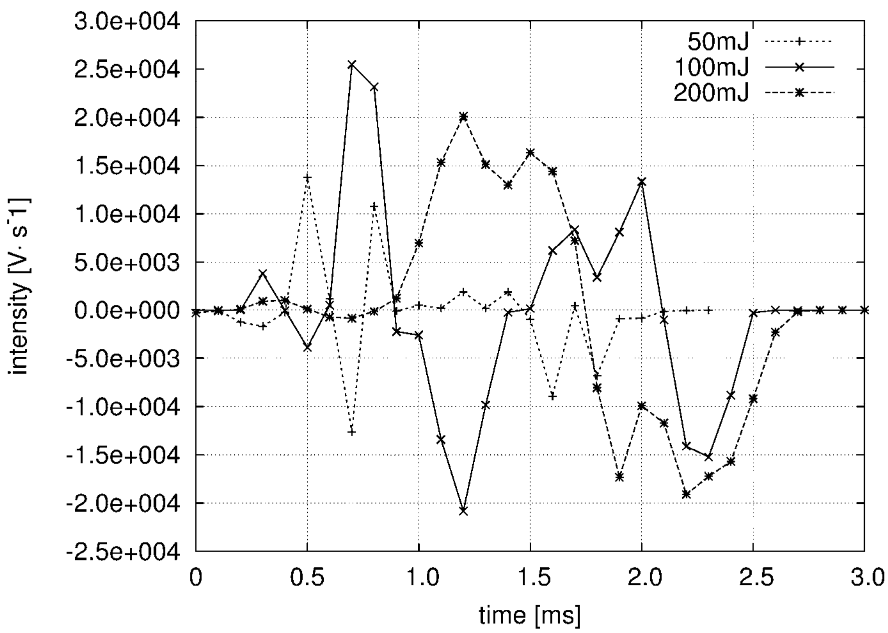

Figure 4. First derivative of experimental results at different impact energies.

Especially for the higher energy levels like 200 mJ the fast stress rise due to impact is clearly recognisable by high amplitude values. At lower energies this behaviour is existent but not always as clear. With further development in the experimental set-up this lack of clarity can possibly be overcome.

A potential method for impact detection can take these amplitudes into account in order to characterise the recorded event in conjunction with the time constants.

Therefore, both values can be used to abstract the signal as a square wave. In result an elementary and comparable event representation evolves which can be used for impact triggering, structural life predictions and the like.

FINITE ELEMENT MODELING

In order to study the stress accumulation during impact the modelling and analysis of the experiment in finite element code ANSYS® was performed. The model included appropriate layers of 3D solid elements for both adherents and the adhesive. The sphere was set as rigid body impacting the sample at the given energy levels.

As a relevant dimension of comparison the maximum equivalent stress in the impacted area of the adhesive was computed as a function of time, Figure 5.

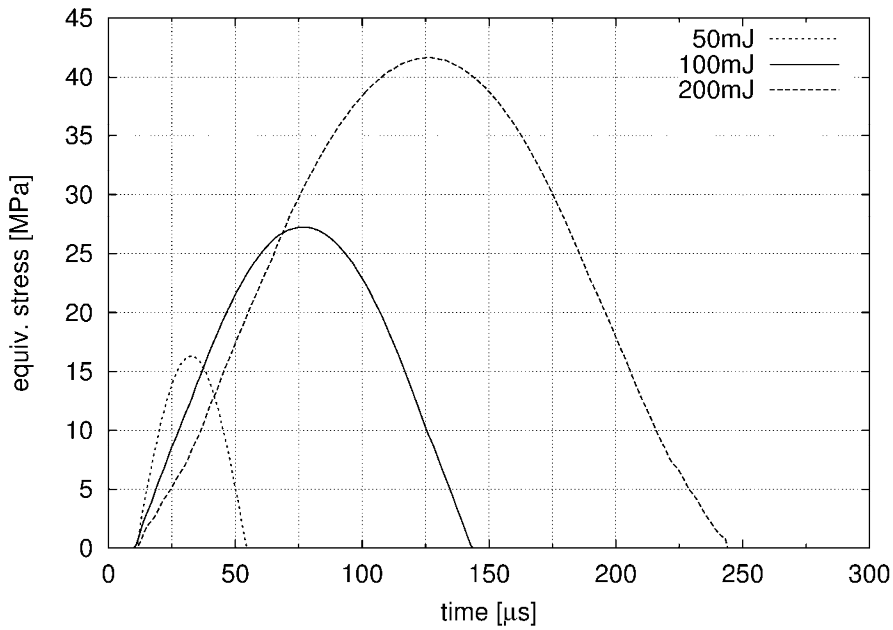

Figure 5. Equivalent stress from finite element calculations at different impact levels.

By comparing the time constants it is well visible, that higher impact rates not only lead to higher absolute stresses but also to longer time intervals. While results show a comparable relative difference between the impact energies there is a significant difference in both time-behaviour and curve progression compared to the measured data. The time constants for one load cycle are around one decimal power higher in measurements relative to calculations. More significantly, the curve character varies. While the simulated curves show a sinusoidal character as assumed in the theoretical considerations, the experimental data are more complex, as depicted in Figure 3. Keeping the mechanisms behind the polarisation changing behaviour in mind, this complexity is expectable.

According to the previous discussion, further development will be concentrated on the improved modelling of the LVIs carried out. Namely, more accurate material models which include for example material relaxation data will be taken into account. Additionally, the effect of vibrations on the stress progression due to impact will be analysed.

SUMMARY

An alternative SHM approach could be developed and tested within this study. In addition to existing, just fibre optic based techniques, a polarimetric in-situ measurement method was established. Therefore the wave guiding and polarisation sensitive properties of most matrices, adhesives and other structural materials could be utilized as sensing element. As a result the structure itself or rather the structural material becomes sensitive.

Signal interpretation was focussed on the detection of dynamic events such as impacts and high-frequent load changes by analysing the change in SOP. For that reason signals are derived in the time-domain to enable the determination of characteristic curve progression parameters like frequency and slopes.

The established analysis was tested during LVI experiments on polymeric bonded aluminium samples. It could be studied that the analysis model is well suited for the detection of LVIs. Additionally the results showed that the detection of different impact loads is possible by analysing the time dependent curve progression. Significant separation between different impact energies were found, especially through abstraction by derivation. More work has to be done in order to statistically confirm the results and to fully understand the observed effects.

The obtained data could be set in conjunction with results obtained by a finite element model. The relative difference in time constants of the signals under varying impacts was comparable to the experimental results. But absolute values as well as the curve progressions showed significant disparities. The outcome of this is that future work will be concentrated on enhancement of the model incorporating material relaxation and vibration analysis. Further investigations on the performance of the described health monitoring approach should be done regarding delamination and crack detection.

As already discussed the polarimetric in-situ health monitoring technique has a wide range of possible applications where polymers are used for structural purposes. Especially systems with FRPs, (structural) adhesives or bulk polymers could benefit from it. In contrast to fibre optic sensors it could be considered to implement the in-situ polarimetric technique in applications where the integration of fibres is technically difficult or impossible (e.g. elastomers).

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