Detection and Quantification of Impact Loads in Fibre Reinforced Polymers

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ABSTRACT

Fibre reinforced polymers offer a high potential to reduce the kinetic energy. They are mainly used where high accelerations could take place. As a consequence of this, fibre reinforced polymers often have a higher risk of being exposed to impact loads. The knowledge of the mechanisms and of the material loading during and shortly after an impact load is essential for an ‘impact-load-monitoring-system’ to predict possible structural failures. Especially a prognosis of structural failures caused by – often unrecognized - barely visible impacts is an important factor, because a sudden structural failure caused by an impact load is one of the most important problems in product development for the aircraft industry. By measuring the structural response at several discrete measurement points an impact can be detected and reconstructed.

Introduction

The material loading during and shortly after an impact load is represented by a Finite-Element-Model. To verify and validate the Finite-Element-Model experimental means of the state of stress on the surface of the FRP shortly after the impact are necessary.

Fig. 1: Pneumatic loading apparatus: A projectile is accelerated by means of a defined quantity of air at a variable pressure. The projectile emits an impulse through an anvil to the specimen and produces an impact load.

At the “Bremer Institut für Konstruktionstechnik” (BIK) and at the “Bremer Institut für angewandte Strahltechnik” (BIAS) experiments using the photoelastic coating technique (PEC) and the holographic interferometry (HI) were carried out to determine the strains within impact-loaded FRP-plates [1,2]. The experimental registration of strain waves in a component after an impact load requires the development of a high dynamic experimental technique. This technique has to fulfill the high demands on the temporal reproducibility of the mechanical process after an impact load. For the experimental registration of the strain waves, the photoelastic coating technique and the holographic interferometry are applied. The experimental set-up is composed of:

- pneumatic loading apparatus device (Fig. 1)
- photoelastic measuring set-up (Fig. 2, left)
- holographic measuring set-up (Fig. 2, right)
Fig. 2: The impact test device consists of the loading apparatus and the optical analysis set-up. The photoelastic element set-up (left) and the holographic interferometry element set-up (right).

The loading apparatus creates brief impact loads with a minimum duration (contact time) of 8 µs and a maximum impact force of approximately 10 kN.

**Exemplary experimental results**

Each photoelastic fringe pattern, recorded by a CCD camera and digitally stored, is analyzed automatically with an image processing system. Fig. 3 shows the fringe pattern from 10 µs to 80 µs after an impact load.

![Fringe Pattern from 10 s to 80 s after the impact.](image)

The analysis of the isochromatic patterns yields to the spatial and temporal distribution of the difference in principal strains. In the investigation of ultra-fast bending problems of thin plates by means of stress coating, several factors have to be considered to deduce from the experimental results to the strain of the unbonded specimen.

**Validation of the Finite Element Model**

The first test of the developed Finite Element Model is the qualitative comparison of the flexural wave propagation. As seen in Fig. 4 the qualitative time dependant behavior of the flexural wave propagation can be simulated.
In the next step the difference in principle strain evaluated with the photoelastic coating is compared with the results of the developed Finite Element Model. Fig. 5 illustrates that there is a quantitative accordance between the measured and the simulated difference in principle strain.

In Fig. 6 the deflection of a sample is measured using the holographic interferometry. In this Figure also the results of the deflection estimated by the Finite Element Model can be seen. The Figure illustrates the quantitative accordance between the measured and the simulated deflection.
Both experimental techniques are well-suited for observing the entire surface of the test specimen. The results advised a correlation between the experimental and numerical data in the maximum principle difference of strain and also in the maximum amplitude. The Finite Element simulation is adequate to describe the flexural wave propagation in fibre reinforced polymers. The influences of reflection and superposition of waves, especially according to a damage has also been assayed with the finite element simulation. Damage caused by impact loads arise primary direct at the impact point. The flexural waves are damped and they die down very fast. No secondary damage caused by reflection or superposition is observed.

**Localization of the impact**

In general, three points are necessary to evaluate the point of impact (Fig. 7).

\[ \beta = 60^\circ - \alpha \]

Fig. 7: Experimental set-up to localize an impact load – the two equations I) and II) has to be solved
The velocity of a flexural wave depends on the stiffness, the density \( \rho \), on the thickness of the fibre reinforced polymer \( h_{FRP} \) and the angle of propagation [3]. The wave velocity can be calculated out of

\[
c(\alpha)^2 = \omega^2 \frac{E(\alpha)h_{FRP}}{12\rho}
\]  

(1)

with \( c \): wave phase velocity, \( E(\alpha) \): Young’s Modulus. In case of isotropic material with constant flexural wave velocity, the unknown time \( t_1 \) and the angle \( \alpha \) can be calculated easily using equation I) and II) from Fig. 7 and the basic equations

\[
t_2 = t_1 + \Delta t_2
\]  

(2)

and

\[
t_3 = t_1 + \Delta t_3
\]  

(3)

to

\[
t_i = \frac{t^2 - \Delta t_i^2}{2\Delta t_i + 2l \cos(\alpha)}
\]  

(4)

and

\[
\alpha = \arccos \left[ \frac{(2l\Delta t_2^2 - (\Delta t_2^2 - l^2)(2l^2\Delta t_2 - 2l^2\Delta t_3 + 2\Delta t_2\Delta t_3 - 2\Delta t_2^2\Delta t_3) - (2l^2\Delta t_3^2 - 2l^2\Delta t_2 - 2\Delta t_2\Delta t_3 - 2\Delta t_2^2\Delta t_3))}{(2l^2\Delta t_2^2 - 2l^2\Delta t_3 - 2\Delta t_2\Delta t_3 - 2\Delta t_2^2\Delta t_3)^2} + 1 \right] + \sqrt{\left( \frac{(2l\Delta t_2^2 - (\Delta t_2^2 - l^2)(2l^2\Delta t_2 - 2l^2\Delta t_3 + 2\Delta t_2\Delta t_3 - 2\Delta t_2^2\Delta t_3) - (2l^2\Delta t_3^2 - 2l^2\Delta t_2 - 2\Delta t_2\Delta t_3 - 2\Delta t_2^2\Delta t_3))}{(2l^2\Delta t_2^2 - 2l^2\Delta t_3 - 2\Delta t_2\Delta t_3 - 2\Delta t_2^2\Delta t_3)^2} + 1 \right)^2 - \frac{(2l^2\Delta t_3^2 - 2l^2\Delta t_2 - 2\Delta t_2\Delta t_3 - 2\Delta t_2^2\Delta t_3)^2}{(2l^2\Delta t_2^2 - 2l^2\Delta t_3 - 2\Delta t_2\Delta t_3 - 2\Delta t_2^2\Delta t_3)^2} - 1}
\]  

(5)

If the flexural velocity depends on the angle of propagation the equations (2) and (3) are not as easy to solve. This is why the problem is solved numerically for non-isotropic specimen.

**Measured values**

- \( \Delta t_2 = 21.4 \mu s \)
- \( \Delta t_3 = 24.1 \mu s \)

**Sensor distance**

- \( l = \text{const.} = 0.14 \text{m} \)
- \( v = 2200 \text{ m/s} \)

Fig. 8: Localization of an impact load, the time delays \( \Delta t_2 \) and \( \Delta t_3 \) have been measured
Fig. 8 shows an exemplary localization of an impact load. The test specimen was isotropic. The sensor distance (0.14m) and the flexural wave velocity (2200 m/s) are constant and known. The time delays $\Delta t_2$ and $\Delta t_3$ were measured. The time delay $\Delta t_2$ was 21.4$\mu$s. The time delay $\Delta t_3$ was 24.1$\mu$s. Using the equations (4) and (5) the calculation for time $t_1$ is approx. to 22.8$\mu$s. Out of equations (2) and (3) follows for $t_2 = 44.2\mu$s and for $t_3 = 46.9\mu$s. With $v = 2200 \text{m/s}$ this leads to the distances of $d_1 = 5\text{cm}$ from sensor I, $d_2 = 9.7\text{cm}$ from sensor II and $d_3 = 10.3\text{cm}$ from sensor III. The location of the impact can be determined to the coordinates $(4.1, 2.9)$ if sensor I is the origin of coordinates. In the next step the experiments has to be carried out with non-isotropic test specimen.

**Quantification of the impact**

![Diagram showing the quantification process]

Fig. 9: Basic principle to quantify the impact load

Prospective, the validated Finite Element Model starts with an estimated force progression at the calculated point of impact. The result of the simulation is now compared with the measured values. If the difference is minor than a defined threshold the simulation stops. Otherwise the force progression is updated. The simulation is looped until the difference of the calculated and measured values do not exceed the threshold anymore. The result will be the impact force progression.

**Conclusions**

Numerical and experimental investigations of wave propagation and therewith associated dynamic state of strain after an impact load has been performed. The experiments has been carried out with photoelastic coating and holographic interferometry. Both techniques are well-suited for observing the entire surface of the test specimen. The results advised a correlation between the experimental and numerical data in the maximum principle difference of strain and also in the maximum amplitude. The Finite Element simulation is adequate to describe the flexural wave propagation in fibre reinforced polymers. The knowledge of the flexural wave propagation in FRP and the feasibility to describe them in a finite element simulation is a valid attempt for an 'impact load monitoring' to detect, reconstruct impact loads in FRP materials. First investigations point out that it is possible to detect the point of the primary impact in isotropic specimen.

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**References**