In Situ Ultrasonic NDT of Fracture and Fatigue in Composites

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Abstract. Fibre-reinforced composites subject to high static and dynamic loads require new advanced NDT-methods to assess damage and prevent failure at an early stage of deterioration of their performance. Mechanical properties of polymer and plastic based composites are mainly studied using static tensile tests to obtain a stress-strain relation for a reference sample which is then analysed to derive material stiffness, strength, toughness and ultimate failure load. The new testing techniques are preferably to be non-contact and capable of monitoring various stages of deformation *in situ* thus predicting further developments in mechanical behaviour. For this purpose, a new approach based on ultrasonic wave velocity variation due to material nonlinearity over the fracture and/or fatigue cycles is developed. Flexural wave velocity is used as a sensor of a local dynamic stiffness of a glass fibre-reinforced composite. The remote operation is achieved due to a non-contact excitation-reception of the waves using air-coupled ultrasound. It enables real-time monitoring of local stiffness alteration through a loading cycle and to identify basic stages in mechanics of fracture for polymers and composites.

1. Introduction

Damage and failure in polymer-based composites have a broad variety though they are much less obvious than in metals. In order to understand the processes resulting in damage one needs to investigate its development at their early stages. This is a demanding task for emerging modern materials (e.g. polymer materials reinforced with glass or carbon fibres, ceramics, etc.) with many different applications where these materials may perform even much better than metals. As the ways how the composites fail also differ from metals, modern fracture monitoring techniques must be developed for the challenges where new materials and applications are involved.

In the last decades, many existing NDT-techniques were improved or new approaches emerged. Progress in elastic wave research brings about the new topics like nonlinear effects and interaction of remote air-coupled ultrasound with modes of the inspected component. The intention of this paper is to highlight the performance of a new method for nondestructive monitoring of damage in polymers and composites that combines remote access with nonlinear elastic phenomena. In particular, the nonlinear acoustic approach is used to investigate the development of damage in polymer-based fiber-reinforced composites subject to tensile and cyclic loading. It was found that a sensitive and remote NDT-techniques can be based on velocity variation with strain for air-coupled elastic waves which respond to local structural changes of materials in real time.

2. Acoustic Velocity Variation with Strain

In a linear solid medium, acoustic wave velocity is determined by stiffness and mass density and is independent of the wave amplitude. If the solid is deformed beyond the elastic limit determined by Hooke`s law, the elastic nonlinearity results in a variation of wave velocity with static strain ε [1]:

$$v(\varepsilon) = v_0(1 - \beta_2\varepsilon - \frac{3}{2}\beta_3\varepsilon^2 - ...), \quad (1)$$

where v_0 is the wave velocity in an unstrained body, β_n are the parameters of nonlinearity whose values characterise the presence of defects or damage in a material. In particular, material nonlinearity increases sharply due to both micro(meso)-scale structural changes (micro-cracking, delaminations, etc) and macro-scale defect generation.

To monitor damage development, $v(\varepsilon)$ is measured locally in the expected fracture area; the damage induced can be revealed by determining β_n as functions of the mechanical state of material (strain, stress, number of fatigue cycles, etc.). Since a major contribution to $v(\varepsilon)$ is from the second-order terms, the parameter to be determined is: $\beta_2 = -(\partial v / \partial\varepsilon) / v_0$. Hence, one has to measure the local velocity of an acoustic wave as a function of static strain. The value of β_2 defines the rate of stiffness variation: positive values correspond to softening of the material (e.g. due to damage induced defect generation) while a negative sign means stiffening (e.g. due to molecular drawing in polymers). Thus, local velocity (and β_2) monitoring can be used to read-out information on the development of damage and fracture in materials and components.

3. Experimental Methodology

In our experiments, the Focused Slanted Transmission Mode (FSTM) of air-coupled ultrasound [2] was applied for non-contact measurements of local velocity of flexural waves in sheet-like specimens of polypropylene (PP) and polycarbonate (PC) based composites. The “dog-bone” shaped specimens (length 100 mm; thickness 2.8 mm; width 15 mm) were fabricated from pure PP and PP reinforced with flow-oriented short glass fibres (GF) (20% weight fraction). The molten blends were prepared with and without adding a chemical matrix-fibre coupler at the temperature of 230 ^{0}C.

The testing experiment used a tensile machine with a maximum force of 2000 N and automated recording of stress-strain ($\sigma(\varepsilon)$) diagrams. The ambient temperature was kept at 23 ± 2^0 and an atmospheric humidity of $50 \pm 5\%$ according to DIN 291-23/50-2 standard. To avoid time dependent visco-elastic effect, a low speed of separation of the test-piece grips (0.5 mm/min) was maintained to provide a quasi-static deformation.

The air-coupled FSTM was carried out with a CW-input of 20V p/p voltage and ultrasound frequency 393 kHz. A circular area of 6-7 mm diameter around the expected fracture was inspected with a weakly focused ultrasonic beam incident on the surface of the specimen at the angle of flexural wave excitation. In the course of tensile tests, both phase and amplitude of the output were automatically recorded with a digital lock-in amplifier (PerkinElmer 7280). The data on phase variation ($\Delta\varphi$) were then processed to derive flexural wave velocity (v_{a_0}) and nonlinearity parameter (β_2) as functions of strain.

4. Experimental Results

4.1. Impact of Fibers and Matrix-Fiber Coupling

The experimental results of $\sigma(\varepsilon)$ and $v_{a_0}(\varepsilon)$ measurements shown in Fig. 1 illustrate the tensile behavior of pure PP material. A quasi-linear low-stiffness (Young modulus ~ 1 GPa) deformation of the specimen (at $\varepsilon < 2\%$) changes for plastic tension followed by necking and ductile flow without fracture up to $\varepsilon > 16\%$. The nonlinear material behaviour derived from the velocity data is illustrated in Fig. 2. The data in Figs. 1 and 2 reveal the local stiffness variation in the tested area of maximum deformation: overall softening of the

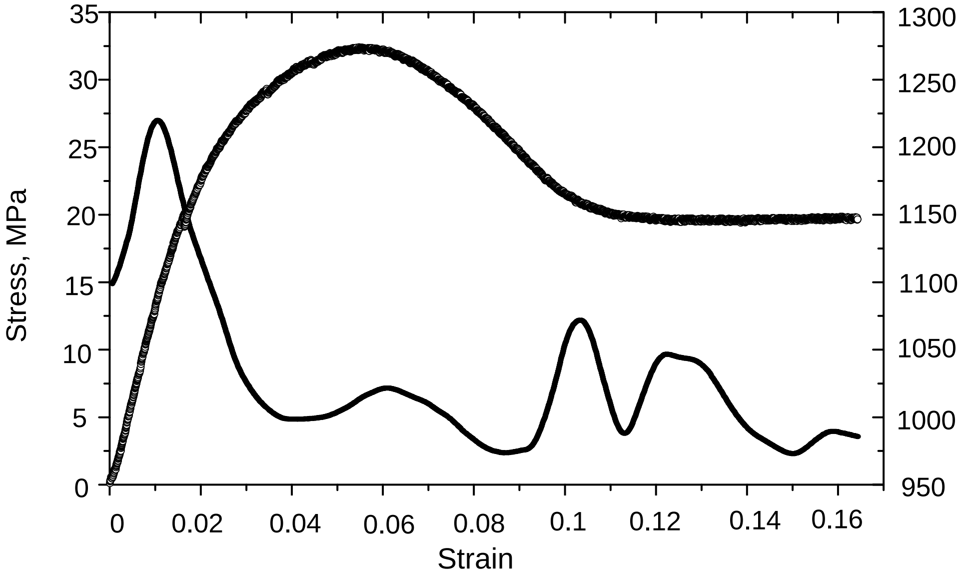

Figure 1. Stress-strain (circles) and flexural wave velocity (solid line) as functions of tensile strain in pure polypropylene.

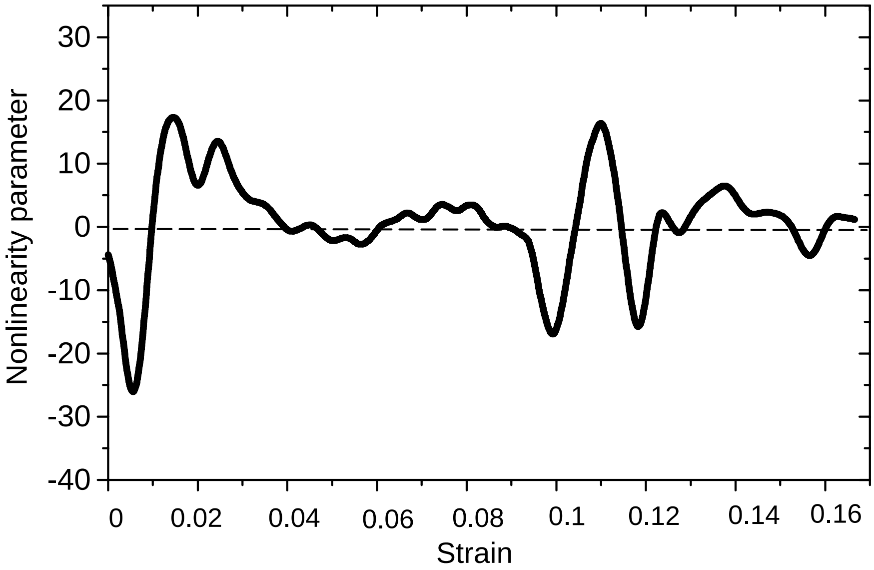

Figure 2. Nonlinearity parameter as a function of tensile strain in pure polypropylene.

material due to the damage induced alternates with hardening ($\beta_2 < 0$) caused by untangling of polymer molecules at small strain and molecular drawing in the necking area. Local hardening prevents material from fracture; instead, the strain increases at rather low tensile load (maximum tensile strength ~32 MPa, Fig. 1) due to damage (necking) propagation to softer areas along the specimen.

The damage development changes when material is reinforced with GF. Two types of GF-reinforced PP (GFRPP) were studied, respectively, with and without chemical fiber-matrix coupler. The fiber orientation in the specimens measured by the birefringence technique [3] was 60^0 – 70^0 to the loading direction in the area of expected fracture. The impact of the fibre-matrix coupling on the fracture mechanics can be seen by comparing the data in Figs. 3 and 4. In both cases, the presence of fibres results in a two-fold increase of material stiffness (Young modulus ~ 2 GPa) and higher tensile strength. For the lower fiber-matrix adhesion (no coupler), a typical brittle fracture is observed at low ductility ($\varepsilon \approx 2.5\%$) (Fig. 3). The β_2-curve illustrates the mechanics of fracture: similar to the pure PP case, the reinforced material "resists" by hardening (areas with $\beta_2 < 0$) until the fiber-matrix coupling fails. The positive values of β_2 for $\varepsilon > 2.5\%$ indicate softening of the material evidently due to fiber-matrix delamination right before the fracture.

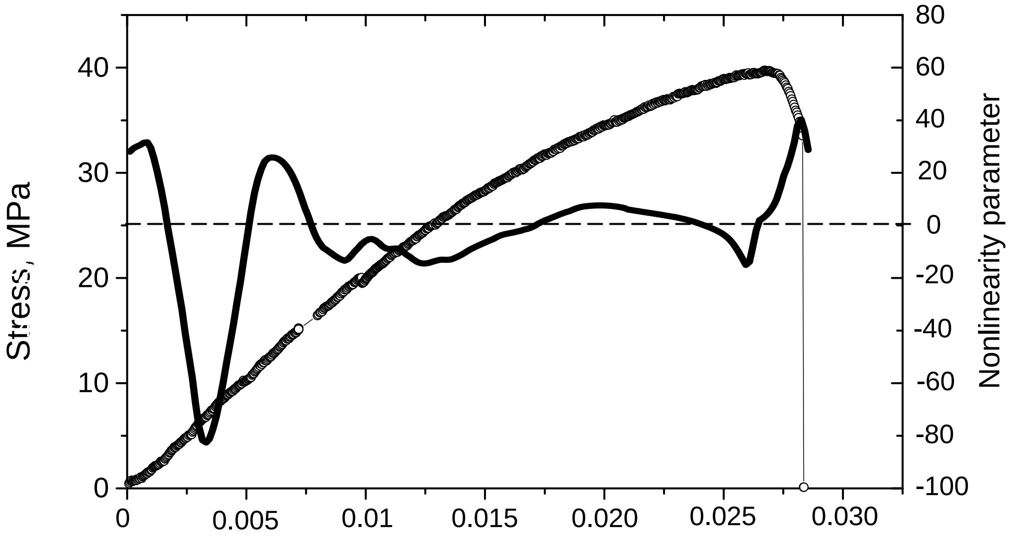

Figure 3. Stress-strain (circles) and nonlinearity parameter (solid line) as functions of tensile strain in intact GFRPP without fiber-matrix coupler.

The matrix deformation increases substantially when the chemical coupler is added into the blend. In this case, the deformation changes for plastic strain and the ductility grows up to $\geq 5\%$ (Fig. 4). It is accompanied by material hardening and a higher tensile strength (~ 45 MPa) that confirms the higher fiber-matrix adhesion and supports the failure mechanism by fiber-matrix debonding in GFRPP. Unlike the previous case, the nonlinearity parameter turns deeply negative before fracture which indicates a strong drawing of the matrix in the area of fracture before material fails due to fiber-matrix debonding.

4.2. Impact of Welding Lines

Injection molding of polymer based composite products of large size and/or complicated shape usually requires a few injection sources and some compound molds which inevitably

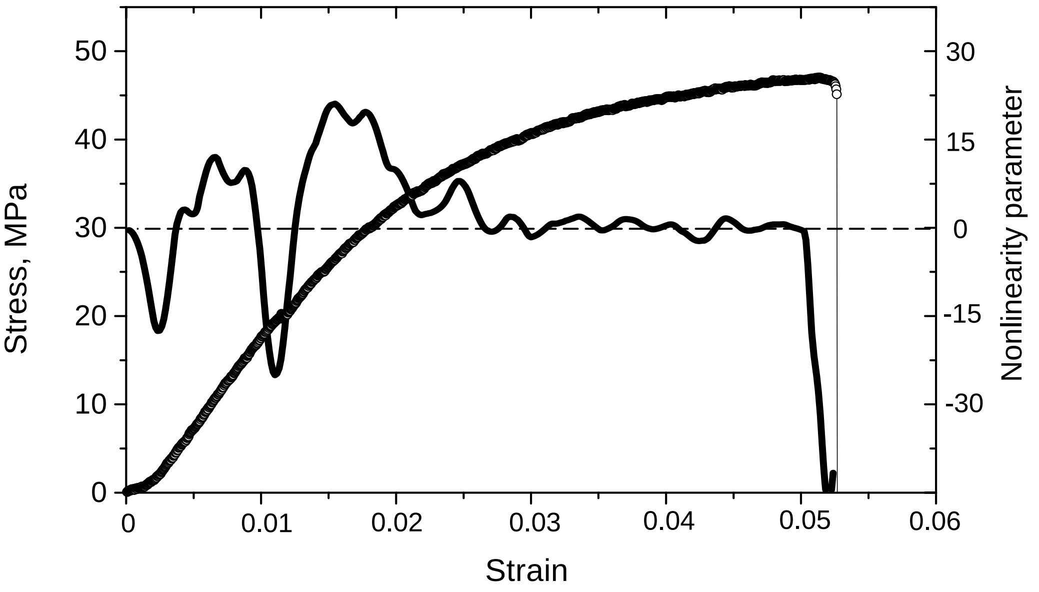

Figure 4. Stress-strain (circles) and nonlinearity parameter (solid line) as functions of tensile strain in intact GFRP with fiber-matrix coupler.

separate flows of melted fiber-matrix blend. The interaction between the flows forms welding lines whose quality strongly depends on the technological conditions of the molding process and can influence the development of damage and the ultimate strength of the material. To produce the welding lines, circular obstacles of 15mm diameter were inserted into the molds to separate the blend flow.

The impact of the welding line on damage development was first studied for pure PP (Fig. 5). In this case, the stress-strain dependence is virtually identical to that obtained for intact material (Fig. 1) with the Young modulus ~ 1 GPa, high ductility (>16%), and a tensile strength of ~33 MPa. However, the material nonlinearity reveals a somewhat different behavior with sharp peaks of negative β_2 (Fig.5). They correspond to mechanical

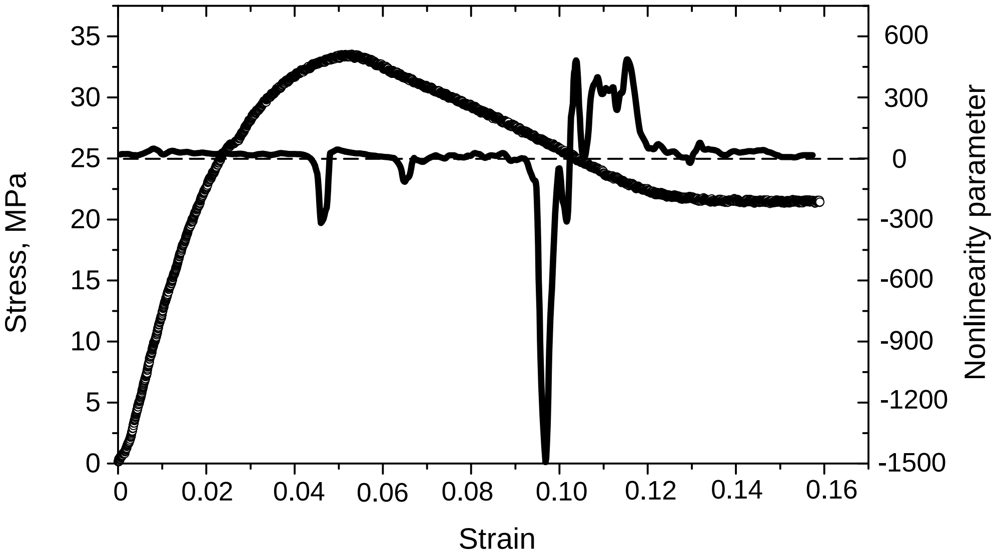

Figure 5. Stress-strain (circles) and nonlinearity parameter (solid line) as functions of tensile strain in a welded specimen of pure polypropylene.

instability of the area around the welding line: at certain (threshold) values of tensile stress and strain the local stiffness “jumps” to the higher values (unstable hardening). Such a drastic change in the material structure is indicated by the gigantic values of β_2 in Fig. 5. It is also accompanied by the “clicks” emitted by the material and clearly heard even at some distance. The welding line area whitens instantly that indicates intensive crazing of the locally drawn material. The micro-scale collective local drawing causes a step-wise increase in stiffness of the welding line (negative spikes of β_2) which prevents it from brittle fracture and initiates a ductile deformation instead.

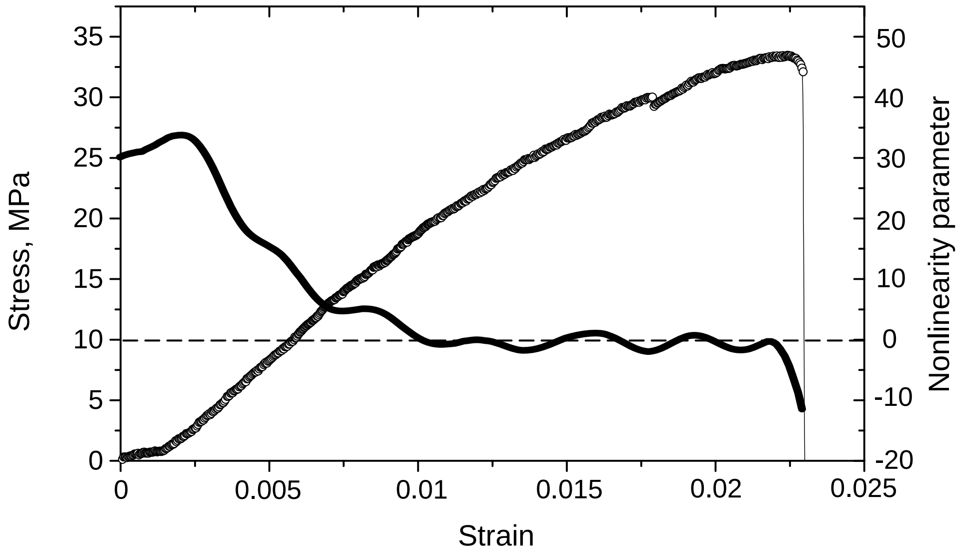

Figure 6. Stress-strain (circles) and nonlinearity parameter (solid line) as functions of tensile strain in a welded specimen of GFRPP with fiber-matrix coupler.

The deformation scenario simplifies considerably when the welding line is introduced into fibre-reinforced material (Figs. 6 and 7). The matrix-fiber adhesion has little effect on damage development: the stress-strain curves demonstrate a typical brittle fracture with a low ductility ($\varepsilon \sim 2\%$) and substantial reduction in tensile strength (from

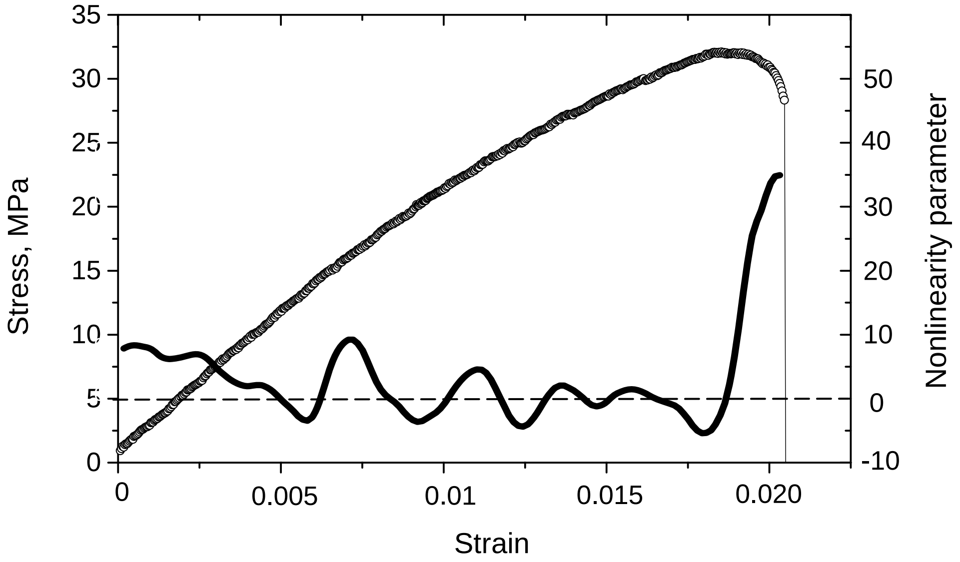

Figure 7. Stress-strain (circles) and nonlinearity parameter (solid line) as functions of tensile strain in welded specimen of GFRPP without fiber-matrix coupler.

~ 45 MPa down to ~ 32 MPa) for GFRPP both with and without fiber-matrix coupler. The nonlinear behavior is also similar in both cases and, unlike the intact GFRPP, reveals gradual material softening with quite low indication of hardening. Therefore, the presence of glass fibers in the welding line prevents substantial drawing (and hardening) in either matrix (see, intact GFRPP, Figs. 3 and 4) or welding line (pure PP case, Fig. 5). As a result, damage develops in the welding line itself which proves to be a "weaker link" and provides brittle fracture of the welded material. Interestingly, that the sign of β_2 before the fracture again indicates different material behaviour: failure due to fiber debonding (positive β_2, Fig. 7) changes for matrix drawing (negative β_2) when the fiber-matrix coupler is added (Fig. 6).

The nonlinear approach can also be used for monitoring damage induced by cyclic mechanical loading. For that, the behavior of acoustic wave velocity is measured over a number of closed loading cycles: velocity hysteresis can be an indicator of defects accumulation in a material.

In brittle materials and composites, one would expect a hysteretic velocity behavior because of cracking accumulation with each consecutive loading cycle. To verify this assumption we measured the flexural wave behavior as a function of stress applied for cyclic loading of a thin polycarbonate plate with glass fiber bundles. The bundles of long glass fibers were first bonded with an epoxy resin layer (matrix) and then embedded into polycarbonate substrate. Accumulation of irreversible damage is illustrated in Fig. 8, where phase measurements in the area outside the bundles adjacent to the fiber ends are presented. In this area intensive cracking at the epoxy matrix-polycarbonate interface is clearly seen optically. A strong hysteretic behavior of the acoustic wave phase shift in Fig. 8 confirms irreversible damage in the composite induced by cyclic mechanical loading.

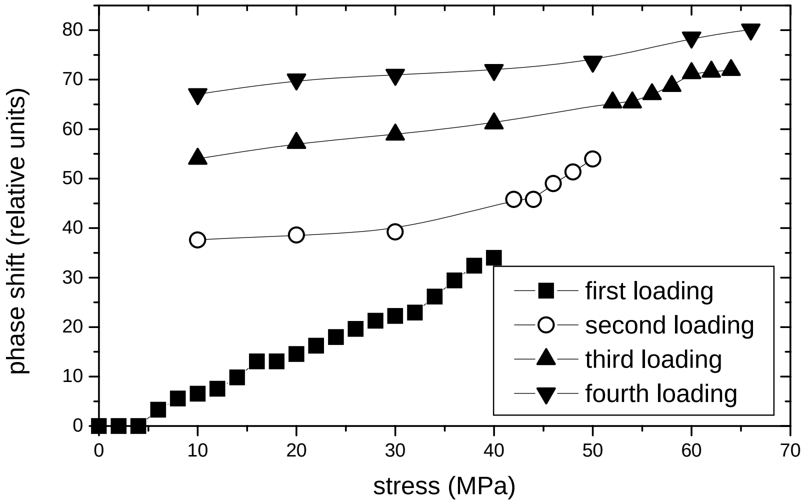

Figure 8. Phase shift of FSTM-output for cyclic loading of GF-bundle embedded in a polycarbonate plate.

5. Conclusion

The results of measurements performed on fibre reinforced polymers with and without chemical fiber-matrix-coupler indicate that the nonlinear approach is well suited to monitor the mechanisms of deformation and their changes during material failure. The nonlinear parameter is obviously a sensitive tool for material characterization which enables to improve our understanding of the material behavior beyond Hooke` law limitations. This information is vital for NDT of damage development and characterization of material performance in extreme conditions including aerospace and nuclear applications.

References

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