Research Article

Przemyslaw Lopato, Grzegorz Psuj, Michal Herbko*, and Ireneusz Spychalski

Evaluation of static bending caused damage of glass-fiber composite structure using terahertz inspection

https://doi.org/10.1515/eng-2024-0088
received August 05, 2024; accepted September 09, 2024

Abstract: Composite materials find increasing applications in modern industry and transport. However, they may lose desirable mechanical properties due to external mechanical excitations, ultraviolet radiation, moisture penetration, or other factors. Therefore, an effective way to assess the condition of materials is necessary. In this article, a nondestructive evaluation of glass fiber-reinforced composite subjected to five-stage static bending is presented. For this reason, pulsed excitation terahertz imaging was utilized, and a data processing/exploration scheme was proposed. The proposed, novel approach consists of an efficient data registration algorithm based on surface approximation (for surface roughness and unevenness elimination) and a parametrization scheme applied for the signals gained from the time response of the glass fiber-reinforced polymer layer. Obtained parameters enable the global description of the evaluated material state and prediction of failure effectively, even in the early stages of destruction.

Keywords: nondestructive testing, terahertz imaging, composite materials, layered structures, deformation, bending

1 Introduction

Polymer composite materials are increasingly prevalent in various structural applications due to their exceptional properties such as high strength-to-weight ratio and corrosion resistance. As these materials are subjected to mechanical loads during service, it becomes critical to ensure their structural integrity through efficient and accurate nondestructive testing (NDT) methods. NDT techniques allow for the assessment of internal states and the detection of potential defects without causing any damage to the material, thus playing a vital role in maintaining safety and reliability.

Several NDT techniques are commonly employed for evaluating polymer composites. Ultrasonic testing (UT) is one of the most widely used methods, relying on the propagation of ultrasonic waves through the material. By analyzing the reflections of these waves from internal discontinuities or boundaries, UT can detect surface, subsurface, and internal defects. This method is extensively used across industries like aviation, energy, and metallurgy, particularly for examining materials such as metals and polymer-based composites [1–3].

Digital radiography (DR) is another effective NDT technique, providing enhanced defect detection through digital imaging. Unlike traditional radiography, DR enables more efficient and repeatable inspections, making it suitable for applications in sectors like foundry, automotive, and aviation [4,5].

Laser shearography offers a different approach by using optical techniques to detect subsurface discontinuities. It works by observing surface strain fields and is particularly valued for its high efficiency and ease of automation, making it ideal for use in industries like automotive and shipbuilding [6–10].

Thermography is also a significant NDT method, which involves heating the composite material and analyzing the resulting temperature distribution with thermal imaging cameras. This technique can identify structural defects based on thermal emissivity changes, though it often requires advanced image processing to address surface heterogeneity [11–15].

Recently, terahertz (THz) imaging has gained attention as a promising NDT technique for composite materials. The THz region of the electromagnetic spectrum lies between infrared radiation and microwaves [16,17]. THz waves can

*** Corresponding author: Michal Herbko,** Center for Electromagnetic Fields Engineering and High Frequency Techniques, Faculty of Electrical Engineering, West Pomeranian University of Technology, Szczecin, Poland, e-mail: michal.herbko@zut.edu.pl
Przemyslaw Lopato, Grzegorz Psuj: Center for Electromagnetic Fields Engineering and High Frequency Techniques, Faculty of Electrical Engineering, West Pomeranian University of Technology, Szczecin, Poland
Ireneusz Spychalski: Faculty of Mechatronics and Electrical Engineering, Maritime University of Szczecin, Szczecin, Poland

penetrate these materials with minimal attenuation, providing valuable insights into their internal structure. In addition, THz radiation is nonionizing and safe for biological tissues, broadening its potential applications [18,19]. In recent years, a significant effort has been made to research the use of THz radiation in NDT of composites [20,21].

Despite the advantages, the high cost of THz imaging equipment has limited its widespread use in industrial settings. However, the technique's ability to detect early-stage damage and provide detailed information about the internal state of materials makes it a valuable tool for research and specific industrial applications.

In this article, the THz inspection will be utilized for the nondestructive evaluation of gel-coated glass fiber composite subjected to static bending.

2 Examined material and measuring system

The subject of the study is the composite structure shown in Figure 1. Part of it is a sandwich composite with a foam spacer, while the external laminates are made of a composite of glass fiber and polymer resin. The sandwich composite transforms into a regular laminate, while the area of interest in this analysis is the area of the nonsandwich laminate (located near the transition) where the highest stresses and the probability of defect occurrence caused by the sample bending process occur, as shown in Figure 1.

The sample was subjected to a five-stage static bending process. It was assumed that five stages were the minimum number that would allow us to notice both very small changes at the beginning of the process and very advanced damage (preventing further work of the element under any mechanical load) at its end. The first stage indicates a non-bending sample, while the fifth stage indicates a condition in which there are visible delaminations and cracks in the resin and delamination of the gel coat. Between individual states, the deformation of the sample was increased and then brought to its basic shape, in which configuration THz measurements were performed. This procedure allows for more uniform measurement conditions (in a flat sample, the focus of the THz beam is at one depth, which is impossible to maintain in a sample deformed by bending – for a given sample, it allows for a uniform signal-to-noise ratio and no blurring of the signal at other depths).

The nondestructive evaluation of MUT was performed using the measuring system, shown in Figure 2. The main element in this system is a time domain THz spectroscope (THz TDS) TeraFlash pro of Toptica. The spectroscope and the connected photoconductive antennas are responsible for excitation and detection in the time domain of

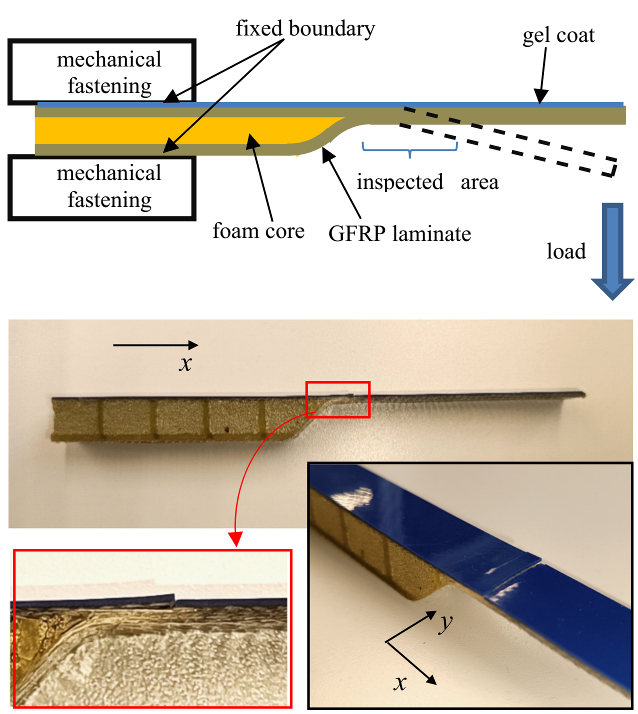

Figure 1: Photo and schematic view of the material under test (MUT) and its setup during deformation application.

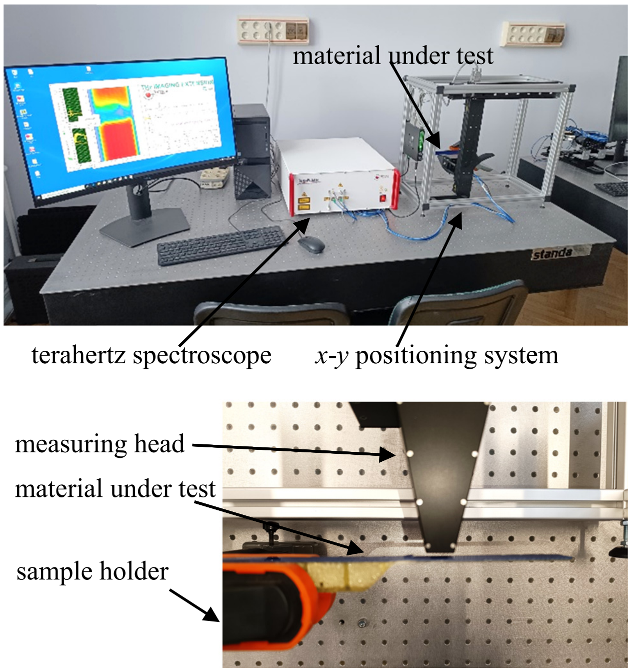

Figure 2: Photo of the measuring system.

picosecond electromagnetic field pulses. The antennas and the system of four curved mirrors (Figure 3) constitute the measuring head that is moved during the inspection. The head allows measurement only in the reflection mode – the THz beam is formed in such a way that after passing through two input mirrors, there is a focal point at the lowest point of the head. If there is a tested material at this point, as a result of reflection, the beam is directed to the system of output mirrors, the task of which is the best possible coupling of the THz beam with the aperture of the PCA – Rx receiving antenna (PCA – photoconductive antenna). The measuring head is attached to the *x–y* positioning system enabling spatial scanning of the tested material. Control of the measurement process, initial signal processing, and visualization of results are carried out on the measurement computer.

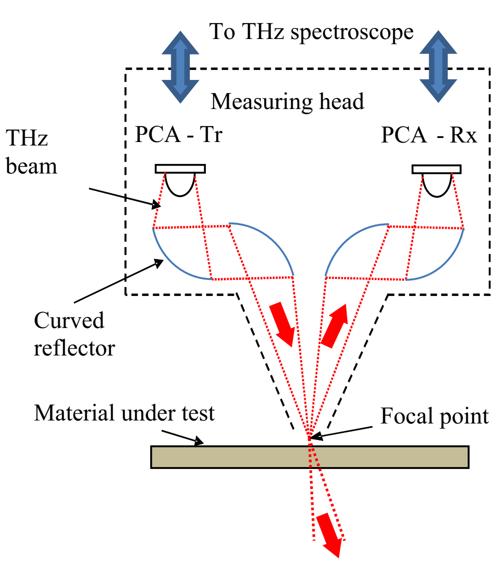

Figure 3: Simplified scheme of THz measuring head.

3 Material state assessment algorithm and measurements results

The evaluated material was successively scanned using the system and procedures presented in the previous section. Figure 4 shows an example of a B-scan signal obtained from a single scan along the region of interest (ROI) in the *x* direction, corresponding to stage 1 of the damage.

The beginning of the interaction of the THz pulse and MUT is a straight line for $t_D = 150$, resulting from the reflection of the pulse from the flat gel coat surface. It is also the largest pulse in terms of amplitude, which results from the largest difference between the characteristic impedances of neighboring materials (air and gel coat). The reflection from the gel coat/glass laminate boundary (t_D = 280) is no longer as uniform (due to the uneven surface of the laminate covered with gel coat) and is no longer characterized by such a large amplitude as before (due to the smaller

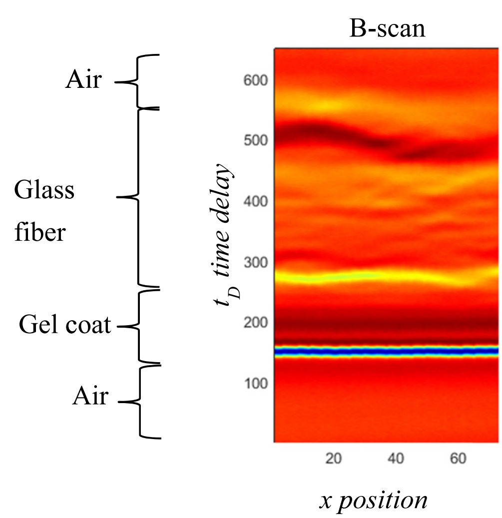

Figure 4: Exemplary B-scan measurement result. Time delay is expressed in time steps (1 time step = 78.125 fs; a whole range of time delay shown in the vertical axis is 50 ps) and *x* position is expressed in space steps (1 space step = 0.25 mm; a whole range of position shown in the horizontal axis is 17.5 mm).

change in characteristic impedance of this boundary and smaller energy of the interacting impulse). The reflection from the end of the tested material – the glass laminate/air boundary is the least represented due to its high blur (t_D = 480…580) and relatively low amplitude. This is because the pulse recorded in the case of this reflection propagated along the longest path (passing through the material thickness twice – including scattering on the nonhomogeneous structure of the glass fiber). Despite the aforementioned factors reducing the signal-to-noise ratio of the response of individual boundaries between layers, it is possible to determine areas in the signal (time windows) that correspond to the interaction with individual material layers (gel coat and glass laminate). This constitutes the basis for the material condition assessment algorithm developed and presented later.

Examples of measurement signals obtained in the experiment for individual stages of material degradation are shown in Figure 5. In the second stage, very slight (hardly noticeable) changes occur. A clear change is noticeable from stage 3. Then there is a loss of continuity of the gel coat layer (crack visible in the photo), which is reflected in the part of the signal responsible for reflection from the air/gel coat boundary. Changes also begin to appear in the part of the signal corresponding to the interaction with the glass laminate layer. The aforementioned effects within both layers intensify as the experiment continues in stages 4 and 5.

As damage to the gelcoat layer is very easy to detect, either using the THz method or even visually, this work focused on the evaluation of the glass laminate layer, which determines the mechanical and strength properties of the technical infrastructure elements containing the tested connection. The material evaluation algorithm is proposed in Figure 6. The algorithm is designed to statistically evaluate the glass laminate layer, so analysis is mainly required for this layer. Unfortunately, it is hidden behind a layer of gel coat, the condition of which may affect the readings of the laminate layer. Therefore, the first step in the algorithm is to determine the time delay t_D resulting from reflection at the air-gel coat boundary. This will be the starting (reference) point for further determination of the time window corresponding to the interaction of the THz pulse with the glass laminate layer. The problem with determining the reference point occurs in the case of severe deformation and delamination of the gel coat, which is shown in Figure 5. A deformed fragment of the gel coat may confuse the procedure of determining the time window and lead to incorrect analysis. Therefore, the proposed algorithm includes a material surface approximation block. It allows the elimination of fast-changing components, leaving only slowly changing components resulting from the actual geometry of the material. The work uses a third-degree approximation polynomial, but the approximating function can be freely selected for various shapes of the material surface, depending on the application. The results

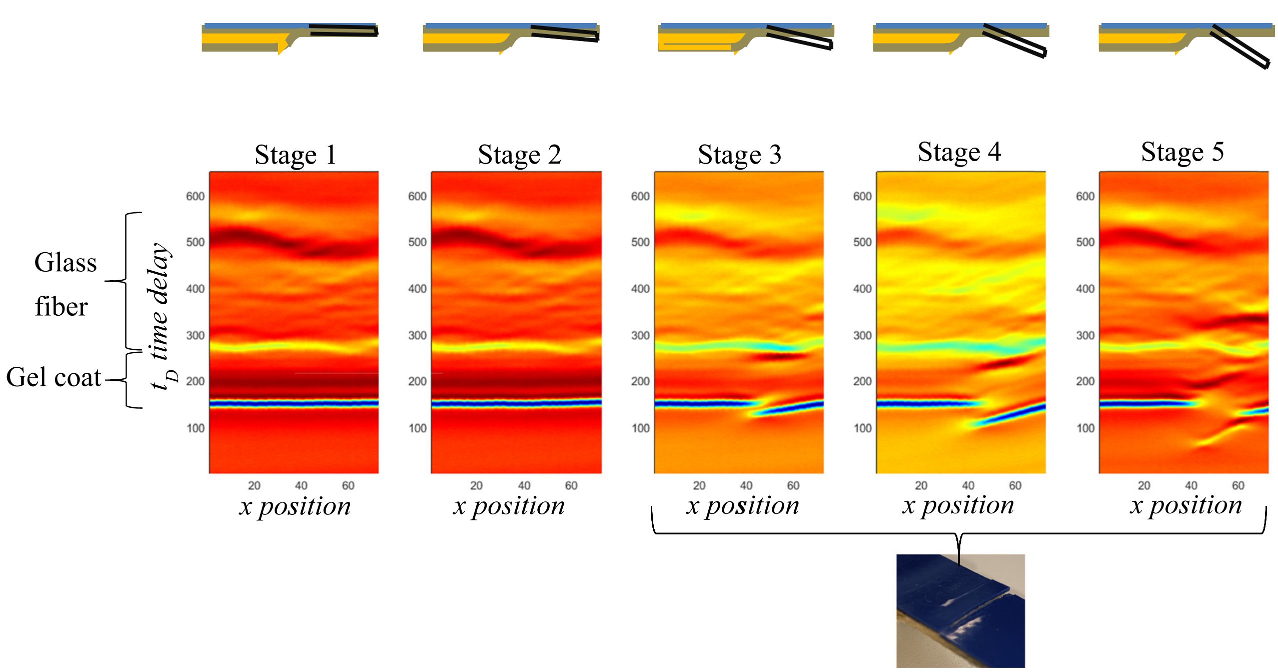

Figure 5: Exemplary B-scan measurement result.

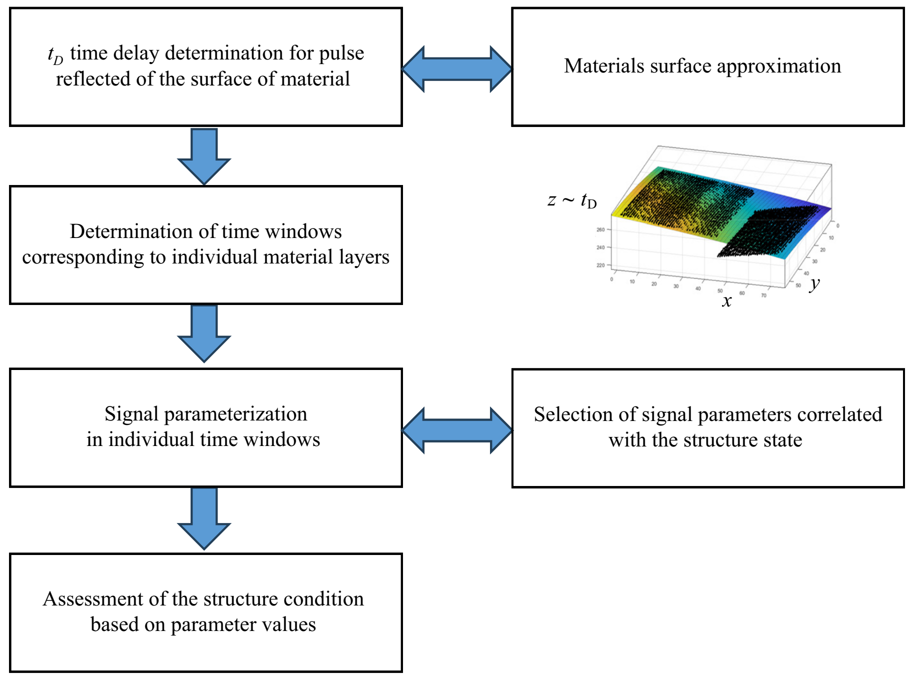

Figure 6: Material condition assessment algorithm.

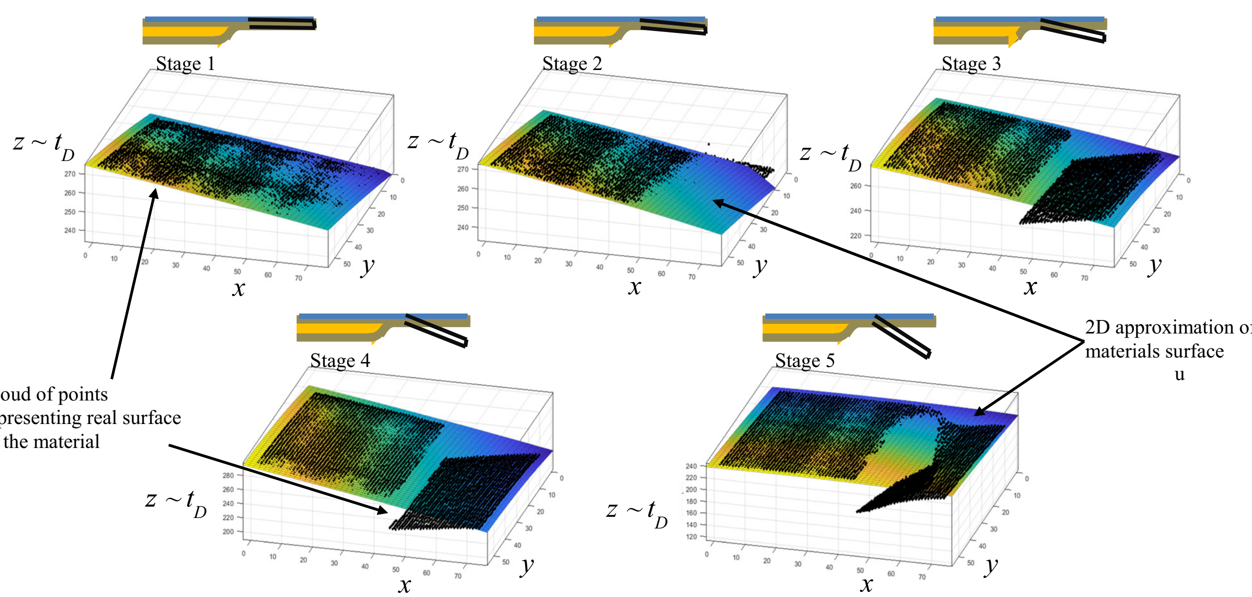

Figure 7: Material surface approximation results – determination of the time delay corresponding to the reflection of the THz pulse from the material surface (gelcoat).

of the approximation of the surface of the tested material for individual stages of material degradation are presented in Figure 7.

After appropriately determining the reference plane (the air/gel coat boundary, ignoring any local changes in geometry resulting from delamination or cracking of the gel coat), the algorithm proceeds to determine time windows corresponding to the interaction with the glass laminate. The gelcoat/laminate boundary (beginning of the time window) is detected as the center of the peak (position of the maximum value) resulting from the reflection from the aforementioned boundary. The end of the analyzed time window is determined similarly based on the diffuse pulse (resulting from reflection from the laminate/air boundary). Then, for each measurement point

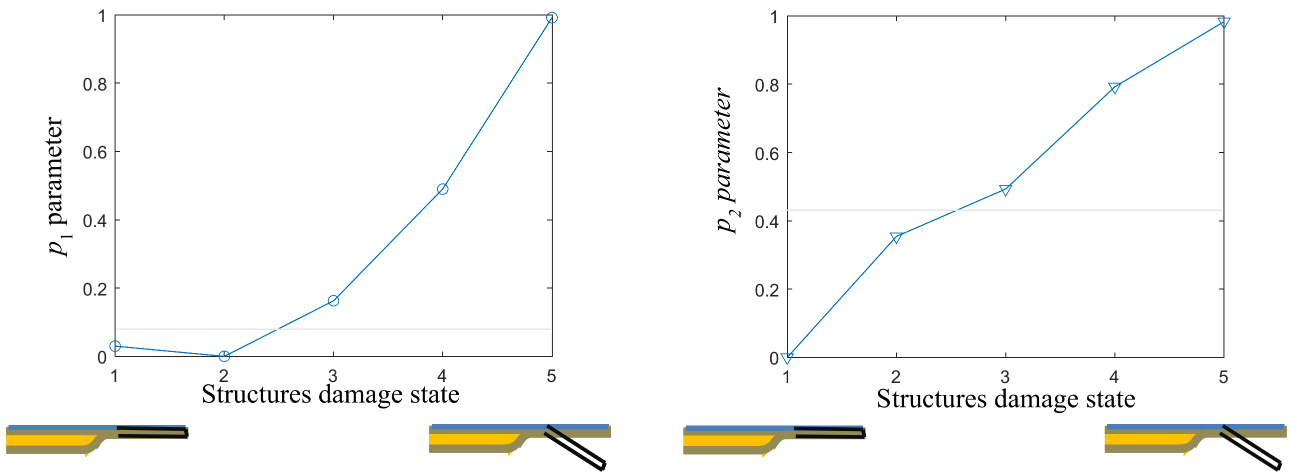

Figure 8: Selected parameters (p_1 and p_2) of B-scan signals calculated in region of interest over the time window correlated with response of glass fiber material.

(x, y), the signal contained in the time window is parameterized – selected statistical parameters are determined:

- p_1 – The normalized average peak-to-peak value of the signal calculated over the entire ROI surface for a time window correlated with the response of the glass laminate.
- p_2 – The normalized minimum signal value calculated over the entire ROI surface for a time window correlated with the response of the glass laminate.

The last part of the proposed algorithm is the assessment of the structure condition based on parameter values. In the first two stages, the material showed no signs of degradation. In stage 2, the applied bending degree was mainly within the elastic range of the stress–strain curve. Starting from stage 3, material degradation in the bending zone begins to be visible both visually and in response to the THz examination. Therefore, the middle value between stages 2 and 3 was adopted as the thresholds of selected statistical parameters determining the degradation state of the bent glass laminate. The method of selecting the threshold value can be determined in many ways and will be the subject of further research. The distribution of selected parameters for various stages of material damage is presented in Figure 8. Parameter p_1 has low values for stages 1 and 2 but starts to increase noticeably in the case of higher stages (3–5), which enables relatively easy detection of the damage state. Parameter p_2 has a quasi-monotonic nature with a steady increase in the whole range of degradation, which enables us to predict the damage state before it happens. Such a combination of information constitutes a reliable tool for material assessment.

4 Conclusions

THz imaging with pulsed excitation has great potential for use in dielectric testing of composite materials. Due to certain similarities in the physical phenomena occurring, it is often possible to use (with certain modifications) defect detection methods developed for UT. Moreover, THz inspection in the reflection mode enables noncontact measurements with access to only one side of the test material, which is particularly important in the practice of industrial NDT inspections. The work proposes an algorithm for testing a composite structure made of fiberglass subjected to bending, enabling automatic assessment of the state of the laminate under the gelcoat layer. For this purpose, the approximation of the surface of the tested material was used (enabling the reduction of the impact of deformations/cracks in the gelcoat on determining the time window related to the impact of the glass fiber material) and the statistical analysis of the received B-scan signals.

As a result of the proposed algorithm and the analysis performed, parameters enabling the assessment of the internal condition of the composite material were obtained. Parameter verification, especially of the p_1 parameter, allows for the assessment of whether the material remains within the elastic range–indicating that damage from the bending process is either absent or minimal–or if the material has begun to exhibit irreversible effects from deformation, such as internal cracks in the resin polymer and delamination.

Funding information: This work was conducted within the project “RE-TERA- Reconfigurable THz devices for EM waves manipulation and sensing applications," co-financed by the Polish National Agency for Academic Exchange (NAWA, Poland) and German Academic Exchange Service (DAAD, Germany) under the grant no. PPN/BDE/2021/1/00012/U/00001, ID: 57602825.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and consented to its submission to the journal, reviewed all the results, and approved the final version of the manuscript. PL was responsible for the concept of the article, algorithm development, and funding acquisition. PL, MH, and GP were involved in the measurements. GP, MH, and IS were responsible for the preparing a sample and bending/deformation process. All authors wrote and reviewed the manuscript and discussed the results.

Conflict of interest: Author G.P., who is the co-author of this article, is a current Editorial Board member of Open Engineering. This fact did not affect the peer-review process. The authors declare no other conflict of interest.

Data availability statement: All data generated or analyzed during this study are included in this published article.

References

[1] Spytek J, Mrowka J, Pieczonka L, Ambrozinski L. Multi-resolution non-contact damage detection in complex-shaped composite laminates using ultrasound. NDT E Int. 2020;116(102366):1–11. doi: 10.1016/j.ndteint.2020.102366.

[2] Panda RS, Rajagopal P, Balasubramaniam K. Characterization of delamination-type damages in composite laminates using guided wave visualization and air-coupled ultrasound. Struct Health Monit. 2016;16(2):142–52. doi: 10.1177/1475921716666411.

[3] Ulbrich D, Kowalczyk J, Jósko M, Selech J. The analysis of spot welding joints of steel sheets with closed profile by ultrasonic method. Case Stud Nondestr Test Eval. 2015;4:8–14. doi: 10.1016/j.csndt.2015.09.002.

[4] Ewert U, Zscherpel U, Bavendiek K. Replacement of film radiography by digital techniques and enhancement of image quality. Online NDT J. 2007;12(6):1–14.

[5] Katunin A, Wronkowicz-Katunin A, Dragan K. Impact damage evaluation in composite structures based on fusion of results of ultrasonic testing and X-ray computed tomography. Sensors. 2020;20(7):1867. doi: 10.3390/s20071867.

[6] Ki-Tea P, Hyun-Seop S, Jin-Taek J. Data processing techniques for the evaluation of cable tension of bridge by laser vibrometer, safety reliability. In: Deodatis G, Elingwood BR, Frangopol DM, editors. Risk and life-cycle performance of structures & infrastructures. London: Taylor & Francis Group; 2013.

[7] Li Z, Tokhl MO, Zhao Z, Zheng H. A compact laser shearography system for on-site robotic inspection of wind turbine blades. J Artif Intell. 2021;1(3):166–73. doi: 10.37965/jait.2021.0008.

[8] Ibarra-Castanedo C. Quantitative subsurface defect evaluation by pulsed phase thermography: Depth retrieval with the phase. PhD thesis. Quebec, Canada: University Laval; 2005.

[9] Huang YY. Applications of digital shearography for testing of composite structures. Compos Part B. 1999;30(7):763–73.

[10] Sirohi R. Shearography and its applications – a chronological review. Light Adv Manuf. 2021;3(1):35–64. doi: 10.37188/lam.2022.001.

[11] Maldague X. Nondestructive testing of materials using infrared thermography. London: Springer; 2007.

[12] Wang F, Sheng J, Sfarra S, Zhou Y, Xu L, Liu L, et al. Multimode infrared thermal-wave imaging in non-destructive testing and evaluation (NDT&E): Physical principles, modulated waveform, and excitation heat source. Infrared Phys Technol. 2023;135:104993. doi: 10.1016/j.infrared.2023.104993.

[13] Muc A, Pastuszak PD. Prediction of subsurface defects through a pulse thermography: experiments vs. numerical modeling. Proceedings of 15th ECCM. Venice, Italy; 2012.

[14] Szymanik B, Psuj G, Lopato P. Qualitative evaluation of 3D printed materials' structure using active infrared thermography and signal analysis based on LSTM neural neural networks. Int J Appl Electromagn Mech. 2022;69(3):359–73. doi: 10.3233/JAE-210197.

[15] He M, Xie Y, Wu Z, Li Z, Wang Y, Hou G. Study on a method for suppressing influence of nonuniform surface emissivity of material in eddy current thermography. AIP Adv. 2023;13(8):085103. doi: 10.1063/5.0161247.

[16] Yakovlev VE, Zaytsev KI, Fokina IN, Konasik VE, Yurchenko SO. Nondestructive testing of polymer composite materials using THZ radiation. J Phys Conf Ser. 2014;486(1):012008. doi: 10.1088/1742-6596/486/1/012008.

[17] Lopato P. Double-sided terahertz imaging of multilayered glass fiber-reinforced polymer. Appl Sci. 2017;7(7):661. doi: 10.3390/app7070661.

[18] Duan F, Wang YY, Xu DG, Shi J, Chen LY, Cui L, et al. Feasibility of terahertz imaging for discrimination of human hepatocellular carcinoma. World J Gastrointest Oncol. 2019;11(2):153–60. doi: 10.4251/wjgo.v11.i2.153.

[19] Zhang Y, Wang C, Huai B, Wang S, Zhang Y, Wang D, et al. Continuous-wave THz imaging for biomedical samples. Appl Sci. 2021;11(1):71. doi: 10.3390/app11010071.

[20] Chady T, Łopato P. Testing of glass-fiber reinforced composite materials using terahertz technique. Int J Appl Electromagn Mech. 2010;33(3):1599–605. doi: 10.3233/JAE-2010-1290.

[21] Palka N, Krimi S, Ospald F, Miedzinska D, Gieleta R, Malek M, et al. Precise determination of thicknesses of multilayer polyethylene composite materials by terahertz time-domain spectroscopy. J Infrared Millim Terahertz Waves. 2015;36:578–96. doi: 10.1007/s10762-015-0156-6.