Comparative Studies of GFRP Composites Using Pulsed Thermography and Transmission Terahertz Non-Destructive Testing Methods

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Abstract: Composites are materials that have replaced traditional construction materials in numerous applications in various fields. Due to the possibility of creating the required material properties, fiber-reinforced composites are most often used. Despite competition from carbon and aramid fibers, the earliest glass fibers produced are used in many applications. One of the areas where glass fiber reinforced composites (GFRP) make a significant contribution to structural applications is aviation. Because both during production and operation, composites are exposed to damage, which often occurs in the internal structure of the composite, works are being carried out to develop the most effective method of non-destructive testing to detect such damage. The article presents a comparison of the results of non-destructive testing of glass fiber-reinforced composite samples. A comparison of the results of the possibility of detecting defects in the form of milled holes of different diameters and depths inside the samples was made. These damages are not optically visible on both surfaces of the samples. In non-destructive testing, infrared thermography and transmission terahertz methods were used. The obtained results indicate a great possibility of using terahertz radiation, especially in thicker structures of the GFRP composite, where thermographic methods are not as effective as in thin ones.

Keywords: thermography, terahertz radiation, non-destructive testing, composite, glass fibers

1. Introduction

Composites are more effective in their performance compared to metals because of their fundamental characteristics. Several distinct features of composite materials make them to be essential materials in aerospace and automotive such as; excellent damping characteristics, light weight, resistance to corrosion destruction, and stress-free attainment of complex forms [1]. Fiber-reinforced composites (FRP) have a large share in many applications.

Fibers as reinforcing materials offer two advantages. Firstly, the bulk material is always stronger when produced as small diameter fibers due to the natural exclusion of large-scale defects. Secondly, the fiber configuration allows the tailoring of properties in the specific directions.

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FRP composites consist of two main components: a load-bearing component, mainly fibers, and a polymer matrix that serves as a binder and fiber protection [25]. Therefore, the fibers should meet specific requirements regarding strength, stiffness, stability of properties in a specific temperature range, resistance to chemical agents, etc. The matrix acts as a load-transferring medium between individual fibers, fills the space between the fibers, and also protects the fibers against the harmful effects of the external environment e.g., moisture. It also ensures the uniform transfer of loads to the fibers and the redistribution of stress transfer in the event of failure of some fibers.

Glass fiber became commercially available in 1939 and is the most commonly used fiber for reinforcing polymer matrix composites and is known as GFRP (Glass Fiber Reinforced Plastics). Despite the rapid evolution of carbon and aramid fibers, glass fiber-reinforced composites are still used in many applications. Especially in the aviation industry and the production of yachts and boats.

Composites can be damaged both during operation and in the production phase. Temperature and humidity are among the most important environmental factors affecting the condition of composites during their long-term use. Polymer composites are particularly sensitive to temperature increase [3].

For example, FRP composites used in many applications can experience the following defects during production:

- resin-rich (fiber-poor) regions;
- voids (e.g., at roving crossovers in filament winding and between layers having different fiber orientations, in general). This is a very serious problem; a low void content is necessary for improved interlaminar shear strength. Hence, the importance of the debulking step;
- microcracks (these may form due to curing stresses or moisture absorption during processing);
- debonded and delaminated regions;
- variations in fiber alignment.

Another type of damage is impact damage to the composite structure, which is one of the most critical damages.

Determining the effects of impact damage can be divided into two areas:

1) impact damage resistance which is related to the response and damage caused by impact [4],
2) impact damage tolerance, associated with the reduced stability and strength of the structure due to the damage [5, 6].

Non-destructive testing methods are used to detect defects in composites. One of the commonly used methods is infrared thermography. The objects of the research included in the article are GFRP samples. Compared to, for example, a composite reinforced with carbon fiber, GFRP has unfavourable thermophysical parameters (thermal conductivity and thermal diffusivity) both along the fibers and perpendicularly to them. This is a significant limitation regarding the thickness of the tested GFRP samples. Therefore, we are looking for a method that would be more effective in detecting defects in thicker NDT objects made of GFRP.

We conducted comparative tests using infrared thermography and terahertz radiation to assess their effectiveness.

2. Methods

2.1. Pulsed thermography

Pulse thermography is one of the most popular methods currently used in the non-destructive testing of composite materials. This is evidenced by the number of publications concerning this method. This type of test involves the use of a lamp, laser, etc. to generate a pulse (or series of pulses) of thermal excitation, which lasts from a few milliseconds for materials with high thermal conductivity (e.g., metals) to several seconds for materials with low conductivity [7–12]. You can also use a pulse cooling the surface of the tested object (e.g., a stream of cold air, liquid nitrogen, etc.). Pulse thermography can be performed using both the reflection and transmission approaches. A sequence of images (thermograms) is recorded with equal intervals between images. After switching off the radiation source, the object cools down to the ambient temperature. In the cooling phase, the temperature distribution on the surface of the tested object is determined and analysed. Depending on the thermal properties of the test material and those of sub-surface defects occurring in it, areas of higher or lower temperatures at the surface will indicate locations where there may be material defects. Often, special techniques for processing thermograms must be used to identify areas with defects.

In our tests, we used a flash lamp. Using this lamp, a thermal pulse of 6 kJ and a duration of 5 ms was generated. Changes in the temperature field on the surface of the sample were recorded with an IR camera in sequences consisting of 500 images with a resolution of 640 × 512 pixels, recorded with a frequency of 25 Hz. Both reflection and transmission modes were used.

2.2. Transmission terahertz

In non-destructive active thermographic tests, we observe changes in the time of the temperature field on the surface of the tested object under the influence of a source of thermal radiation. Using terahertz radiation in non-destructive testing, we take advantage of the ease of penetration of this radiation through non-metallic materials.

In non-destructive testing, terahertz radiation is used in two classic testing methods: reflection and transmission. In both methods, there must be a source of terahertz radiation and a receiver by means of which changes in the terahertz signal are recorded as a result of absorption and reflection by the tested material and discontinuities in its internal structure. In the reflection method, both the radiation source and the receiver are on the same side of the tested object.

In our research, we used the transmission method in which the radiation source and receiver, in our case a line scanner, are located on opposite sides of the tested object (Fig. 1). Such a setting enables the detectors to receive a greater signal, which is linked to the distance that the signal must pass. It is important for lower power sources as the one used in our investigations.

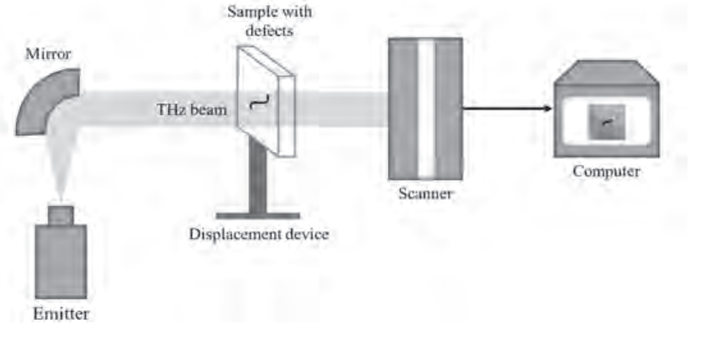
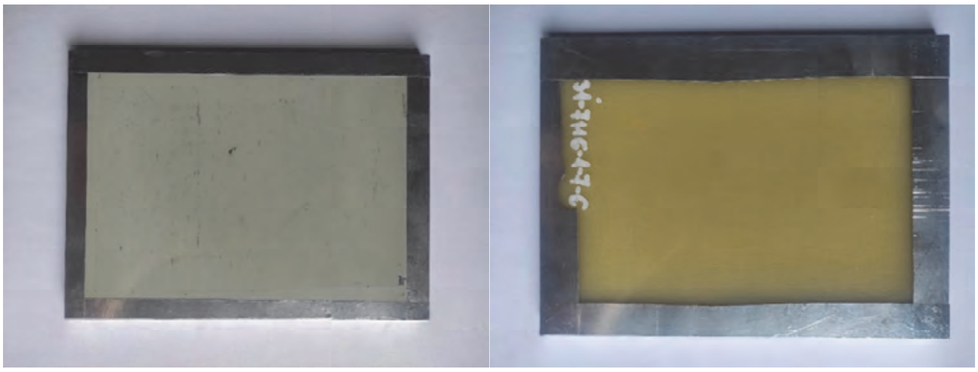


Fig. 1. Schematic representation of the terahertz investigation setup in transmission mode [13]
Rys. 1. Schematyczne przedstawienie konfiguracji terahercowego stanowiska w trybie transmisji [13]

The terahertz setup consisted of a line scanner Linear (512 × 1 pixels image resolution with a pixel pitch of 0.5 mm and frequency of ~300 GHz), and a terahertz source in the form of generator THz IMPATT (frequency 292 GHz ±5 GHz and power of ~10 mW). This source includes novel reflective THz optics based on a specially configured high-gain horn antenna in combination with a metallic mirror. This generator considerably improves the THz imaging capabilities of our linear scanner by increasing the amount of power reaching the sensor array. This equipment was sourced from the company Terasense Group, Inc.

3. Samples

For comparative tests, the Air Force Institute of Technology in Warsaw/Poland made 7 samples of glass fiber-reinforced composites. The material from which the samples were made was a typical material used in aviation applications. All samples measuring 140 × 190 mm and a thickness of about 10 mm consisted of two plates of equal thickness of about 5 mm. Blind holes of various diameters and depths were milled in the front plate (Fig. 2a). When examining the samples, we did not know how many defects in the form of holes or where they were located in individual samples. The front surfaces of these plates were covered with a layer of varnish to mask the location of the defects. The back plate (Fig. 2b) was glued on the side of the holes and ensured masking of their location.



a) b)

Fig. 2. View of the GFRP composite sample a) front side, b) back side
Rys. 2. Widok próbki kompozytu GFRP a) strona czołowa, b) strona tylna

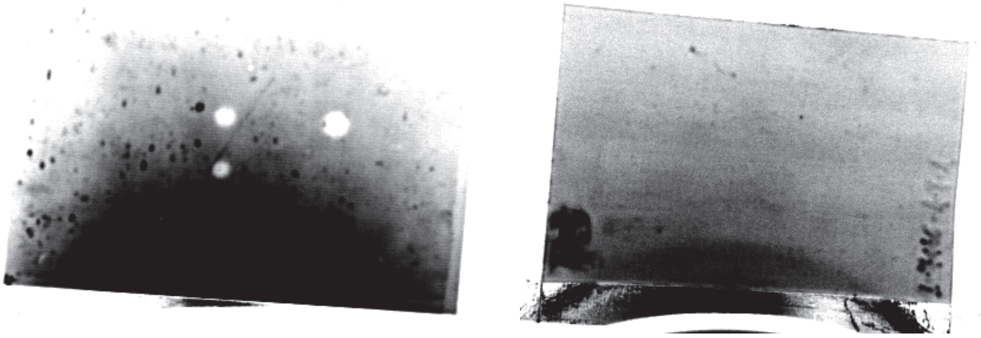
4. Results

Figure 3 presents the results obtained by the IR pulsed reflection method. The sequence of stored thermograms was subjected to image enhancement in order to detect defects. IR-NDT software from AT-Automation Technology GmbH [14] was used. The 1st derivation function was applied. The first derivative is calculated from the reconstructed infrared image. This analysis makes it possible to detect points of inflection of the temperature function recorded over time. Inflection points indicate the presence of defects and their location. This analysis was applied to all the thermographs presented below.

As you can see in this figure, using the reflection method from the front side, we managed to identify three defects (bright spots – Fig. 3a). Defects with the largest diameters (7 and 10 mm) were detected, located 1 and 2 mm below the surface of the sample. The reflection method from the back side turned out to be ineffective. No rare defects were detected (Fig. 3b). This proves that the thickness of about 5 mm of this material is the limit for this method.

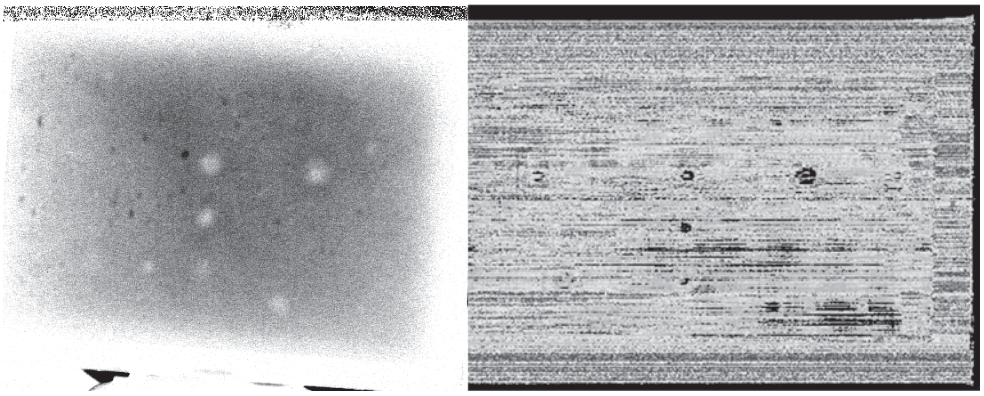
Using the pulsed transmission IR method for the same sample 1 we can identify many more defects (Fig. 4a) than with the reflection method. A similar number of defects (Fig. 4b) can also be detected using the terahertz transmission method. The detected defects were 2–10 mm in diameter and 1–3 mm below the surface of the sample.

Very similar results were obtained for samples 3 and 6 shown in Figures 5 and 6. It is clearly visible that the defects presented in the terahertz images have sharply outlined edges and the shape of the defects. The image of defects on thermograms is blurred and larger than the real defects. The defects in these samples (3 and 6) had the same range of diameter and subsurface depth as in sample 1, only differences were in their location and number.



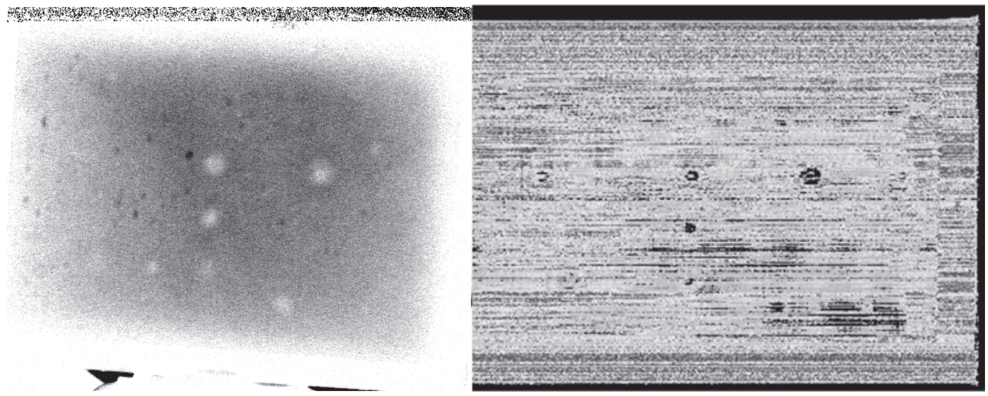
a) b)

Fig. 3. Resulting thermograms of sample 1 of the GFRP composite after reflection tests a) front side, b) back side
Rys. 3. Wynikowe termogramy próbki 1 kompozytu GFRP po badaniach metodą odbiciową a) strona czołowa, b) strona tylna



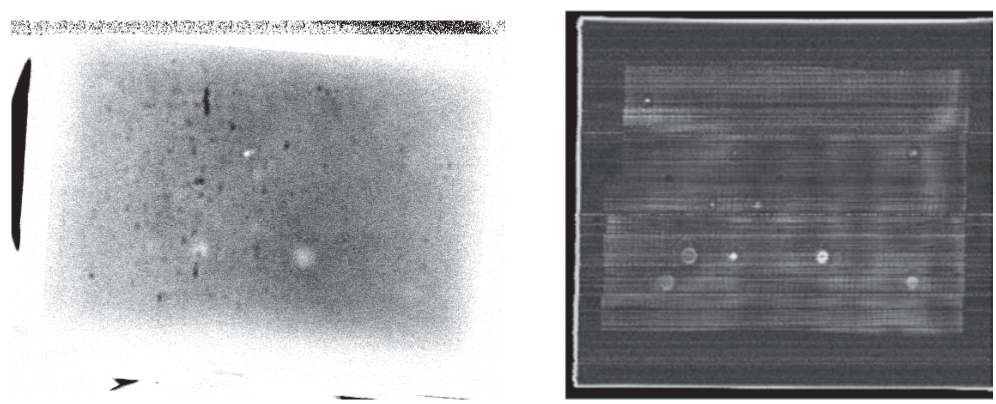
a) b)

Fig. 4. Transmission method – sample 1 of the GFRP composite a) resulting thermogram, b) terahertz image
Rys. 4. Metoda transmisyjna – próbka 1 kompozytu GFRP a) termogram wynikowy, b) obraz terahercowy



a) b)

Fig. 5. Transmission method – sample 3 of the GFRP composite a) resulting thermogram, b) terahertz image
Rys. 5. Metoda transmisyjna – próbka 3 kompozytu GFRP a) termogram wynikowy, b) obraz terahercowy



a) b)

Fig. 6. Transmission method – sample 6 of the GFRP composite a) resulting thermogram, b) terahertz image
Rys. 6. Metoda transmisyjna – próbka 6 kompozytu GFRP a) termogram wynikowy, b) obraz terahercowy

5. Conclusions

The thermophysical parameters of the GFRP composite are a significant limitation as to the thickness of the tested samples using infrared thermography. An alternative to this type of material in non-destructive testing can be terahertz method. For the material presented in this article for infrared thermography methods, it is about 10 mm. Our experience shows that using a source with a power of about 10 mW for the terahertz transmission method, one can test this material with a thickness of even between 50–60 mm.

As you can see in the terahertz images, there are disturbances on them. They are mainly caused by the non-uniform movement of the tested sample. In our further work, we will look for methods to eliminate sources of interference.

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Badania porównawcze kompozytów GFRP z wykorzystaniem metod badań nieniszczących – impulsowej termografii i transmisji terahercowej

Streszczenie: Kompozyty to materiały, które zastąpiły tradycyjne materiały konstrukcyjne w licznych zastosowaniach w różnych dziedzinach. Ze względu na możliwość tworzenia wymaganych właściwości materiału, najczęściej stosuje się kompozyty wzmacniane włóknami. Pomimo konkurencji ze strony włókien węglowych i aramidowych, najwcześniej wyprodukowane włókna szklane są wykorzystywane w wielu zastosowaniach. Jednym z obszarów, w którym kompozyty wzmocnione włóknem szklanym (GFRP) wnoszą znaczący wkład w zastosowania konstrukcyjne, jest lotnictwo. Ponieważ zarówno w trakcie produkcji, jak i eksploatacji kompozyty narażone są na uszkodzenia, które często występują w strukturze wewnętrznej kompozytu, prowadzone są prace nad opracowaniem najskuteczniejszej metody badań nieniszczących pozwalających wykryć takie uszkodzenia. W artykule przedstawiono porównanie wyników badań nieniszczących próbek kompozytów wzmocnionych włóknem szklanym. Dokonano porównania wyników możliwości wykrywania defektów w postaci wyfrezowanych otworów o różnej średnicy i głębokości wewnątrz próbek. Uszkodzenia te nie są widoczne optycznie na obu powierzchniach próbek. W badaniach nieniszczących wykorzystano termografię w podczerwieni i transmisyjną metodę terahercową. Uzyskane wyniki wskazują na duże możliwości wykorzystania promieniowania terahercowego, zwłaszcza w grubszych strukturach kompozytu GFRP, gdzie metody termograficzne nie są tak skuteczne jak w strukturach cienkich.

Słowa kluczowe: termografia, promieniowanie terahercowe, badania nieniszczące , kompozyt, włókna szklane

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