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COMPOSITES THEORY AND PRACTICE

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# THERMOGRAPHIC STUDIES OF COMPOSITE STRUCTURES SUBJECTED TO STATIC AND FATIGUE LOADS

**In this work, a brief review of various approaches using Infrared Thermography (IRT) as a non-destructive method applied for better understanding of fatigue behaviour and the damage process is presented. Rapid determination of fatigue limits obtained with the use of IRT is in very good agreement with the conventional experimental testing program for a wide range of materials including various types of composites. In addition, it creates the possibility of locating, evaluating and monitoring fatigue damages both within standard specimens and structural components. Despite these achievements, there is little work concerning the use of IRT in the analysis of curved composite structures with delaminations subjected both to static and/or fatigue loads. In this paper, stepwise methodology, how composite curved panels can be incrementally tested in order to characterize and control real damages occurring during static loads is presented with emphasis on the possibility of using it for fatigue tests. It was shown that artificial delamination does not propagate in contrast to real defects which can be monitored by active thermography tests after each load step. The presence and evolution of damages caused by static loads has a great impact on the thermal behaviour of the curved composite panel and can be observed by changes in the temperature contrast on the investigated surfaces. Future works will concern application of the proposed methodology with the use of Active Infrared Thermography (AIRT) in the quantification of failures occurring during fatigue testing of curved composite elements.**

**Keywords:** **Active Infrared Thermography, multilayered composites, fatigue**

## BADANIA TERMOGRAFICZNE STRUKTUR KOMPOZYTOWYCH PODDANYCH OBCIĄŻENIOM STATYCZNYM I ZMĘCZENIOWYM

**Zaprezentowano przegląd różnych podejść wykorzystania termografii w podczerwieni (IRT) jako nieniszczącej metody stosowanej w celu lepszego zrozumienia zjawisk zmęczeniowych i procesu uszkodzeń. Metoda szybkiego określania wytrzymałości zmęczeniowej z wykorzystaniem IRT wykazuje bardzo dobrą zgodność ze standardowymi procedurami dla szerokiej grupy materiałów, włączając w to różne typy kompozytów. Dodatkowo, omawiana metoda stwarza możliwości lokalizacji, oceny i monitoringu uszkodzeń zmęczeniowych zarówno dla standardowych próbek, jak i komponentów strukturalnych. Mimo tych osiągnięć, istnieje bardzo mało prac dotyczących wykorzystania IRT do analizy zakrzywionych struktur kompozytowych z delaminacjami obciążonych zarówno statycznie, jak i zmęczeniowo. W artykule zaprezentowano metodologię polegającą na badaniu zakrzywionych paneli kompozytowych po każdym kroku obciążenia w celu oceny i kontroli rzeczywistych uszkodzeń powstałych podczas obciążeń statycznych z naciskiem na możliwość wykorzystania jej do testów zmęczeniowych. Sztuczna delaminacja nie propaguje w przeciwieństwie do prawdziwych defektów, które mogą być monitorowane przy wykorzystaniu testów aktywnej termografii w podczerwieni po każdym kroku obciążenia. Obecność i rozwój uszkodzeń spowodowane przez obciążenia statyczne mają znaczny wpływ na zachowanie termiczne zakrzywionych paneli kompozytowych oraz mogą być obserwowane dzięki kontrastom temperaturowym na badanych powierzchniach. Dalsze prace będą dotyczyć zastosowania zaproponowanej metodologii z wykorzystaniem Aktywnej Termografii w Podczerwieni (AIRT) w celu kwantyfikacji uszkodzeń w zakrzywionych elementach kompozytowych powstałych w wyniku obciążeń zmęczeniowych.**

**Słowa kluczowe:** **zmęczenie materiału, aktywna termografia w podczerwieni, kompozyty wielowarstwowe**

## INTRODUCTION

Infrared thermography (IRT) is a non-destructive method which has been successfully applied to detect artificial defects in multilayered composites [1]. However, there is also the need to establish and develop fast and reliable procedures for assessing the safety of multilayered composites utilized in a wide range of high-performance applications subjected to cyclic loads. It should also be noted that the classical fatigue limit determination method is time-consuming and it requires a large number of specimens which might be economically unjustified.

On the background of the broad spectrum of non-destructive testing methods, only acoustic emission (AE) [2] and infrared thermography [3] are used for in situ fatigue damage characterization due to the limitations of the testing apparatus. AE has proved to be able to characterize damage accumulation but it does not give exact data of the failure position. Emerging testing technology which IRT is, offers more possibilities for not only detecting but also localizing and characterizing failures of composite structures caused by both static and fatigue loads. It was shown in [4] that an infrared camera can be used as a viable tool for localizing and monitoring fatigue damage.

Initially, it was noticed that there is a correlation between growing temperature and the physical processes of fatigue behaviour of the material [5]. The experimental data has shown that the application of stresses above the fatigue limit produce a higher increase in temperature and a lower number of cycles to reach the stabilisation temperature increment. Three characteristic phases of fatigue cycle could be correlated with the surface temperature of the investigated specimen [6].

There are numerous works where thermographic methods have been applied to the study of fatigue behaviour of isotropic: steel specimens [7, 8], aluminium alloys [9, 10] or cast irons [11, 12]. Additionally, in [13, 14] the influence of blind holes on the fatigue strength of metal specimens was analyzed. Further development of fatigue limit determination for steels on the basis of infrared thermographic testing can be found in [15-18]. Recent scientific works concerning the utilization of IRT for the fatigue behaviour of higher strength steels have developed quantitative methodology for fatigue strength assessment and prediction [19, 20].

The application of IRT has also been successfully used to determine the high cycle fatigue strength of woven composite laminates under tensile and compressive loadings [21, 22]. However, IRT methods should be divided at this moment into active (AIRT) and passive (PIRT) approaches. The difference consists in the origin of the infrared radiation emitted by the investigated surfaces. In the first case, the investigated material does not require an external supply of energy, unlike active procedures which need an additional stimulation of heat. These two approaches are used for fatigue behaviour characterization. A passive technique usually describes a temperature increase in time during cyclic loads due to hysteretic heating. Examples of the qualitative and quantitative results of the fatigue behaviour of glass fibre reinforced polymers (GFRPs) [23, 24], woven [25, 26] and braided [27] carbon fiber reinforced polymeric composites can be found in the references. Active thermographic methods, e.g. pulse, lock-in, pulse-phase procedure have shown their usefulness in detecting and evaluating defects occurring in plates [28-30] but a lack of or little literature could be found where these active approaches are used to quantify failures occurring during the fatigue testing of plates [3] or shells. Therefore, this work is focused on the possibilities of using AIRT for fatigue behaviour characterization of multilayered curved composite components.

It should also be noted that there have also been attempts to measure and characterize artificially damaged composite structures subjected to cyclic loads [31]. In particular, it is worth mentioning studies on the residual fatigue life assessment of glass fibre reinforced composites with delaminations [32].

In order to use the effect of synergy and extend the limits of particular non-destructive methods, hybrid testing systems are presently being developed for monitoring and quantifying the fatigue behaviour of materials. For example, combinations of standard techniques such as AE, Digital Image Correlation (DIC) and IRT [33], Lock-in thermography and AE [34], PIRT and AE [35], DIC and IRT [36] have been introduced. This leads to creating better coupled techniques which can more accurately monitor, assess and predict damages occurring in composite structures subjected to cyclic loads.

## FATIGUE LIMIT DETERMINATION

In multilayered composites reinforced with long fibres, fatigue failure is the effect of the accumulation of damage mechanisms such as fiber breakage, fiber debonding, matrix cracking and delamination. This effect has a great impact on deterioration of the thermomechanical properties such as stiffness reduction, tensile strength, damping, thermal conductivity etc. It should be noted that damping is effective and confirmed by experimental studies measuring damages in fiber composites [37]. The total work done during the loading and unloading of the tested specimen is irreversibly absorbed by the damping of the material. The most important causes, from the IRT point of view, of damping is the thermoelastic effect and damage accumulation because they have a direct impact on the thermal behaviour of the material. An example of *S*/*N* data for woven carbon fabric/epoxy composites with high cycle fatigue strengths (HCFS) obtained by the IRT technique marked, is presented in Figure 1. Construction of this graph required arduous tests of many specimens using the same loading frequency during more than 250 hours. It can be seen that the conventional approach is a very expensive and time-consuming test, therefore there are numerous attempts to attain rapid and reliable determination of the fatigue limit of both test specimens and mechanical components.

The method for rapidly determining the fatigue limit of steel with the use of IRT (called the Risitano method, after the researcher who originally invented it) was first proposed in 1986 [38]. On the basis of experimental investigations, it was stated that the fatigue limit can be correlated to the stabilisation temperature in the second phase and to the initial temperature slope in first phase of the fatigue cycle. According this procedure, the fatigue limit could be determined by plotting the stabilisation temperature and the initial temperature slope against the applied stress and finding the interception of these curves of the stress axis.

 

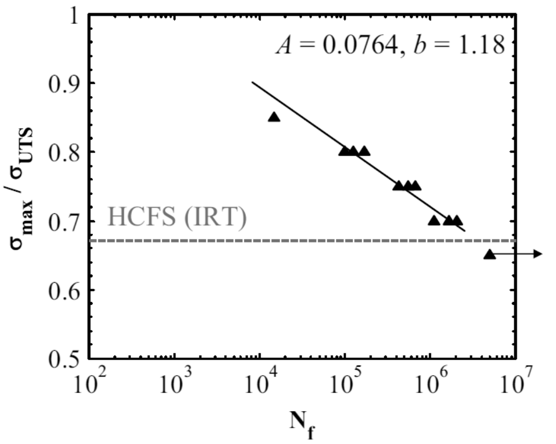


Fig. 1. Example of fatigue S-N experimental data for woven carbon fabric/epoxy composites with high cycle fatigue strengths (HCFS) obtained by IRT technique marked [26]

Rys. 1. Przykładowe zmęczeniowe dane eksperymentalne S-N kompozytu epoksydowo-węglowego z oznaczoną wytrzymałością wysokocyklową uzyskaną przy pomocy techniki IRT [26]

Application of the described method requires a very limited number of specimens or mechanical elements (theoretically one but in practice the mean value of three specimens), a short testing time, small number of cycles and what is interesting, the same specimen can be used for different levels of loading, which offers considerable savings in costs. It should also be noted that the established methodology enables the analysis of complex elements in terms of both structure and shape. From the beginning of the fatigue test, it is possible to predict the failure zone. The proposed Risitano's procedure and results were further verified and compared for different materials and structural components, which had an influence on the adoption of it by various research centers and the automotive industry [39, 40]. he discussed method exhibits excellent agreement with the results obtained through conventional experimental test programs. The methodology described by Risitano is also protected by a patent licence [41].

## ACTIVE INFRARED THERMOGRAPHY

Basically, infrared thermography is a complex process that allows one to study a part of the electromagnetic spectrum known as infrared radiation. Using heat measurement theory, non-contact temperature measurement and further signal processing, its visualization and computation is possible.

Active Infrared Thermography is based on monotonic or periodic supplying of external energy to the investigated object. To reveal hidden flaws by this type of method, a dynamic temperature field (heating or cooling) is generated. This is due to the equal temperatures of the defective and healthy (non-defective) areas of examined material during the steady state, therefore it is necessary to excite the investigated material. Pulsed IRT is currently the most popular among other active thermographic methods due to its quickness of inspection and ease of deployment in the field of measurements and data interpretation. It uses an energy excitation source to rapidly induce the surface of the investigated material, then an infrared camera records series of thermograms at constant intervals in a time domain, both during the heating and cooling stages. When the thermal waves reach the defect, it changes their propagation rate, producing thermal contrast on the surface. Pulsed thermography is an indirect process because the subsurface features of the material are inferred by the surface temperature response. It should be noted that the pulse period must be chosen carefully to prevent failure of the analyzed material. The results are visualized throughout the creation of a thermal image (thermograms) sequence which maps the temperature distribution on the surface of the examined object in the time domain. This process is schematically illustrated in Figure 2. Among the broad possibilities of pulsed thermography applications, it is also important to determine the limitations of this method.

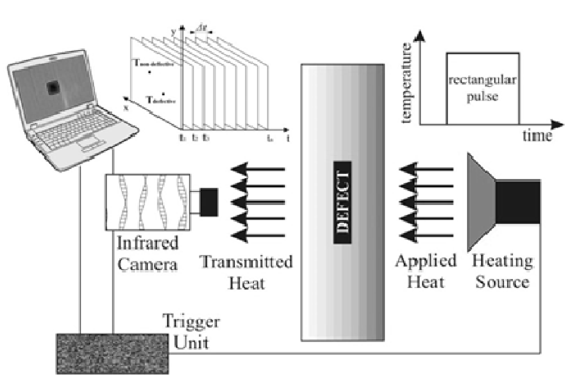


Fig. 2. Principle of pulsed infrared thermography

Rys. 2. Zasada impulsowej termografii w podczerwieni

Subsurface anomalies occurring in the investigated object are identified due to their temperature representation on the surface. The basic and most commonly used measure of defects is the temperature difference between the pre-selected reference area which is assumed to be non-defective, and the defective area. This temperature difference is called in TNDT&E nomenclature absolute thermal contrast $C_a$. It is schematically illustrated in Figure 3.

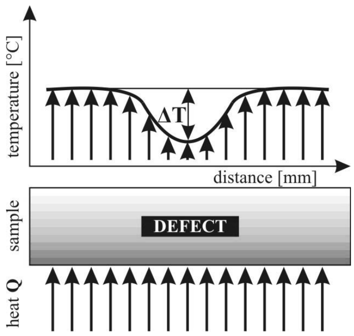


Fig. 3. Absolute thermal contrast $C_a$

Rys. 3. Absolutny kontrast termiczny $C_a$

 

It should also be noted that thermal contrast must not be confused with the temperature difference between the considered thermogram and reference thermogram which is denoted here as *dC*.

## EXPERIMENTAL PROCEDURE

### Specimens

The tested material studied is a woven roving glass/epoxy resin composite. The specimens were manufactured with 8 layers. The geometry of the specimens was cylindrical with a nominal thickness equal to 2 mm, length 300 mm and inner radius 92 mm (Fig. 4). The laminate had a nominal fibre volume of 60% and the ply thickness equals 0.25 mm. The examined composite panels were produced with the use of the hand lay-up technique, which is considered the simplest and most widely used.

In order to make a compromise between realistic representation and ease of preparation of the delamination, Teflon film in the form of a single square with a thickness equal to 0.7 mm was introduced during the manufacturing stage in the middle of the laminate specimens between the 4$^{th}$ and 5$^{th}$ layer. The position of these inserts in relation to the specimens is shown in Figure 4. Additionally, to minimize the end effect and to prevent crushing, both ends of the investigated specimens were encased in steel matrices and epoxy resin.

The tested structures were covered with an appropriate matt black paint layer with emissivity equals 0.95 in order to improve surface emittance, homogenize surface emissivity and to prevent recording of the effects of translucency.

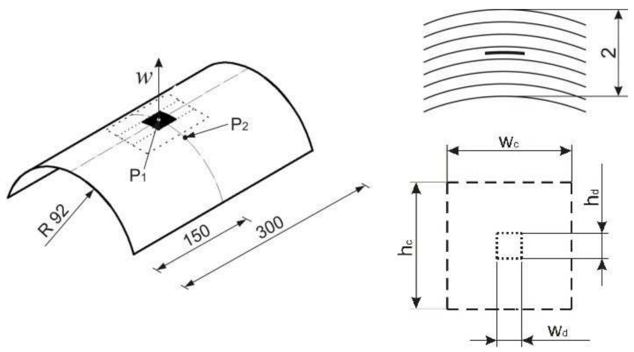


Fig. 4. Geometry of investigated specimens

Rys. 4. Geometria badanych próbek

### Test station

The system used in this study consists of a Flir A325 camera with a frame rate of 60 Hz and a focal plane array pixel format of 320x240, a halogen lamp, a computer and a trigger box. All the AIRT measurements were completely controlled by the PC with the use of IR-NDT software. The same program was also used to acquire, partially process and analyse the data. Additional analysis of the thermogram sequences was carried out using more user friendly Researcher Pro ver. 2.10 software. The same program together with Researcher Pro 2.10 were used to process the acquired data. To monitor possible delamination growth increment, specimens can be subjected to thermographic analysis during each step of loading. Furthermore, the tests were monitored using a standard camera. In addition, the modular test rig includes various types of halogen lamps, a wattmeter, computer and trigger box. All these components are mounted on a very stable base that allows the exchange of individual parts depending on the applied procedure. Figure 5 shows the complete experimental setup used in the current investigation.

Fig. 5. Experimental setup

Rys. 5. Stanowisko badawcze

### Test procedure

The AIRT procedure applied in the current investigation is based on rapid heating of the sample surface by a high intensity halogen lamp dedicated especially for curved structures. The temperature is observed both during the heating and cooling stages by a highly sensitive infrared camera which records series of thermograms at regular intervals in a time domain. Thermographic inspection was carried out after each load step in the transmission mode, where the IR camera and the thermal stimulation unit were arranged on the opposite sides of the investigated object. Examinations of composite structures subjected to fatigue load can be done after a determined number of cycles or characteristic stages of analysis (e.g. beginning of failure, damage evolution, final failure).

During analysis of the thermal images, the differential technique was employed in order to mitigate the environmental disturbances. It consists in subtracting the initial temperatures of the reference image from each subsequent thermal image obtained at any given time. As a result of this operation, the differential sequence of the thermograms is obtained.

The cylindrical panel was loaded in the loading machine with a manual displacement control. In all the tests, the load was applied in the axial direction until the final failure form occurred. The loading conditions were represented by the plate boundary displacement values measured in [mm].

## RESULTS AND DISCUSSION

Experimental analysis was carried out under various quasi-static loading conditions represented by plate boundary displacement values $d$ measured in [mm] since the cylindrical panel was compressed in order to investigate the delamination initiation and propagation. In Figure 6 representative thermograms of the cylindrical panel subjected to compression are presented. As can be seen, the artificial defect, namely the PTFE insert embedded during the manufacturing stage, appears as a cold spot. The temperature around the defect is higher than within the delaminated area; this temperature contrast indicates the presence of a defect and pinpoints its location. It is caused by the different thermo-mechanical properties of the composite material, the Teflon insert and air voids (real delamination). In essence, owing to these differences, it is possible to reveal subsurface discontinuities.

As the load increases, crack propagation caused by static loads can be seen in the middle of the laminate. However, artificial delamination does not initiate and propagate failure but it has an influence on the final failure form. The moment that the sample is unable to carry the load any more is defined as critical end-shortening and it is equal here to 2.99 mm.

In Figure 7, the evolutions in time of the subtracted thermogram sequences for various loading conditions in defective and non-defective areas are presented. The thermal behavior of non-defective areas exhibit the same character in contrast to delaminated regions where a decrease in temperature can be observed. As time passes, due to the thermal diffusion in all directions, the temperature on the sample surface tends towards an equilibrium, thus blurring the previously observed temperature contrasts.

Figure 8 presents the evolution in time of absolute thermal contrasts $C_a$. What is interesting, despite the lack of propagation of the embedded defect, thermal changes can be observed within the artificially delaminated area in accordance with load increments. It may indicate opening of the delaminated area.

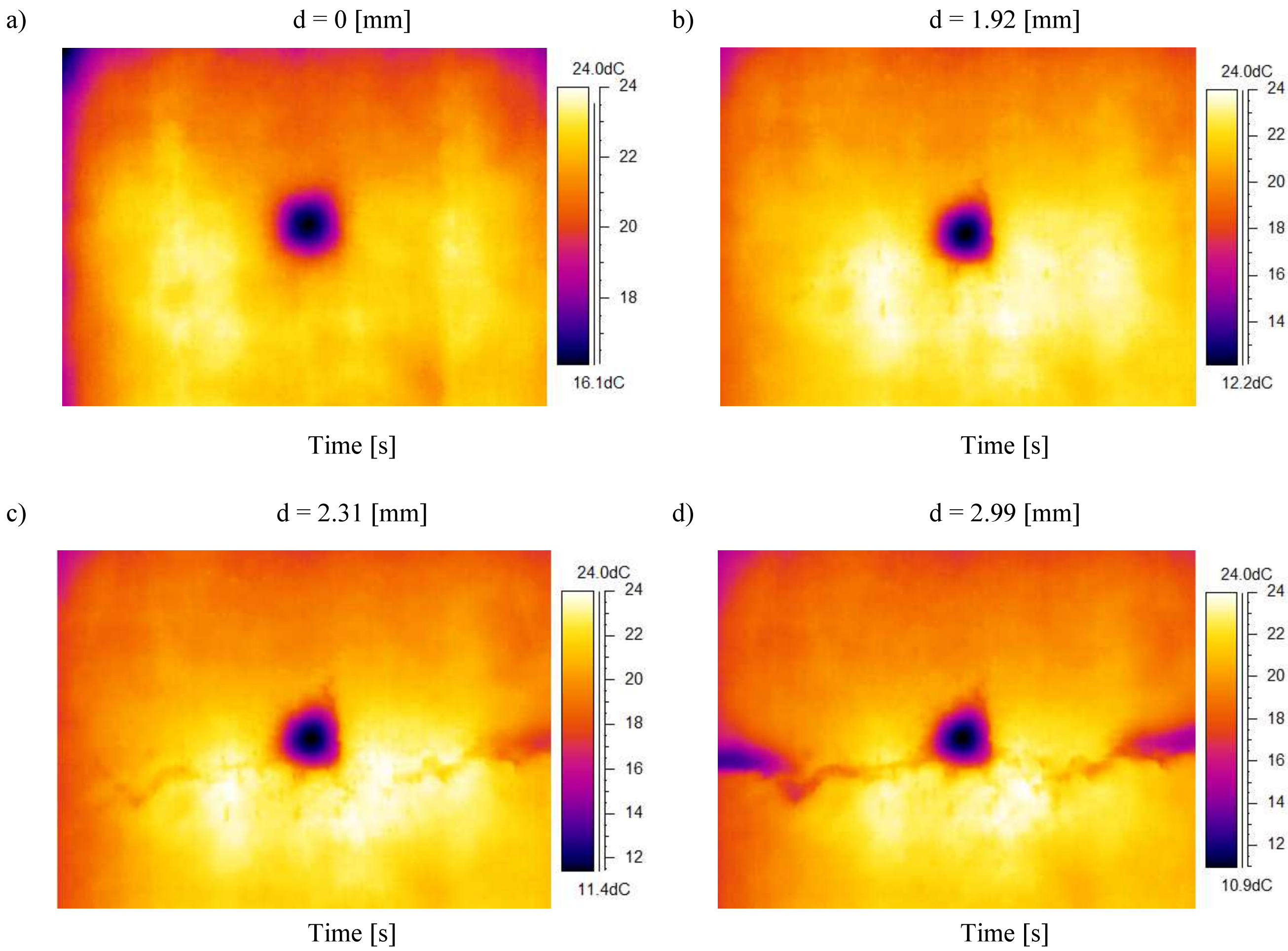


Fig. 6. Thermograms of cylindrical panel subjected to compression

Rys. 6. Termogramy panelu cylindrycznego poddanego ściskaniu

 

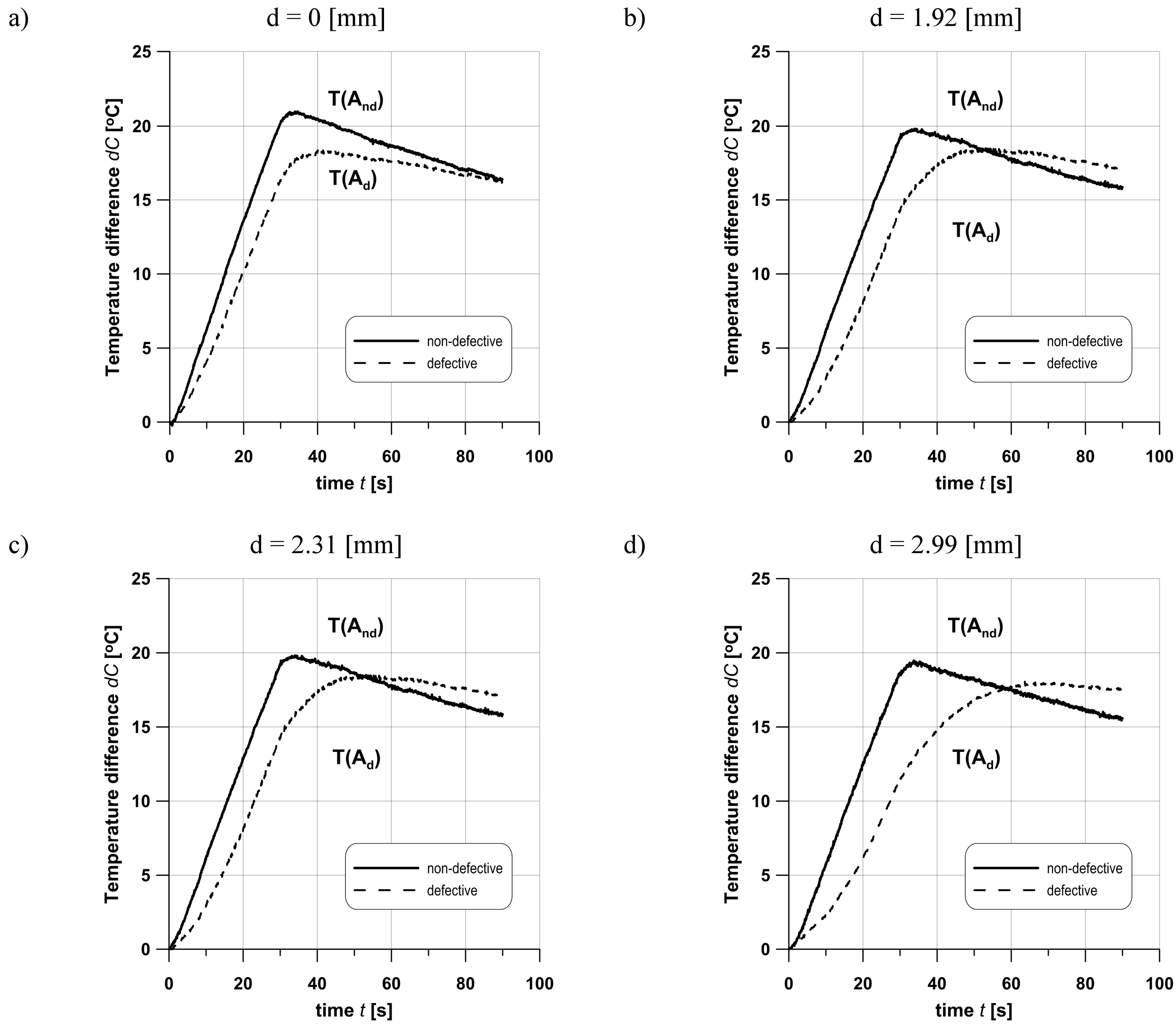


Fig. 7. Evolution in time of temperature difference *dC* for various loading conditions in defective and non-defective areas

Rys. 7. Przebieg różnic temperatur *dC* w czasie przy różnych obciążeniach dla uszkodzonego i nieuszkodzonego obszaru

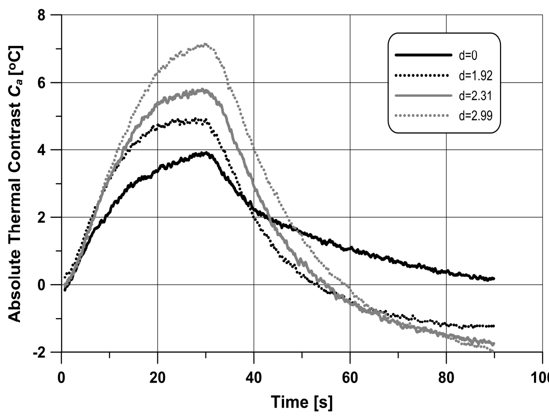


Fig. 8. Evolution in time of absolute thermal contrasts $C_a$

Rys. 8. Rozwój w czasie absolutnych kontrastów temperaturowych $C_a$

The results of the experimental tests clearly demonstrate that the detection and monitoring of artificial and real damages in curved composite panels by means of AIRT is very effective. However, more challenging is quantitative evaluation of the interactions between particular failure forms.

## CONCLUSIONS

In this paper, experimental tests on a glass fibre reinforced composite panel were performed in order to better understand the damages of these structures, focusing on delamination with regard to delamination initiation and evolution. It can be concluded that the AIRT tests can be successfully applied to the non-destructive characterization of defects and their progressive evolution in curved composite structures subjected to static and fatigue loads.

The fatigue behaviour (fatigue limit and the fatigue S-N curve) can be rapidly determined with a limited number of specimens in a short testing period, and good agreement is achieved between the predicted values and the obtained results.

Future works may include AIRT studies of curved composite structural components with delaminations subjected to cyclic loads from the point of view of assessing critical damage states and predicting damage development in the vicinity of artificial delamination.

## Acknowledgment

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