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NON-DESTRUCTIVE EVALUATION OF COMPOSITE STRUCTURES USING DIGITAL IMAGE CORRELATION

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1. INTRODUCTION

In the 21st century, the industrial use of fiber-reinforced polymer composites as structural materials is growing, mainly due to their high specific strength and stiffness. Nowadays, we can also find composite mass products in our homes; typical examples the bathtubs, junction boxes, housing for electrical hand tools, printed circuit boards, and many automotive components.

Without denying the importance of mass products, my thesis focuses on polymer composite products in the narrow sense, which are typically heavy-duty and high-value, mainly filament-reinforced structures such as the load-bearing structures of many aircraft, helicopters, mass transit and competitive sports equipment, as well as blades up to 100 meters long for offshore wind turbines.

One of the severe disadvantages of composites is that they are capable of catastrophic, i.e., sudden, almost unpredictable, total failure in the event of overloading. This is exacerbated by the fact that defects and damage accumulated during manufacture and operation can reduce the maximum load-bearing capacity of the structure. As a result, loads initially rated as nominal may cause an overloaded condition. An accident in this way not only causes significant material damage but can also claim human lives. Periodic condition monitoring of safety-critical structures is, therefore, essential. However, the problem is that, although detection of structural failures is possible with available techniques, the complex failure of composites makes it very difficult to predict residual properties and lifetime.

To avoid catastrophic failure of composites, structures are currently significantly over-designed, increasing both their weight and manufacturing costs. Another solution to prevent catastrophic failure is to increase the toughness of composites, which is also a subject of intense research today. However, overloading would still result in irreversible damage to the structure, after which replacement of the damaged component would be unavoidable, costly, and time-consuming. It would therefore be preferable to prevent failure, which requires that critical structural damage is detected and repaired in time and that it is possible to estimate the residual load with high accuracy.

Therefore, there is a need to develop estimation methods. In response, I laid the foundations for a digital image correlation-based condition estimation method that can estimate the structural integrity of the composite and the residual properties after partial damage, subject to certain constraints. It is also able to meet the requirements of the times: fast, accurate, automatable, human factor excludable, scalable, comparable with finite element simulations, and integrable into existing quality control systems.

2. CRITICAL ANALYSIS OF THE LITERATURE, OBJECTIVES

After reviewing the damage patterns typical of high-performance, filament-reinforced, densely cross-linked polymer composites, I concluded that many failures can be avoided with proper storage and manufacturing quality assurance, and therefore, these are not the issues I focus on in my research.

However, the unavoidable problem is the set of in-service failures, which I found the most critical the delamination, since, in many ways, it can occur in the structure, significantly reduce its load-bearing capacity, and often remain entirely hidden. Of all engineering materials, composites are the most difficult to evaluate because they are inhomogeneous, anisotropic, layered structures. However, the growth of this family of materials requires increasingly effective testing methods to ensure their use to avoid catastrophic failure.

A review of the most common non-destructive test (NDT) methods shows that no universal inspection method can detect all types of defects under all conditions. Each method has its advantages and disadvantages compared to the others. To determine the development direction, I have grouped the NDT methods used for composites according to the most critical aspects (**Table 1**). One of the aspects considered is the flexibility of the method, and the other is the level of flaw characterization that can be achieved by the method.

Flexibility can be evaluated in terms of several aspects, such as the size of the range that can be tested, which can be limited or scalable. An important question is whether accuracy deteriorates as the area under investigation increases. Flexibility can also be characterized by whether the test equipment is mobile or stationary.

Another important feature, also related to flexibility, is the need for accessibility of the component under test, i.e., how many sides of the tested part need to be accessed and touched by the test tool. A similarly important consideration is whether it can be used in an industrial environment or whether laboratory conditions are required for its operation.

Method	Flexibility			Flaw detectability		
	Examined area	Mobility	Accessibility	position	shape	severity
SHM sensors	scalable+	built-in	built-in	+	-	-
X-ray tomography	Limited (small) geometry -	fixed place -	full --	++	++	++
Traditional transmission X-ray	increased with test time -	mobile +	both sides --	+	+	+
Ultrasound scan	increased with test time+	mobile +	at least one side touch -	++	++	+
Infrared thermography	scalable ++	mobile ++	non-contact ++	+	+	-
Shearography	increased with test time+	mobile +	the equipment itself must be touching the test object +	+	+	-
DIC	scalable ++	mobile ++	non-contact ++	+	+	-

Table 1 Comparison of flexibility and failure characterization of common NDT methods

For the second aspect, the level of flaw characterization provided by the test method, I took the first level of the listed NDT methods, i.e., the ability to detect the presence of a flaw, as a baseline. The following classes provide information on the position of the flaw, the shape of the flaw, and finally, the severity of the flaw; these are found in the table. The determination of the severity of the defect may start with the ability of the method to separate aesthetic and structural defects. Still, improvements are being made to ensure that the method can determine the residual strength of the structure, which can be used to determine whether the component is still in an acceptable condition or needs to be repaired or replaced. The more accurate the condition estimation method, the fewer safety factors are required when determining the hazard of structural failure and residual properties. Suppose the method could detect defects with high confidence before they become a problem. In that case, the safety factor used in the design could be reduced, resulting in a more efficient and sustainable structure.

In my opinion, it would be advantageous for industrial applications if, for example, a defect could be detected in a non-contact, highly efficient way by a single side test from the accessible hit side, and also the test method could also estimate the severity of the defect. Examining Table 1, I found that there is a great need for a new method that could take advantage of the benefits of optical testing methods (non-contact, speed, mobility, scalability, etc.) and estimate the depth of the defect, the severity of the defect, and the residual strength of the structure in a way that is not possible with optical testing. Until now, this has only been possible with tests such as ultrasound, which is slow and requires contact and contact material, and computer tomography (CT) equipment, which is expensive, fixed, and stationery.

In reviewing the optical tests, the digital image correlation method (DIC) caught my attention because it is the only one where both the test excitation and the response of the test object to excitation are mechanical in nature. The excitation is a known mechanical load, such as tensile. The response, a change in the surface strain field, is related to the integrity of the structure. The great advantages of the specified excitation and response are that they are simple to interpret and can be validated by finite element simulation.

DIC tests are most often used for accurate strain measurement or a deeper analysis of failure in the case of destructive tests. Some studies have aimed to identify critical locations for failure by using elongation outliers and sudden changes in the strain field. Other research and industrial applications have aimed at validating their simulation results. In these studies, the tests were carried out at high load levels, where the faults were already in the propagation phase. In contrast, DIC testing as an application for non-destructive failure detection and condition assessment of polymer composites is still in its infancy, and no standards exist. A few related literature articles are presented in the chapter on DIC testing.

Based on the literature analysis, the main objective of my Ph.D. thesis is to develop an optical strain measurement-based NDT method (NDT-DIC) for detecting delamination defects in filament-reinforcing polymer composites (thesis 1).

This required several sub-objectives, ranging from the design of the measurement procedure and setup, through the optimization of the test parameters and surface preparation, to the effect of delamination defects on the surface strain field and I aimed to prove that the method works for composites made with different technologies, materials, and layering. I also aimed to test different layering techniques and different loads. These were done in my preliminary and main experiments.

The DIC test requires mechanical loading, which I had to limit in some aspects to achieve a quasi-non-destructive test. One element of this is that I used tiny loads, for example, as small as required to determine the initial elastic modulus, where theoretically only instantaneous elastic deformation occurs in the cross-linked material. On the other hand, I also used another NDT method, the AE method, as a complementary test to the DIC to establish the non-destructive limit. The fulfillment of the sub-objectives and understanding of the applicability conditions and limitations of the new test method led to Thesis 1.

In Chapters 4.1-4.5, I investigated the effect of foil-induced clean layer separation on the strain field (Thesis 2). This method ensured the most controllable and reproducible delamination, theoretically free from other defects and their possible distorting effects on the strain field.

The effects of the delamination were necessary to be understood, but in practice, they usually occur in conjunction with other forms of failure, such as barely visible impact damage (BVID). From Chapter 4.5 onwards, I focused on studying composites containing BVID damage. To do this, I first had to define how BIVD differs from pure ply delamination (thesis 3), and then I developed a method for estimating the severity of BVID damage (thesis 4).

For pure delamination and BVID, I have also compared the NDT-DIC test with a competing optical technique, the IRT method, to demonstrate that the development has advanced state-of-the-art in non-destructive condition assessment.

3. MATERIALS AND METHODS

This chapter lists the raw materials for the composites used in my experiments. I also describe the testing equipment used, its operation, and the settings used in my work.

3.1. Materials

Reinforcing materials

- E 220 (Saint-Gobain Vertex s.r.o., Litomysl, Czech Republic) biaxial glass fabric (bag woven, surface weight: 220 g/m^2),
- Sigratex C W200-PL1/1 (SGL Technologies GmbH., Meitingen, Germany) biaxial carbon fabric (bag woven, surface weight: 200 g/m^2),
- PX35FBUD030 (Zoltek Zrt., Nyergesújfalu, Hungary) unidirectional (UD) carbon fabric (surface weight: 309 g/m^2) containing Panex35 50k rovings.

Matrix materials

- IPOX MR 3012 (IPOX Chemicals, Budapest, Hungary) aliphatic epoxy resin (viscosity at 25 °C: 100-200 mPa-s) and IPOX MH 3124 amine-based crosslinking component (viscosity at 25 °C: 80-120 mPa-s). The mixing ratio is 100:40 by weight, according to the manufacturer's recommendation.

- Araldite LY 1564 (Huntsman International LLC, Monthey, Switzerland) (viscosity at 25 °C: 1200-1400 mPa·s) and Aradur 3487 amine-based crosslinking component (viscosity at 25 °C: 30-70 mPa·s). The mixing ratio is 100:34, according to the manufacturer's recommendation.

Materials used for the artificial formation of a delamination defect

- Politetrafluoroethylene (PTFE) film (0,1 mm) (PEMŰ Zrt., Solymár, Hungary),
- PTFE film (15 μm) (Airtech International Ltd., California, USA),
- Polyethylene terephthalate (PET) film (0.2 mm) (Kovács és Társa Kft., Budapest, Hungary),
- Formula Five Mold release wax (Rexco, Conyers, USA).

3.2. Methods

Thermal imaging camera

Infrared thermography measurements were performed using a FLIR A325sc (Teledyne FLIR LLC, Wilsonville, Oregon, USA) thermal imaging camera and the associated FLIR ResearchIR software. The vanadium oxide detector in the instrument was capable of 14-bit, 320 px × 240 px imaging, providing a resolution of 0.615 mm/px with an 18 mm integrated lens system and 600 mm inspection distance. The wavelength detection range of the thermal camera was 7.5 - 13.0 µm, the minimum distinguishable temperature difference between two pixels was 50 mK, and the temperature measurement accuracy was ± 2 K.

The thermal camera was calibrated before measurement, taking into account the temperature and humidity of the lab, the reflection temperature, the material fitting parameter, and the camera's distance from the measured surface. I placed the camera perpendicular to the surface to be measured on a tripod. After post-curing, the test was carried out by placing the specimens at 80 ± 2 °C (min. four h in an oven) in front of the camera, which was started and recorded the cooling process to room temperature at a rate of 7 fps. The results were evaluated on a comparative basis, i.e., whether the camera image showed a local temperature difference characteristic of the coating removal process that differed significantly from the reference. On the other hand, it was also done in a quantitative way, when a measuring line passing through the artificial error was placed in software on the camera image, with temperature data assigned to each pixel so that a temperature curve characteristic of the damage was obtained, the deviation of which from the damage-free reference curve was investigated.

Universal materials testing machine

Mechanical testing of the specimens was carried out on a Zwick Z250 (Zwick GmbH & Co. KG, Ulm, Germany) with a speed range of 0.001 - 600 mm/min and a load capacity of 250 kN. For non-destructive testing, a 20 kN load cell and a 20 kN load capacity vise gripper were used. I used a 250 kN load cell and a 50 kN wedge gripper for the tensile tests. The tensile tests were carried out in a tension-controlled manner. The results were recorded using the Zwick TestXpert II 3.41 software supplied with the equipment and evaluated in MS Excel. I connected the two devices to control the tensile tester based on the specimen elongation measured by the DIC. This way, the software of the tensile testing machine did not assign the crosshead displacement to the force values, but the elongation values were taken from the DIC software. I also varied the crosshead speed, the geometry of the specimen, and thus the gripping distance several times according to the purpose of the experimental series. Therefore these parameters are reported in the experimental section in the description of the different measurements.

Optical strain measurement

I used the Mercury Monet 3D type (Sobriety, Kurim, Czech Republic) optical strain gauge for the optical strain measurement. The equipment consisted of 2 industrial cameras with 5 megapixels (Mpx) resolution and a maximum frame rate of 60 Hz, 2 25 mm lenses, two light-emitting diodes (LED) light sources, and a computer (Intel Core i7-7700K processor, 16 GB RAM, Patriot Hellfire 480 GB M.2 SSD) running Mercury RT v2.6 software. I also used two tripod camera tripods for the measurement setup. The DIC equipment was split in two and used as two 2D DIC units, i.e., I mounted a camera with a lens and an LED light source on a tripod. I placed the two units on either side of the machine, with the cameras facing one side of each specimen fixed between the machine's mounting jaws.

Hardware settings: the cameras were viewed perpendicular to the specimen surface at a distance of 340 mm from the geometric center of the specimens. I set the lenses' aperture to f/5.4, giving the sensor sufficient field depth and light for my measurements. I adjusted the focus using the focus rings on the lenses using the focus adjustment algorithm in the software.

Software settings: with the illumination on, I set the shutter speed in the software to 0.25 ms, which gave me a sharp image of the specimen deforming under load. The sampling frequency, i.e., the rate at which the images were taken, was set to 10 Hz, which proved sufficient to monitor the effects of mechanical tests at a loading rate of 1-2 mm/min, while the storage requirements and processing time for data recorded during 1-2 minute tests remained within the acceptable range of 1-10 minutes.

I then calibrated the cameras using a standard calibration plate and the software instructions. The calibration plate used had a pitch of 5 mm. The software automatically corrects the lens distortion and calculates the resolution of the layout in the test plane from the series of images taken during calibration. The software gives the resolution as a specific value, for example, 0.194 mm/px, which means that a pixel has a side length of 0.194 mm, i.e., 5.15 px per mm length.

After calibration, I placed the virtual test probes on the surface of the specimen. The probes consist of one or more test points. For each test point, the software assigns a test window to identify it in the different images. The distance of the test points from each other and the size of the test windows can be adjusted, which I have experimented with by varying these parameters. For my final measurements, I used a window size of 40 px x 40 px, with a distance of 10 mm between test points.

The following software default settings significantly change the image correlation results, so I never changed them in my tests, leaving the following settings, determined from the preliminary experiments, in all cases: 0.2 confidence interval, which means that the point found has a 95% probability of falling within the ± 0.2 px zone of the area under investigation; full affine transformation, which carries four types of displacement: translation, stretching, shearing and rotation; high-speed mode, i.e., a point is searched only near the original position, not on the whole image, so the calculation is faster.

AE examination

AE signals were collected using a Sensophone AED404-Streamer (Geréb & Társa Műszaki Fejlesztő Kft. Budapest, Hungary) and two Micros30s (Physical Acoustic Corporation, Princeton Junction, USA) microphones with an operating frequency range of 150-400 KHz and a peak sensitivity of 65 dB. Data were evaluated using the SENSOPHONE AED64.v19 acoustic-emission software package.

The advantage of the two-microphone arrangement is that not only the time evolution of the acoustic energy released in the composite test piece under load but also the position of the energy source can be determined, given the distance between the microphones and the sound propagation velocity in the composite. Thus, in addition to the active propagation of the error, the approximate location of the error can also be determined.

I prepared for a general measurement as follows: to start the measurement, I clamped the specimens between the jaws of the materials testing machine, then, using tweezers to make the best use of the available space, I clamped the microphones to the specimen. (The spacing of the microphones was different for different specimen sizes, which is described in the test description.) In each case, I used a suitable amount of coupling material, Oxett silicone grease (T-silox Ltd, Budapest, Hungary). The maximum test cut-off frequency range of 100-400 kHz, a minimum dead time of 5 ms, and a threshold level of 25 dB was used for all measurements. In the software, I recorded the coordinates of the microphones relative to each other. I determined the sound propagation velocity in the test specimen with the help of the algorithm built into the software, which depends on the material, the layer order, and the microphone reading force. It was found to be between 2000 and 4000 m/s. Also, using an algorithm built into the software, I calculated the attenuation of the test specimen. The SENSOPHONE software was linked to the software of the material testing equipment so that the AE measurement was started at the same time as the mechanical measurement so that the tests were synchronized in time.

To filter out noise from the computer and capture, I also tested a four-microphone setup, where two microphones were responsible for linear localization, while the other two microphones were used in guard mode to filter out signals from outside the test area. I found no significant difference in the quality and quantity of incoming signals between the two- and four-microphone setups, so I used the two-microphone setup in my tests.

4. SUMMARY

My work aimed to develop an evaluation method based on digital image correlation for the condition assessment of polymer composites. The new method is characterized by the ability to estimate the depth of failure, the hazard of failure, and the residual strength of the structure under certain constraints, while retaining the advantages of optical testing methods (non-contact, speed, mobility, scalability, etc.), in a way not typical of competing for optical testing methods. Until now, this has only been possible with tests such as ultrasonic testing, which is slow and requires contact and contact material, or expensive CT equipment with a fixed and stationary test bench. Another advantage of the new method is that DIC, as an optical strain measurement method, is a well-established and accepted technique, generally used for accurate strain measurement and analysis of failure processes. However, with the new method presented in this thesis, a new field of application becomes available, the non-destructive state estimation of composites. As the DIC equipment is considered standard equipment in materials testing laboratories, this new method could rapidly spread, and the associated knowledge base could grow rapidly. Due to the complexity of condition assessment problems, no single method can provide a solution in all situations, but the new method presented here may be a prominent feature of non-destructive failure detection methods in the future.

To lay the foundations for the new test method, I first developed a reproducible method for creating artificial, clean delamination in the composite specimens on which I performed the DIC measurements. The clean delamination was achieved by using double-stacked PTFE films treated with form-release wax and placed between the predetermined layers during the build-up of the layered order. In different types of specimens, I developed the delamination at different depths so that I could test the failure detection capability of my method for different depths of failure.

During the preliminary experiments, I developed the NDT-DIC measurement setup and determined the recommended hardware and software settings for the test. The most crucial software parameter was the distance between the test points on the surface to be tested. This parameter was optimized using the analogy of the finite element analysis element size convergence test. I determined the optimal settings to achieve the highest possible accuracy, considering the computation time and data storage requirements. I found that the surface preparation of the specimens was essential for an efficient and reproducible test. I, therefore, examined the surface patterns of different models under the microscope. I measured the size distribution of the dye stains and the ratio of white to black areas in the different patterns and compared these with the setup parameters for DIC testing and the phenomena observed during the test. Based on this, I quantified the pattern design to be used for further studies.

The test load to be applied for the NDT-DIC test shall be kept within the non-destructive range. To ensure this, I have specified a low test load that does not result in a higher elongation than required to determine the material's elastic modulus. For a tensile test, this is the initial, entirely linear phase of the elongation curves, where, in theory, only the instantaneous elastic deformation component of the cross-linked polymer appears. As each material and layer order can withstand a different force load to achieve the elongation range under test, it is simpler to define the test load limit in elongation. This was not a problem, as I measured the elongation of the specimen with DIC with high accuracy anyway and even controlled the operation of the tensile testing computer on this basis.

AE tests were performed to verify/prove the non-destructive load limit. It is well known that a huge number of events occur during the failure of composites; for example, I recorded about 10 000 events during the complete failure of a composite specimen. Compared to this large number, the NDT-DIC test recorded ~300 events up to 0.3 % strain rate at a load rate of 1.5 mm/min, while at a load rate of 1 mm/min, ~30 events were recorded, which is negligible compared to the total failure rate, in the order of 3 % and 0.3 %. If I were to analyze the failure rate not by the number of events but by their cumulative energy, I would get an even smaller damage rate since failures occurring at increasingly higher strain rates also tend to dissipate more energy, so the events in the range I am examining are even more insignificant. Nevertheless, I have investigated how the signals arriving before the non-destructive limit can arise from destructive events. I have experimentally demonstrated that matrix cracks and fiber-matrix disconnections can occur. Fiber rupture associated with a high-frequency event was very rare. Still, at this load level, the ruptured fibers could have been prestressed or weak fibers anyway, which would have ruptured even at low loads during product use. It is essential to point out that the small number of failure events before the 0,3 % test tensile load does not mean that the failure is propagating, as the number of events did not increase after the initial events when the test load was kept at the same level. Hence, the material/structure was stable at this load over the long term. In contrast, when the specimen was held at 0.4% elongation, new events continued to occur during the AE test, indicating that the failure had propagated and the structure could not withstand the load. Based on this, it can be stated that a test load limit has been successfully defined below which the failure DIC test can be considered quasi-non-destructive.

Test specimens with pure delamination at different depths were not only made in real life, but also in a finite element environment. It can be shown that the DIC measurements and the simulations resulted in surface strain field patterns similar in nature. This implies that the DIC investigation qualitatively validated the method of generating the layer separation in the finite element environment, and on the other hand, the subsequent DIC can be validated and complemented with the simulations. I found that the size and depth location of the delamination greatly modified the effect of the defect coming out on the surface of the composite structure: both the range of strain field values and the strain field pattern changed. I have presented and proved a theory for the pattern of the investigated and simulated surface strain fields on delamination placed at different depths.

Accordingly, pure delamination can be detected from the strain field pattern because delamination locally splits the specimen into two asymmetric laminates that do not move together under the test load. Thus, stress-collecting edges are formed at the edges of the delamination, and bending, twisting, and shearing stresses may be applied to the area between the edges, which may also increase the elongation of the area above the ply separation.

By comparing the measured strain fields with analytical calculations, I have found that the magnitude of the unconventional deformation due to the coupling elements in the case of clean delamination affects the detectability of the failure. The coupling elements are affected by material properties and layer thickness in addition to the layer order, and I investigated their influence on the failure detectability. In terms of material properties, a significant mismatch between high stiffness and material moduli is advantageous; for example, in composites, carbon UD is such. Increasing the layer thickness while increasing the coupling element value also increased the strength of the composite, which thus had opposite effects in terms of failure detection.

I have found that using the NDT-DIC method with the determined set-up parameters is sufficient to analyze the range of strain field values to determine the presence of pure delamination since a range of strain field values can be determined from a self-reference or reference specimen from which deviation indicates the presence of a defect. However, to characterize the defect (size and depth), it is necessary to analyze the strain field pattern.

After examining the pure delamination defects, I started to examine the barely visible impact damage that occurs during use. These also contain delamination that can propagate under additional loading, compromising structural integrity. The artificial defects were developed in the composite specimens using an instrumented drop-weight machine, on which I then again performed DIC AE and IRT tests. In the strain field of impacted specimens, the change in load-carrying capacity in the vicinity of the damage, rather than the effect of the coupling elements, dominantly shapes the surface strain field pattern. The active, i.e., load bearing, bridging, and inactive, i.e., not or only partially load bearing, regions were observed. I introduced two damage indicators to the characterization of the damage. Indicator X is the difference between the mean and maximum values of the strain field, the indicator Y is the difference between the mean and minimum values of the strain field at the load level under investigation. The presence of a structural failure can be detected by comparing the evolution of the indicators with each other or with an indicator measured on a reference test. As the load increases, the value of the indicators increases, and the asymmetric behavior of the indicators becomes more pronounced, indicating the presence of a failure. This means that at higher load levels, a given defect is more detectable and also that detection of smaller defect sizes is more likely at higher load levels. Still, of course, the load cannot be raised above the non-destructive elongation range. I found a strong correlation between the introduced indicator X and the reduction in impact energy and residual strength. This provides an opportunity to characterize the severity of the failure, which makes the NDT-DIC test superior to competing optical tests.

I considered it important to compare NDT-DIC measurement results with other NDT methods already accepted in the industry. The effects of pure delamination and composite BVID failure on the surface strain field were also indicated with high efficiency by the NDT-DIC test on both sides of the specimens. AE-based localization worked under high load to estimate the location of the failure, however, it is not a non-destructive failure detection test. In the case where AE was used as a complementary test to the NDT-DIC test, significantly fewer signals were available due to the low load, so the source of the events could only be interpreted by comparing the strain maps recorded on the specimens. The source of the AE signals coincided with the location of the active zones identified by DIC, but used alone at this load level, AE could not be used for localization.

While for the DIC test, the foil incorporated in the layered order could be considered as pure delamination for modeling the delamination, for the IRT test it was more like an inclusion with thermal properties too close to the base composite material, and thus conventional IRT was not effective for detecting the failure. For BVID failures, above a certain impact energy, the failure detection capability with IRT also increased with increasing impact energy. This was due to the increased heat dissipation surface area caused by cracks and fractures appearing in the damaged area. The disadvantage, however, is that these damaged areas usually appear only on the back side of the impact, which is not always accessible in practice, so in my opinion, the failure detection capability of IRT was inferior to the DIC method, which even identified BVID failures formed with lower energy from both sides.

5. THESES

In this chapter I present my main scientific findings in the form of four theses.

Theses 1.

I developed a digital image correlation-based non-destructive structural damage detection method (NDT-DIC), which is suitable for detecting delamination in continuous fiber-reinforced composites using small deformations (e.g., 0.15% elongation), which originated by external loading.

The small deformation, which provides a quasi-non-destructive test, varies quantitatively for different materials and is therefore determined as part of the measurement method. To detect and localize the presence of damage, I have introduced an elongation limit value formed from the maximum of the reference strain fields. I have shown that surfaces with strain above the limit value, significantly overloaded relative to the average test load, with incomplete structural integrity can be selected and coincide with an artificial flaw of known position and extent. [1-4]

Theses 2.

I have proven that the depth location of clean delamination in a known layered sequence can be determined by the NDT-DIC method from the fact that the magnitude of the coupling elements of the ABD matrices of the fault-bisected plates affects the range of surface strain field values and the ratio of the elements to each other affects the strain field pattern.

For the same layer thickness, higher coupling elements result in a higher elongation range, i.e., higher defect detectability. Increasing the layer thickness increases the value of the coupling elements, but at the same time a more dominant opposite effect appears, the stiffness of the composite laminate increases, which overall reduces the range of elongation field values, which reduces the defect visibility. The ratio of the coupling elements shapes the strain field pattern, allowing the depth location of the defect to be determined in a known layering scheme. An image evaluation of the fault locations can be aided by the creation of a reference image series to facilitate identification. [5, 6]

Theses 3.

I have experimentally proved that NDT-DIC can distinguish between clean delamination and hard-to-detect impact damage (BVID) based on the strain field pattern and range of values.

Inspection of the BVID from the impacted side results in a unique strain field pattern that cannot be confused with any other defect. At the impact location, there is a high strain region indicative of damage, and in the load direction there are inactive, i.e. less than average, strain regions on either side of the high strain region, as the load transfer is only partial in that direction. In the transverse load direction, zones of higher than average elongation are observed in the BVID characteristic strain field next to the high elongation part, as these zones absorb the load transferred to the damaged part. In contrast, for pure through-layer separation, the coupling elements of the ABD matrix are primarily responsible for the elongation pattern developed for the test load. For the same test load, the range of elongation field values for a BVID failure of similar size is larger than for a pure delamination pair of the same type of composite. This is due to the fact that in BVID, composite damage shapes have a more significant effect than the effect of coupling elements in pure through-layer delamination. [5,7]

Theses 4.

I have developed a procedure to establish a relationship between the surface strain field obtained from the NDT-DIC test specimen surface strain field, the severity of the impacted failure indicator X_y, and the strength loss. The indicator X_y is the difference between the maximum and average elongation values of the tested elongation field, where y is the test elongation load (e.g. $X_{0,15}$ is the indicator value for an elongation load of 0,15%).

By testing specimens damaged by impacts of known energy in the first step of the procedure, a database of impact energies and strength losses can be constructed, which can be used to estimate the strength loss of composites subjected to impacts of unknown energy in the second step, based on the value of the indicator X.

I have shown that for the quasi-isotopic layered carbon fibre epoxy composite [0, 90, 45, -45, -45, 45, 90, 0°] under investigation, there is an exponential relationship between the values of the introduced indicator and the strength loss in the non-destructive range (0-0.15% elongation). The a correlation coefficient that increases with increasing test load in the range 0.1 - 0.15 %.

Based on the tensile test of the reference specimens, the reference strength was established by averaging. The loss of strength of the damaged specimens was determined relative to this reference value. Of course, this correlation is specific to the material and the stratigraphy, so in other cases, to investigate strength loss, the correlation must first be built up, and I have laid out how this is done. I have proved my claim by testing composite specimens with Araldite LY 1564 epoxy resin matrix and PX35FBUD030 UD carbon reinforced composite specimens with BVID defects artificially formed with impact energies of 10, 13, 15, 20, 25 J. [8]

6. LIST OF OWN PUBLICATIONS

[1] **Hliva V**., Szebényi G.: Kompozit szerkezetek roncsolásmentes anyagvizsgálata. OGÉT 2018: XXVI. Nemzetközi Gépészeti Konferencia, Marosvásárhely, Románia , 2018.04.26-29. In: OGÉT 2018 (Ed.: Csibi-Vencel J., Barabás I.), 192-195 (2018).

[2] **Hliva V.**, Szebényi G.: Detection of delamination in composite structures with DIC method In: FEMS - FEMS (szerk.) FEMS JUNIOR EUROMAT CONFERENCE 2018: The Main Event for Young Materials Scientists, Book of Abstracts Budapest, Magyarország: Akadémiai Kiadó (2018) 224 p.

[3] **Hliva V.**, Szebényi G.: Detection of delamination in polymer composites by Digital Image Correlation - experimental test. Polymers (MDPI), 11, 523-534 (2019). IF=3,164; Q1

[4] **Hliva V.**, Szebényi G.: Polimer kompozitok roncsolásmentes anyagvizsgálatának lehetőségei. Polimerek, 5, 496-500 (2019).

[5] Szebényi G., **Hliva V.**, Tamás-Bényei P.: Investigation of delaminated composites by DIC and AE methods. ICCM22, Melbourne, Australia, 2019.08.11-16., Proc. of International Conference on Composite Materials (Ed.: Mouritz A.), P2311-7, 1-7 (2019).

[6] Szebényi G., **Hliva V.**, Magyar B.: Development of interphase engineering techniques for the ductility improvement in CF/EP composites – Comparison of NDT methods for delamination localization In: Zarrelli, Mauro; Meo, Michele (szerk.) 12th International Conference on Composite Science and Technology Amsterdam, Hollandia : Elsevier (2021) pp. 113-116. , 4 p.

[7] Szebényi G., **Hliva V.**, Magyar B.: Non-destructive evaluation of interfacially engineered composites In: 20th European Conference on Composite Materials (ECCM20)(2022) p. 62011.

[8] **Hliva V.**, Szebényi G.: Non-destructive evaluation and damage determination of fiber-reinforced composites by digital image correlation. Journal of Nondestructive Evaluation (2023). *in Press,* IF= 2.588; Q2