E3S Web of Conferences **446**, 03003 (2023) https://doi.org/10.1051/e3sconf/202344603003
HSTD 2023

Registration of the Growth of Manufacturing Defects by the Monitoring System During the Operation of the Structure

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Abstract. Structural composite materials are currently increasingly used in various fields of modern technology. The potential capabilities of composites exceed those of traditional materials due to particular mechanical characteristics and fundamentally new qualities arising from the simultaneous creation of material and structure. This paper describes the experience of using fiber-optic distributed and piezoelectric sensors to monitor the state of samples of materials used in the construction of aircraft. Characteristic forms of responses from fiber-optic and piezoelectric sensors are presented, which make it possible to determine the growth of delamination that occurs in polymer composite materials under various impacts.

1 Introduction

Questions about detecting and defining defects in polymer composite materials (PCM), which various methods can register, imply a preference for non-destructive testing methods. Despite some shortcomings of such practices, for example, the impossibility of accurately visualizing the structure of internal damage, which is informative for analyzing the causes and mechanisms of material failure, maintaining the material's and system's relative integrity remains a priority for subsequent detailed study. The results of such studies are used to adjust the instructions and programs for technical inspection, design, testing, and operation of essential products in the aviation and rocket and space industries. The importance of such knowledge increases along with using PCM to manufacture various aircraft designs [1–3]. In the technological process of manufacturing, testing, and operation of samples and structures made of PCM, non-destructive and built-in methods are the preferred control methods [4–7]. Introducing a monitoring system is necessary due to assessing the actual load, which often differs significantly from the planned one, in determining the aircraft resource. It is a technically and economically justified measure that allows obtaining data on the degree of structural damage in time, optimizing the technical inspections of controlled objects, and, as a result, reducing the aircraft's downtime for technical inspection or repair.

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One of the essential stages in determining the detected defects in PCM is their classification and division into groups (Figure Fig. **1**). It lets you get a complete picture of various defects and apply common approaches to the analysis, prevention, development, control, and repair of detected damage. Usually, the following classification features are used for division into groups: due to the occurrence of a defect and according to the nature of its development.

Defects during manual and automated integration of the fiber and the laying of the prepreg are gaps and patches formed due to the lack of adhesion between the prepreg and the optical fiber [8-10]. These shortcomings can be eliminated by eliminating the causes associated with manufacturing the prepreg and installing the fiber.

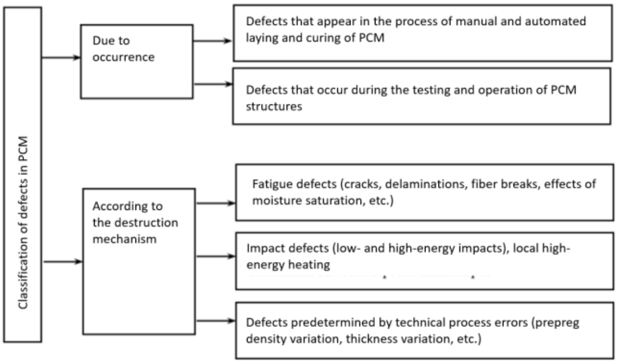

Fig. 1. Classification of defects in PCM.

The defects during the testing and operation of structures include cracks, delaminations, fiber rupture, impacts of various energies, local high-energy heating, etc. These defects are divided into fatigue and impact [11-12]. However, they can also be predetermined by the technological process, which makes them only sometimes wholly removable.

The mechanism of occurrence of fatigue defects is described by several stages, starting from the formation of microcracks in the matrix and microfractures of the fibers and ending with the growth of these fractures and the destruction of the material.

2 Model specification

The simulation object is a prototype laboratory sample of a composite plate containing a delamination-type defect. This sample was developed and manufactured based on aircraft structures made of PCM with a defect obtained during production. The selection is optimal for further investigation of the delamination growth process in composite structures. Modeling was based on the wing box of a prototype wide-body long-range aircraft in the Abaqus/CAE software package in the Dynamic/Implicit solver.

The composite plate has a size of 100x150 mm and consists of 10 layers. The total thickness of the plate is 1.9 mm, and the contact between the layers is glued. A general view of the FEM composite plate with fiber-optic Rayleigh and piezoelectric sensors built into it is shown in the Figure Fig. **2**.

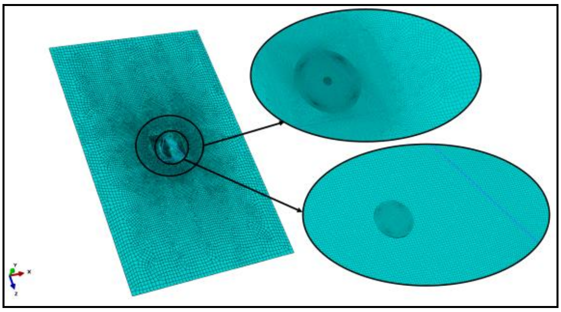

Fig. 2. General view of FEM.

A composite plate with an embedded defect is modeled in layers. Such a model considers each layer's behavior and lays the possibility of stratification between layers. In connection with this, the calculation of such a model requires significant computational resources. A delamination-type defect is specified in the plate between the 5th and 6th layers, and the defect parameters are 1x1 mm (Fig. **3**). The characteristics of the carbon fiber model were used to model the panel.

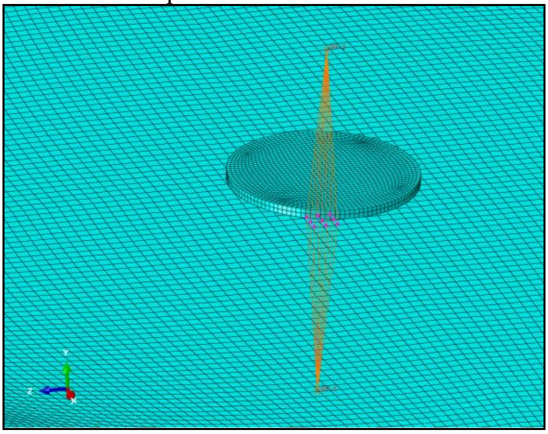

Fig. 3. Layering zone.

When performing computer simulation, a virtual sensor model was created to analyze its properties and behavior during its joint deformation with the structure. In this work, distributed fiber-optic and piezoelectric sensors were chosen as a sensitive element of the structure state monitoring system. The mechanical properties of the fiber optic and piezoelectric sensors are given in Table 1 – Table 2. The following designations are used in the tables:

E is Young's modulus;

ρ is the density of the material;

μ is Poisson's ratio;

G is the shear modulus.

Table 1. Properties of the fiber optic sensor.

E, MPa	ρ, ton/mm^3	μ
86900	2,4E-09	0,29

Table 2. Properties of the piezoelectric sensor.

ρ, ton/mm^3	E1, MPa	E2, MPa	E3, MPa	μ12	μ13	μ23	G12, MPa	G13, MPa	G23, MPa

7.5E-06	60.61	60.61	48.31	0.289	0.512	0.512	23.5	23	23

The piezoelectric and Rayleigh-type fiber optic sensors are essential and widely used sensors with unique features and applications in various fields. Both sensors are devices capable of converting physical quantities into a signal, but they use different principles of operation.

In the distributed measurement method, the optical fiber acts as a distributed sensing element, a sensor. This method is based on recording stimulated Raman scattering, after which the receiving equipment records the scattered signal. Fiber optic sensors have several advantages over classical methods [13]:

- Llightweight.
- High sensitivity.
- Compatibility with structures made of polymer composite materials (PCM).
- Electromagnetic compatibility.

The piezoelectric sensor is based on piezoelectricity, which consists of the appearance of an electric charge when a material is mechanically affected. This type of sensor is compassionate and responds quickly to changes in physical parameters such as strain or pressure. The electric potential determines the strain measurement range of such sensors and varies from microvolts to tens of volts. Piezoelectric sensors are highly durable and resistant to external factors such as vibration, moisture, or high temperatures. Also, these sensors are compact and easy to install.

During the calculation, the fiber optic sensor was simulated by beam elements attached to the surface of the panel, and the deformation signals of the condition monitoring system were recorded. The layout scheme makes it possible to study the deformation response in three directions of reinforcement, and the size of the side of the triangle (44 mm) is selected, taking into account the zone with a defect, which will allow registering both longitudinal and transverse deformations. This socket configuration has the optimal characteristics for this study (Fig. 4).

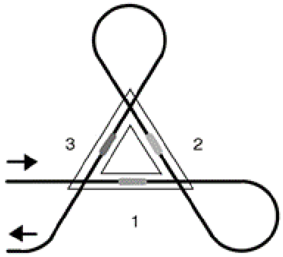

Fig. 4. Configuration of the fiber optic sensor in the form of a prefabricated socket.

Considering the aggressive environment in which the sensors will be located, it was planned to cover the fiber-optic sensor with a polyimide film with an operating temperature of up to +250 degrees. The film does not lose its elasticity over a wide temperature range. Polyimide films retain (in comparison with the original ones) up to 86-90% of the fracture stress (σd), they retain up to 72-80% of the total deformation of the samples (εtotal) and increase the margin for the forced elasticity limit to 5-11%. It has high fatigue and, long-term strength, low creep. It refers to anti-friction materials, non-flammable. Coating thickness ≈ 10 μm. The total sensor diameter, considering the coating, is 100 μm, with the diameter of the light-guiding part 80 μm, respectively [14].

To simulate the growth of a delamination-type defect, the composite plate, which is in a preformed state, was fixed on both sides along all degrees of freedom. The development of the fault was created by displacement applied to the nodes in the delamination zone along and against the OY axis (0.001 mm). The piezoelectric sensor is affected by an electric potential (Fig. **5**).

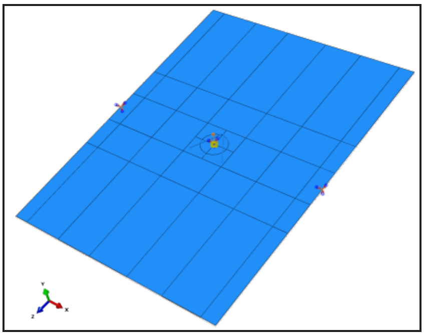

Fig. 5. Boundary conditions for a composite plate with piezoelectric and fiber optic sensors installed on it.

3 Simulation results

According to the described loading of the composite panel, a dynamic calculation was carried out with a load simulating the growth of delamination in the form of a displacement applied to the nodes in the delamination zone along and against the OY axis (0.001 mm).

Figures 6 – 7 show the results of the sample responses to displacements and stresses obtained at a given load, which provide information about the behaviour of the structure in the defect zone. According to the results obtained, the reactions of forces, which were set by moving along and against the OY axis, cause deformations in the panel in the form of growth of a delamination-type defect, which is recorded in the form of a deformation response on the fiber optic and electric potential on the piezoelectric sensors.

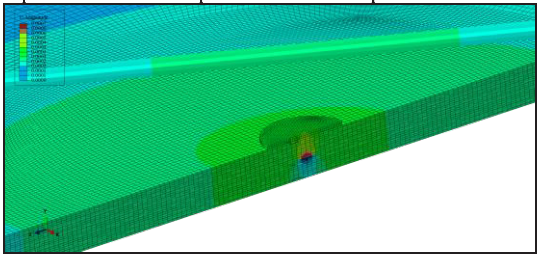

Fig. 6. Displacements of a composite panel under a given load, simulating delamination.

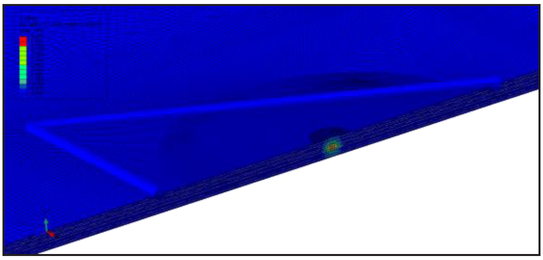

Fig. 7. Composite panel stresses at a given load simulating delamination.

An analysis of the deformation response of the fiber optic and electric potential of the piezoelectric sensors is presented in Figures Fig. **8** – Fig. **10**.

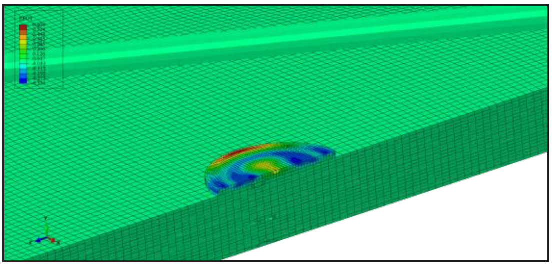

Fig. 8. Results of potential difference (V) of computer simulation of a piezoelectric sensor.

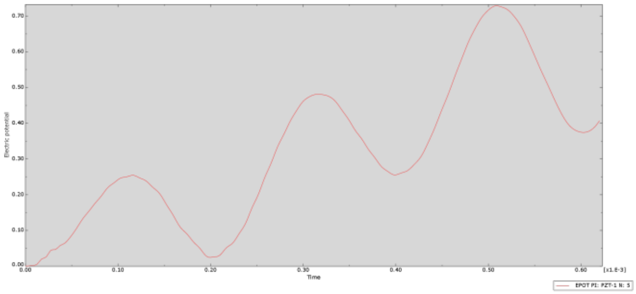

Fig. 9. Graph of the electrical potential distribution along the composite plate.

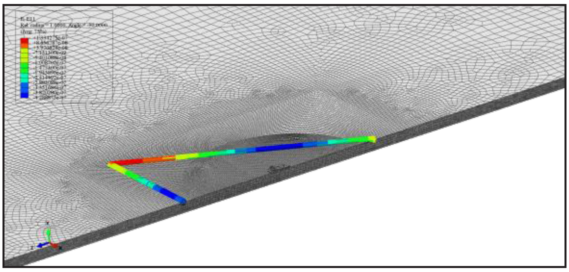

Fig. 10. Results of computer simulation of a Rayleigh-type fiber-optic sensor with stacking in the form of a prefabricated socket.

The simulation results showed that the piezoelectric and fiber optic sensors capture and record the deformations occurring in the composite panel. The Rayleigh-type fiber optic sensor with stacking in the form of a prefabricated socket, with a side of an equilateral triangle of 44 mm, allows detecting deformations within a radius of 22 mm. However, the strain response from the growth of a delamination-type defect is minimal (within the measurement error), which indicates that a different FOS principle is needed for this study (for example, the use of acoustic emission FOS). In turn, the piezoelectric sensor successfully registered the response from the growth of delamination in the structure. However, this sensor has a too-extensive range of 500 mm, which makes it difficult to assess the location of the damage.

4 Conclusions

The study of various methods for detecting defects and damage in composite materials (PCM) is used to select the optimal strategy or their combination to study the causes, nature, and injury development. Such an analysis helps to accumulate experimental statistical data on the state of PCM structures. Then, using these data in the design, testing, and operation of systems will introduce new approaches to the process of aircraft, building structures, and the development of appropriate technical and operational documentation. Modern advances and the level of manufacturing technologies for fiber-optic and piezoelectric sensors make it possible to create and apply integrated control systems for PCM structures. Measuring and monitoring defects in the early stages will allow timely detection of damage at the location of invisible damage in the future. This possibility prevents the design from reaching a failure or pre-failure state.

Thus, this work was devoted to developing and testing a method for registering the growth of a manufacturing defect such as delamination in a composite panel. As a result, fiber-optic and piezoelectric sensors were used to write the development of a fault.

The obtained results of the study indicate that the deformation-type FOS is well suited for monitoring the SSS of a structure but does not describe the growth of delamination and cracks in the design. With low accuracy, the piezoelectric sensor determines the stress-strain state of facilities with a large area and a complex structure but correctly registers the growth of delamination in the form of a difference in electric potentials. Therefore, a combined monitoring system with different types of sensors is needed to control the state of the aircraft structure.

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