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NUMERICAL STUDY OF THE POSSIBILITY OF USING ADHESIVE JOINTS FOR INDIRECT MEASUREMENTS FOR STRESS DISTRIBUTION

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Abstract. *The article covers the subject of examining adhesive joints usage in indirect stress distribution measurements, taking into account contemporary methods of stress distribution measurements, including testing with fiber optic stress sensors. Numerical methods, in particular the finite element method, were used to calculate the stress distribution. The research carried out is described taking into account the following order – firstly, preliminary assumptions regarding sample models and simulation parameters were presented, then the course of the simulation was described, and finally, an analysis of the obtained results was carried out. A control simulation was carried out on a base-glue-fiber sample, which, due to difficulties in assessing the stress characteristics, was retaken in order to calculate the strain convertible to stress. The final results, together with the coefficients defining the measure of compatibility of the characteristics, are presented in the form of graphs and a table.*

Keywords: fiber Bragg grating, stress distribution, numerical simulation

NUMERYCZNE BADANIE MOŻLIWOŚCI WYKORZYSTANIA POŁĄCZEŃ KLEJOWYCH DO POŚREDNICH POMIARÓW ROZKŁADU NAPRĘŻENIA

Streszczenie. *Artykuł poświęcono badaniu możliwości wykorzystania połączeń klejowych do pomiarów pośrednich rozkładu naprężenia, biorąc pod uwagę współczesne metody badania rozkładu naprężenia, w tym badania przy pomocy światłowodowych czujników naprężenia. Do obliczenia rozkładu naprężenia wykorzystano metody numeryczne, a w szczególności metodę elementów skończonych. Przeprowadzone badania opisano uwzględniając następujący porządek – po pierwsze zaprezentowano wstępne założenia dotyczące modeli próbek i parametrów symulacji, następnie opisano przebieg symulacji, a ostatecznie przeprowadzono analizę uzyskanych wyników. Kontrolną symulację przeprowadzono na próbce podstawa-klej-światłowód, która z powodu trudności w ocenie charakterystyki naprężenia została powtórzona w celu obliczenia odkształcenia możliwego do przeliczenia na naprężenie. Ostateczne wyniki wraz z współczynnikami określającymi miarę zgodności charakterystyk zostały przedstawione w formie wykresów oraz tabeli.*

Słowa kluczowe: światłowodowe siatki Bragga, rozkład naprężenia, metody numeryczne

Introduction

Stress distribution measurements are an extremely important tool for engineering and other fields that use structural materials. Analysis of the stress distribution in a material allows better prediction of its behaviour under load and allows the design of more robust and safer structures. For this reason, these measurements find application in many fields where the material used will be subjected to high or varying loads that can affect its properties. When analysing the methods of stress measurement available today, special attention should be paid to the rapidly developing field of optoelectronics.

Due to the increasing use of fiber-optic technology and fiber-optic Bragg gratings in laboratory technology, the first part of this article will analyse the use of FBGs in stress distribution measurements and introduce the subject of numerical methods as a valuable tool in the analysis of adhesive bonds in fiber-optic sensors. In the next section, three simulations will be carried out to determine whether the adhesive in the tested base-glue-fiber sample transmits the stress characteristics to the sensor located on the fiber.

The last part of the article summarizes the conclusions drawn from the conducted simulation, and additionally presents coefficients determining the degree of compatibility of the characteristics of the fiber optic and the base.

1. Stress distribution measurement methods

1.1. Fiber Bragg grating sensors in stress distribution analysis

Various methods are used to determine the stress distribution in laboratory tests, however, in general, strain gauges are most commonly used due to their simplicity of use and lower requirements for signal processing apparatus. However, it should be noted that the measurements performed with them are characterized by disadvantages, which include low sensitivity or susceptibility to electromagnetic interference [12]. Nowadays, due to the previously mentioned disadvantages eliminating the above-described method of measuring stress distribution, there is an increasing use of fiber Bragg gratings in this field. FBG sensors, characterized by their small size with a fiber diameter of 125 μm or less as a standard, have a number of advantages used in laboratory practice, such as high sensitivity and resistance to electromagnetic interference, which makes them a significant advantage in the field of measurement systems. In addition, it is possible to create multiple such sensors in a single optical fiber, which ensures efficient use of the material [6, 10].

In general, laboratory systems based on FBG sensors vary depending on the application, but most have some fixed components such as a light source, a transmission medium, a sensor and a signal analyser, as well as a device that simulates the change of a given parameter, which, in the case of stress analysis apparatus, allows to stretch or compress the test sample with a preset force. Dynamic testing machines are best suited for this role, as they not only allow static tensile testing, but also, with the help of specialized software, allow analysis of the collected measurement data [15].

However, in addition to the discussed advantages, performing measurements using FBG involves significant difficulties in processing sensor information due to the fact that there is no method to directly extract stress values from the transmission spectrum. For this purpose, it is necessary to use numerical methods for solving the inverse problem [9, 11] involving the use of a mathematical model that takes into account the parameters of the grid to find the solution that most closely matches to the spectral characteristics obtained from the spectrum analyser. The measure of the model's fit to the actual spectrum is the value of the objective function defined in the method [13, 14]. The parameter obtained from the solution is the grating period, which is closely related to the stress transferred to the sensor [12].

Another challenge in stress testing is to maintain the reliability and repeatability of the FBG sensor's readings, both of which increase with the use of a suitable adhesive that connects the base to the optical fiber. The bond, which transmits to the sensor the stresses caused by the forces applied to the base of the system, plays an important role due to the fact that these stresses should not only be predictable, but also reflect their characteristics throughout the sample. In this context, predictability is understood as the absence of interference caused by chemical interactions between materials at the interface between the adhesive and the base or the adhesive and the fiber. A suitable bond is therefore characterized by high Young's modulus, high stiffness and chemical neutrality relative to the other materials used in the sample. Meeting all of the above requirements can be achieved through the use of adhesive joints, which are characterised by:

- The adhesive creates a permanent and sealed bond between the base and the FBG, which can be particularly important when the application requires the sensor to be shielded from external factors.
- A high degree of variety in terms of selecting the right adhesive with the required characteristics (e.g. high stiffness, chemical-resistant, resistant to high or low temperatures).
- Adhesive joints are suitable for most surfaces (e.g. wood, metal, plastic), thus increasing the choice of base material.
- Adhesives usually do not react chemically with the glass fibre from which the optical fibres are made.

Whereby the extent to which the adhesive transmits characteristics has been tested in this paper.

1.1. Numerical methods

Analysing the available methods of assessing stresses in the material, special attention should be paid to numerical methods, which, by transforming a differential equation into a system of nonlinear equations, are used, to solve numerical problems (or their simplification), understood as an explicit functional relation between the input data of the problem and the output data [3]. One of the most widely used numerical methods for solving boundary problems in the context of continuum mechanics is the finite element method. It assumes the division of a complex model into a finite number of tetrahedrons contacted by common faces, or triangles connected by common edges, and then solving a system of differential equations describing the behaviour of the material within the element [1]. In the next step, interpolation of the obtained results from the nodes, which are also the vertices of the finite elements, to the entire analysed model is carried out, which makes it possible to evaluate the response of the structure to external forces or temperature changes.

Nowadays, modern engineering software are used for laying out and solving differential equations, as well as calculating and compiling the obtained results [2]. By speeding up the process of analysing models and simplifying the interface, these tools have become common in various fields. As a result, programs specialized in specific types of analysis have been developed. Despite the variety of solutions implementing the FEM algorithm, the general operating procedure remains the same. It consists of several key steps:

- Preparing the analysed model using spatial or planar structure design tools.
- Defining boundary conditions, such as forces or torques.
- Division of the model into finite elements.
- Solving the problem along with presentation of the results.

In the Solid Edge software selected for the simulation presented in this article, the procedure described is divided into two modules. The first module, called "Home", allows you to design a model by creating a sketch and then extruding or revolving it to create a solid. The second module, called "Simulation," contains tools directly related to the finite element method. In this module, the user can also define loads and assign constraints, as well as divide the model into finite elements and solve the problem. Examination of the final results of the simulation carried out is done by using the "Probe" tool, which allows display of individual nodes data, such as strain or stress value. However, the data obtained using "Probe" requires subsequent analysis in a spreadsheet, which provides the ability to present the obtained results in a visually accessible way.

The capabilities of programs using FEM in the field of efficient formulation and solving of complex systems of differential equations, describing the response of a material to external factors, allow the automation of the researcher's work and multiplication of possible studies in a given time frame, so that such systems have become an essential tool for laboratory work or work in other fields that make use of stress analysis. An area showing high potential for the use of FEM, are studies of the properties of materials, where the determination of the parameters of some substances by conventional means proves to be inefficient. In the case of adhesive joints, the complex state of stresses in the bonds leads to the use of FEM simulations [4], which, combined with appropriate analysis of the results, allows the evaluation of adhesive parameters in the context of the transmitted stress characteristics [5], additionally providing information on strength parameters.

2. Simulation and data analysis

The design objectives include the creation of a rectangular sample base with a cut-out constriction in its centre, which is expected to concentrate stresses in the vicinity of the FBG sensor, glued with an adhesive on the surface of the base. The material used for the base should maintain its parameters despite the applied tensile test force and be inelastic, while the adhesive should have the highest possible stiffness to transfer the characteristics of the stresses. Then, the goal is to create a model of the assembly according to the above criteria and to carry out tensile simulations of the sample. Finally, the results obtained should be collated and analysed collectively.

The model common to all the assemblies performed and their simulations is a cylinder-shaped optical fibre with a diameter of 0.125 mm and a length of 140 mm made of glass fiber with a Young's modulus of 72500 MPa and a Poisson's ratio of 0.23, at the same time it was assumed that the FBG sensor with a length of 12 mm was placed in the centre of the fiber.

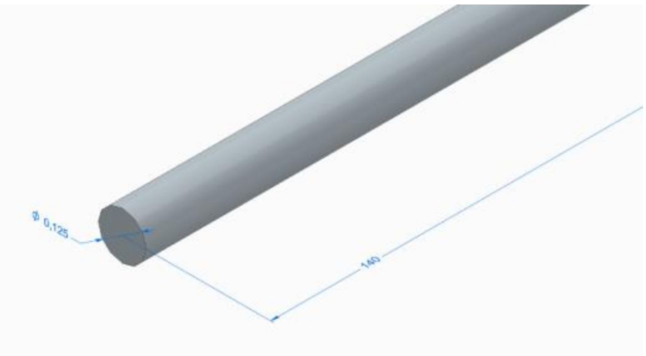

Fig. 1. Model of the optical fiber used in the simulations (due to size only part visible)

The representation of the bond connecting the optical fibre to the base, modelled in a simplified way as a 20x5x1 mm cuboid, was further modified by a 0.125 mm diameter hole passing through the entire length of the adhesive, positioned 1 mm above the lower side of the model. This is to create a place for the optical fibre to resemble the actual location of the fibre in the adhesive. The material adopted for the adhesive for the simulation was a cured epoxy adhesive with a Young's modulus of 3102.64 MPa and a Poisson's ratio of 0.37, which values were both obtained from the software's database and compared with values from the adhesive manufacturers' data sheets [7, 8] to verify correctness. Like the optical fiber itself, the weld model is common to all simulations performed.

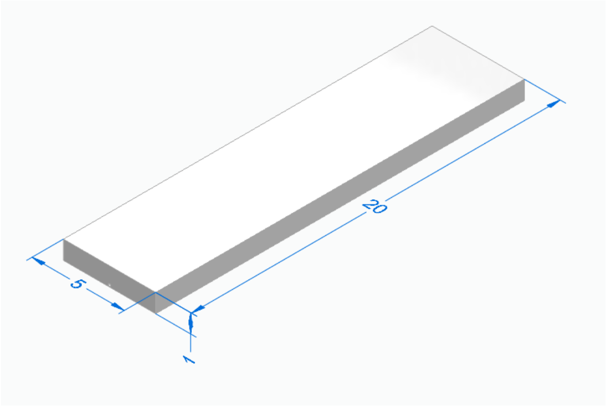

Fig. 2. Adhesive model used in simulations

The base of the sample was made of ABS plastic, which will not change its properties when a tensile test force is applied during the simulation, which was verified in the preliminary tests conducted by performing a tensile test on a prototype base printed with a 3D printer. During the test, a gradually increasing force from 0 to 800 N was applied to the prototype. From the observations and analysis made on the basis of the measurements of the tensile machine, the value of the force at which the base broke was determined to be 750 N. On this basis, a test tensile force of 500 N was assumed.

The simulation includes the design of 3 different variants of the base and stress analysis to verify that the adhesive in the fiber optic-glue-base measurement system transfers the characteristic of the stress from the base to the FBG sensor. Each of the variants will differ only in terms of a 14 mm narrowing at the centre of the base length.

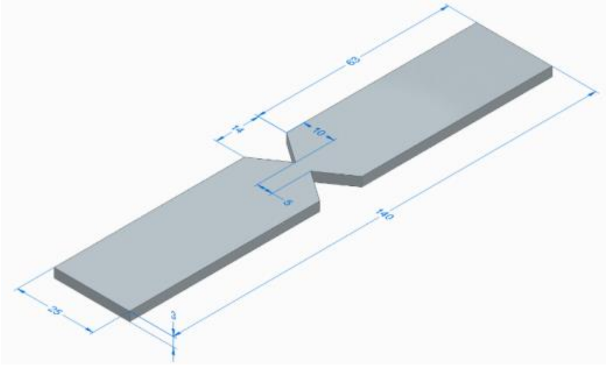

Fig. 3. Base with triangular cut-outs on both sides, used for the first sample

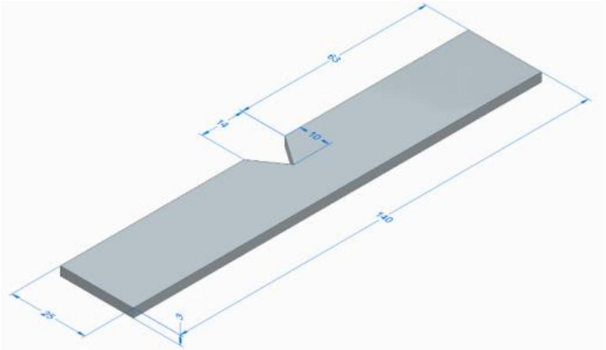

Fig. 4. Base with triangular cut-out on one side, used for the second sample

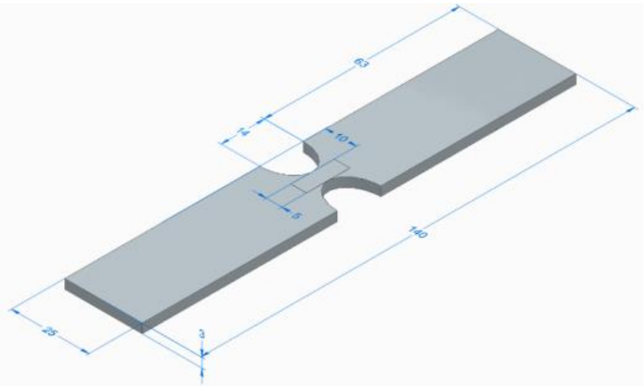

Fig. 5. Base with rounded cut-outs on both sides, used for the third sample

The selected simulation parameters assume the type of analysis to be carried out as static analysis, and the type of mesh as tetrahedral. Of the numerous options available for the final results, only stress and strain calculations will be necessary for the study.

It was assumed that the interactions between the elements would occur only at the contact between the base and the adhesive, and at the contact surface between the adhesive and the optical fiber.

Due to the type of test – static tensile test, two boundary conditions were adopted, fix of the shortest base wall and a tensile force of 500 N applied to the opposite base wall.

The final stage of the simulation setup involves splitting the model into finite elements, that is, the meshing process. In order to find the best solution to ensure the highest possible accuracy of the results, the lowest possible consumption of hardware resources and a stability of simulation, a compromise in the form of a subjective mesh size of 0.7 mm, with a "body mesh" option and the "same mesh component size" for all components, was worked out by trial and error.

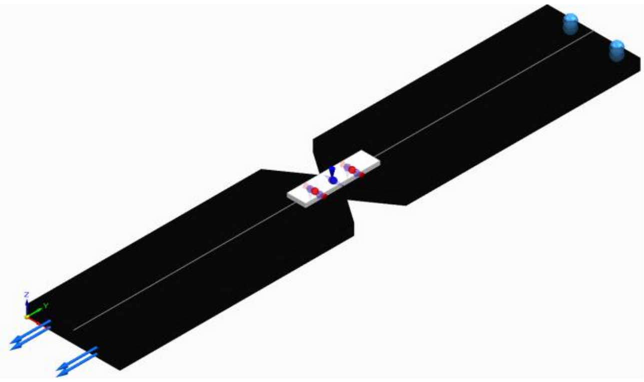

Fig. 6. Sample assembly with visible boundary conditions and marking of interactions between elements

Choosing the option to display the final results, and then analysing the resulting graphical representation, it should be noted that this is insufficient information for a comprehensive analysis (Fig. 7). A tool that provides insight into the results obtained at individual nodes is "Probe." Using the appropriate option, it is possible to obtain values at nodes only from a selected part of the model, for example, the face. The resulting data, consisting of the values and XYZ coordinates of the corresponding node, are not editable, but it is possible to export them to a spreadsheet.

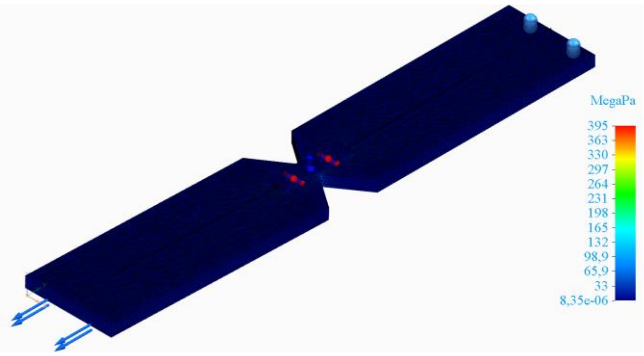

Fig. 7. Representation of the final stress distribution

By compiling the exported stress values with their corresponding coordinates from Solid Edge into a spreadsheet, it is possible to create graphs based on them to allow for an easier interpretation of the data. By aligning the model to the origin of the coordinate system in all simulations, it is possible to compare graphs of stress values as a function of Y-coordinate values with each other.

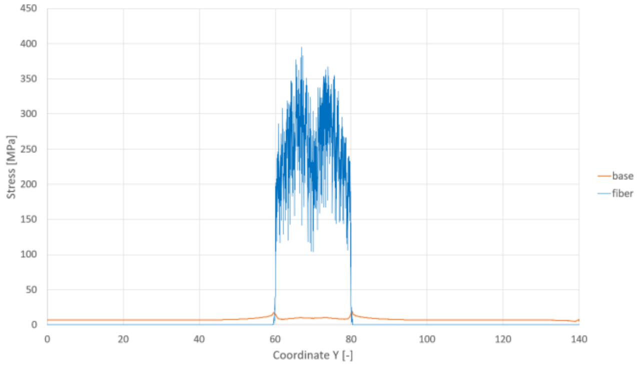

Fig. 8. Plots of stress values from the Y-coordinate, for values on the Surface of the fiber under test (fiber) and values on the base surface in close proximity to the fiber (base)

To create the above graph, the stress values calculated by the program on the surface of the fiber were used, as well as the stress values on the base surface that meet the condition of maximum distance from the fiber of up to 0.5 mm. It should be noted, however, that this graph does not provide the necessary comprehensive information to unequivocally conclude that the adhesive does or does not transfer the characteristics of the stress. It is therefore necessary to return to the simulation and perform analysis in terms of strain.

Proceeding similarly, a plot of the strain value against the Y-coordinate value was created, for the fiber and for selected values from the surface of the base.

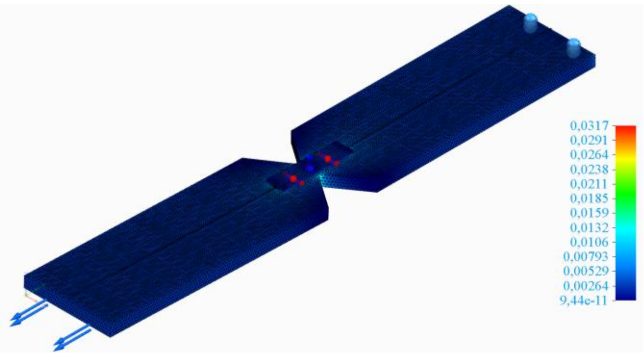

Fig. 9. Representation of the final strain distribution

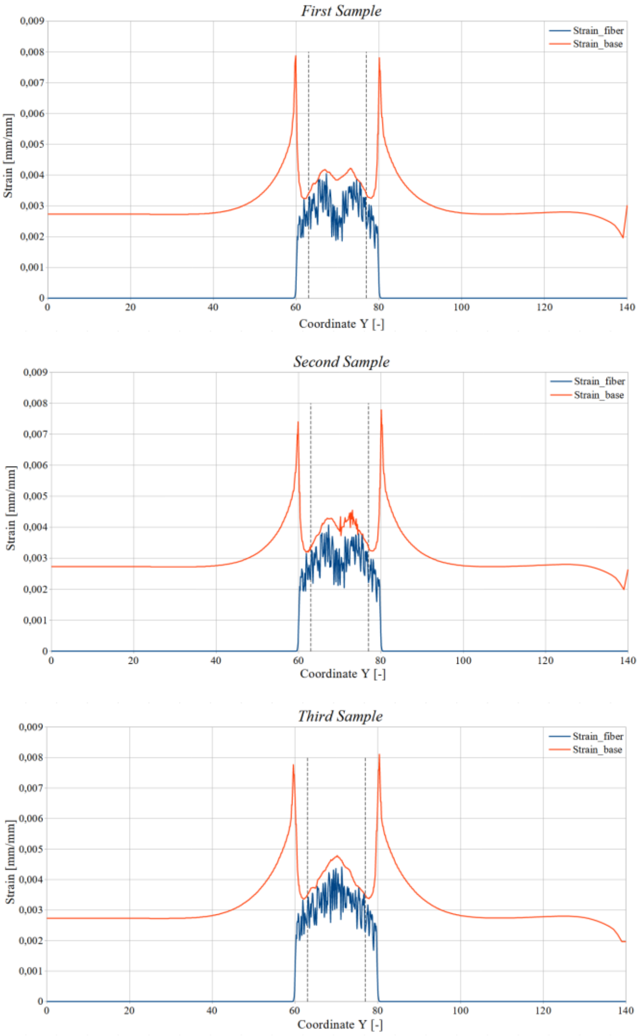

Fig. 10. Plots of strain values from the Y-coordinate, for values at the Surface of the fiber under test (Strain_fiber) and values at the base surface in close proximity to the fiber (Strain_base) with the range of constriction marked with dashed lines. Numeration consistent with Fig. 3–5

From the analysis of the above graphs, it is clear that the characteristics of strain in the constriction area were transferred by the adhesive from the base to the fiber. Working within the scope of applicability of Hooke's law, it is possible, using equation (1), to determine the stress knowing Young's modulus and strain, which allows us to conclude that the characteristics of stress has been transferred by the adhesive.

$$\sigma = E\epsilon \tag{1}$$

The final issue in the study is the determination of coefficients to measure the degree of similarity between the two runs. For this purpose, the RMSE coefficient and the percentage ratio of the value of the lower run to the upper run, both in terms of base constriction, will be determined.

Table 1. Summary of RMSE coefficient and strain ratio

Sample	RMSE [-]	Fiber / Base [%]
1.	0.000981849671899	77.74
2.	0.000998664534084	77.59
3.	0.000914773251793	80.48

3. Summary

In this article, FEM simulation and subsequent analysis of the obtained results were used to investigate the possibility of using adhesive joints in fiber optic stress sensors.

For the analysis, 3 samples differing in the shape of the constriction at the centre of the base were prepared, and then the simulation was carried out, resulting in the strain distribution in the sample. In the course of the study, it was shown that the strain distribution provides more precise and easier to analyse data, for this reason further research was conducted on this model. The compilation of the final data in the graphs (Fig. 10), and the values in the table (table 1) proved the possibility of using adhesive joints with a Young's modulus of at least 3102.64 MPa as a bond connecting the base to the FBG sensor. However, in order to achieve high repeatability of bond parameters, it is also necessary to fulfill the conditions for the correct making of adhesive bond, of which the most important are:

- clean adhesive surface – the adhesive surface must be cleaned of any impurities (e.g. dust) and degreased in order to increase the adhesion of the glue to the surface,
- the right adhesive – selection of a suitable adhesive that does not react chemically with the other components, and based on the requirements of the specific application (e.g. resistance to high temperatures),
- proper application – following the manufacturer's recommendations regarding bonding conditions (e.g. optimum air humidity) as well as curing time and use of right tools (e.g. component mixer)

In addition, the repeatability of bonding in the context of optical stress sensors can be improved by using systems of appropriate clamps to position the optical fibre on the test samples. This type of tool for mounting, positioning and holding optical fibres on test specimens during bonding is the subject of ongoing research work.

The final results presented in this article are based on the simulations performed, but preliminary measurements of the stress distribution using optical fibres with FBG structures were carried out. There are slight differences between the results of the actual measurements and the numerical calculations due to the division of the continuous physical space of the fibre, base and adhesive into a finite number of finite size elements used in the FEM method. These results will be the subject of a subsequent publication.

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