**Janusz Juraszek**

# Influence of the Spatial Structure of Carbon Fibres on the Strength Properties of a Carbon Composite

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**University of Bielsko-Biała,**
**Faculty of Materials,**
**Civil and Environmental Engineering**
Willowa 2, 43-309 Bielsko-Biała
e-mail: jjuraszek@ath.bielsko.pl

**Abstract**
*Advanced lightweight materials such as laminated composites with carbon fibres, cylindrical shells and laminated plates are used in modern civil engineering structures, such as wind power stations, as well as in the defence and automotive industries. This encourages the search for new composite structures characterised by adequately high durability and lightness. This paper determined the strains and displacements of composite specimens reinforced with carbon fibre using an innovative strain measurement method based on the fibre Bragg grating. The results of theoretical analyses were also compared using classical laminating theory and the FEM numerical method with the results of practical tests, which were carried out using the 4-point bending test, characterised by a constant bending moment between the supports and the considerable impact of shearing forces. The actual, highest values of normal stresses that the carbon fibre reinforced sample could transfer were determined. The results obtained may be useful in the design of critically stressed engineering elements, for example, civil structures.*

**Key words:** *carbon fibres, laminate composite, strenght, FEM analysis.*

## Introduction

An essential feature that distinguishes composites from other groups of materials is the ability to compose their properties according to own needs. Structural composites, which constitute the largest group of composite materials and are the subject of further considerations in this paper, are characterised above all by very high strength and stiffness, while maintaining a low density (and thus low mass). This is achieved at the expense of the price, because the technology of composite production is difficult and requires accuracy. Construction composites with polymer matrix commonly used are also characterised by relatively low operating temperatures.

Carbon fibre-reinforced composites are used in many branches of the aerospace, automotive and wind energy industries and are of great importance in technology [1-6]. They are characterised by high strength, low weight, corrosion resistance, good adhesion to the substrate and electrical insulating properties. The basic limitation in the use of these composites is fracture toughness and delamination [6-9].

Interesting results of strength tests of thin-walled composite beams studied using the thermovision technique are presented in [10]. Four-point bend tests of 3-D beams were carried out using a testing machine. Identification of the first cracks of carbon fibres or the carbon composite matrix in the test was made possible thanks to using the Acoustic Emission (AE) method.

This paper presents the results of investigations of carbon composites with a different spatial structure of carbon fibres. The strength of the samples as well as their deformability were determined. An innovative method of measuring strains and displacements based on a fibre optic Bragg grating was used to measure deformability. A detailed description of the fibre optic strain measurement system is presented in [11, 13]. Results of the experimental research were compared to those obtained based on the classical theory of lamination and the finite element method.

## Material and method

The material consisted of samples made of a carbon composite of a varied spatial structure composed of HTS40 F13 12K 800 tex carbon fibres. Samples were taken from a 500 × 500 × 2 mm composite panel with a carbon fibre/epoxy matrix produced using resin transfer moulding (RTM) technology 1 at a resin transfer temperature of 60 °C, injection pressure of 6 bar and processing time of 8 hours. The epoxy resin was used together with EPH294.2 hardener. Unidirectional (1D) RTM composite polyester (PES) plates were bonded using Toho Tenax E HTS40 non-crimp fabric (NCF) with carbon fibre strands of 12K filaments and linear density of 800 tex [12]. Single Toho Tenax HTS40 carbon fibres have an average tensile strength of 4300 MPa and tensile modulus of 240 GPa. The composite plates were produced jointly with the Institut für Leichtbau und Kunstofftechnik, Technische Universitaet Dresden. The method of collecting samples from plates with dimensions of 500 x 500 mm was developed. The basic parameters of the carbon fibres are included in ***Table 1***.

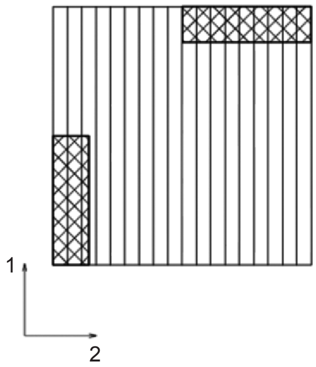
Despite the very good strength parameters, the fibres have disadvantages that prevent them from being used alone for transferring loads (having much worse strength parameters in the direction perpendicular to the fibres, and a low com-

***Table 1.*** *Characteristics of reinforcing fibre.*

| Parameter | Unit | Value |
|---|---|---|
| Density, ρ | g/cm$^3$ | 1.77 |
| Young's modulus, E | GPa | 240 |
| Poisson's ratio, ν | – | 0.21 |
| Kirchhoff modulus, G | GPa | 99.17 |
| Tensile strength, $R_{wt}$ | MPa | 4300.00 |

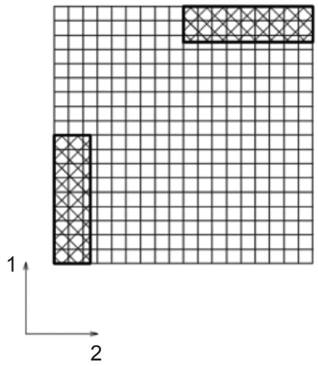
***Table 2.*** *Characteristics of the matrix.*

| Parameter | Unit | Value |
|---|---|---|
| Density, ρ | g/cm$^3$ | 1.13 |
| Young's modulus, E | GPa | 3.16 |
| Poisson's ratio, ν | – | 0.38 |
| Kirchhoff modulus, G | GPa | 1.15 |
| Tensile strength, $R_{ot}$ | MPa | 65.40 |
| Compressive strength, $R_{oc}$ | MPa | 118.00 |



| Sample series number | Number of layers | Fibre content |
|---|---|---|
| 1.1 | 5 | 38% |
| 1.2 | 5 | 38% |
| 2.1 | 7 | 51% |
| 2.2 | 7 | 51% |
| 3.1 | 10 | 68% |
| 3.2 | 10 | 68% |

***Figure 1.*** *Sampling diagram and numbering of samples from unilaterally reinforced laminated panels.*



| Sample number | Number of layers | Fibre content |
|---|---|---|
| 4.1 | 5 | 34% |
| 4.2 | 5 | 34% |
| 5.1 | 7 | 51% |
| 5.2 | 7 | 51% |
| 6.1 | 10 | 68% |
| 6.2 | 10 | 68% |

***Figure 2.*** *Diagram of sampling from panels reinforced orthogonally and bi-directionally.*

pressive strength). Therefore the fibres are embedded in a matrix that transfers external loads to them, further protecting the fibres from external factors and giving them shape. It is required that there is good adhesion between the material of the matrix and the material from which the reinforcement fibre is made, thus preventing movement of the fibres and any chemical reactions between them. Epoxy Resin L (EPH294 hardener) was used as the epoxy resin matrix. The basic parameters of this resin are given in ***Table 2***.

Samples were cut out from six unilaterally reinforced laminated panels with a fibre content of 38%, 51% and 68% as well as from bi-directionally reinforced (plain weave) panels with a fibre content of 34%, 51% and 68% according to the diagram shown in ***Figure 1***.

The first structure analysed was one of the unilaterally reinforced laminated panels with a different volume content of fibres: 38%, 51%& 68%. The number of carbon fibre layers corresponding to them was 5, 7 & 10, respectively. Two series of samples were taken from each of the panels. The first sample number means the batch number, while the second indicates the coordinate system axis along which the sample was cut out. For example, the samples numbered 1.1 and 1.2 were taken from a panel of five layers of plain weave fibres placed unilaterally along axis 1 (vertical lines in ***Figure 1***). The volume content of fibres in the 1.1 and 1.2 series was 38%. After a number of preliminary tests, it was decided to increase the volume content of the 5-layer carbon fibres by 4% in relation to the bidirectional reinforced panels (34%). A series of samples numbered 1.1 was taken along the direction of axis 1 and a series numbered 1.2 cut out along axis 2 perpendicular to the direction of the carbon fibres. The next two series of samples were taken in the same way as the first ones, but from panels with 7 layers of carbon fibres. The next series of samples was cut from the panels with the highest carbon fibre content of 68%, which corresponded to 10 layers. Then arranging individual layers orthogonally to each other was proposed, whereby a bi-directionally reinforced composite was obtained. The collection of samples from the 3 panels with a carbon fibre content of 34%, 51% and 68% proceeded in the same way as for those from the unilaterally reinforced panels. A diagram of sampling from panels reinforced orthogonally and bi-directionally is shown in ***Figure 2***.

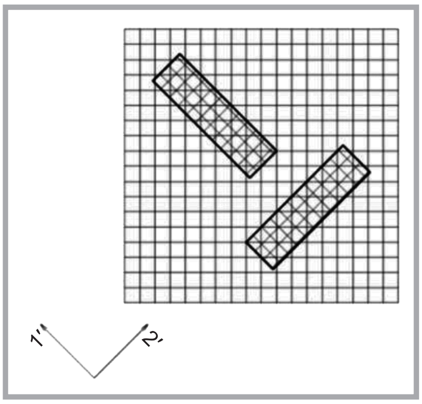


***Figure 3.*** *Diagram of orthogonal panel sampling at angle α = 45°.*

The reinforcement structure analysed so far was characterised by the direction of the sample cut being consistent or orthogonal to that of the carbon fibres. The directions of main stresses for a load test in the form of 4-point bending coincide with those of the fibres. A complex arrangement of stresses exists in many constructions and composite applications, which means that the orientation of carbon fibres in the composite and the directions of main stresses are not the same. This arrangement can be achieved by the appropriate rotation of the fibres during their formation. However, practical implementation of this is difficult. The paper proposes cutting out samples from bi-directionally reinforced panels (orthogonally) at an angle α in the range of 1-89°. After conducting a series of preliminary tests, it was found that the cutting of samples at angle α = 45° is the most interesting from a cognitive point of view. A sampling diagram of 3 composite panels reinforced bi-directionally with a carbon fibre content of 34, 51 and 68%, respectively, is shown in ***Figure 3***.

The 4-point bending test was used to study mechanical properties. It should also be considered that in the case of 4-point bending, the volume of the sample under load (stress) is greater than the corresponding volume in the case of 3-point bending. If we consider Weibull statistics, it is to be expected that the mechanical strength measured through 4-point bending will be lower than that measured through 3-point bending. Weibull statistics say that the bigger the volume, the higher the probability of finding a longer crack or flaw in general. Therefore the 4-point bending test is recommended if tensile stress is the dominant one.

In addition, it should be noted that there is a constant bending moment between the P forces. The lower fibres are only stretched while the upper ones are compressed. Shearing occurs at the point where the load is applied. The highest shear stress value occurs in the middle of the sample thickness, while the highest normal stress – fibre at the fibre ends,

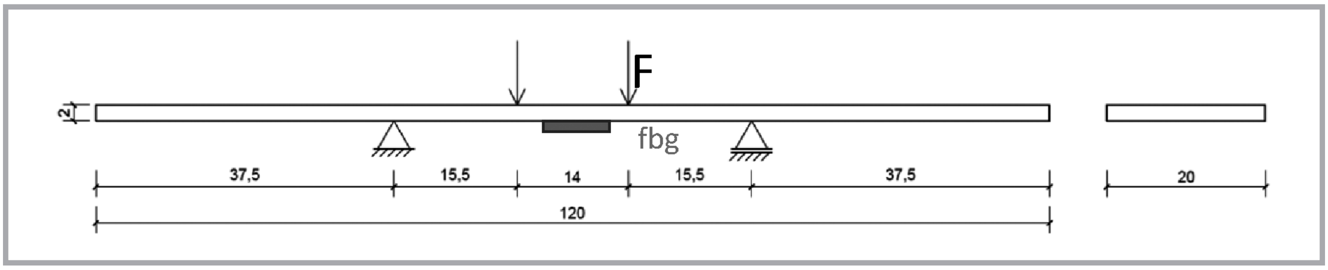


***Figure 4.*** *4-point bending diagram.*

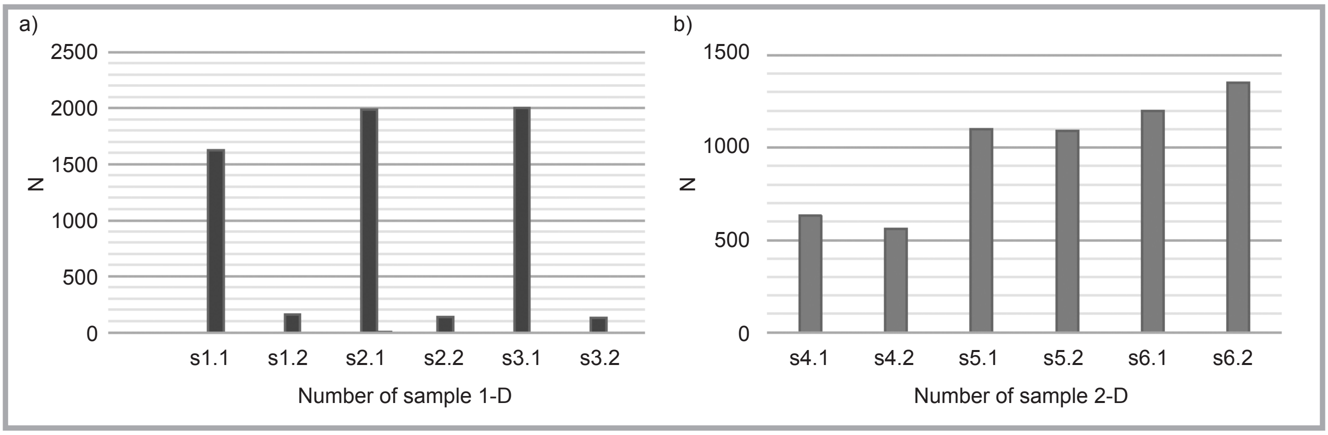


***Figure 5.*** *Comparative charts of the load capacity for a) 1-D samples, b) 2-D samples.*

which is where the highest bending moment is present. The reduced stress was determined on the basis of the H-M-H hypothesis. In the study of strains and displacements of the samples, an innovative method based on optical fibre sensors (single-mode) with a Bragg grating was used. The sensors, registering the deformations, were placed on the lower surface of the sample in its central part. They were connected to an optical interrogator – FGG 800, which enables measurement at a frequency of 2kHz, supplying the sensors with light and measuring the change in the light wavelength. A static diagram of the 4-point bending test is shown in ***Figure 4***. The test sample dimensions were 120 × 20 × 2 mm.

## Research results

As a result of the tests conducted, the highest values of force and displacement that the sample could transfer were determined. Analysing the values of experimentally determined forces, it can be concluded that an increase in the percentage of carbon fibres increases the load capacity of the sample. This is especially evident for samples cut along the direction of carbon fibres in the panel, i.e. direction 1. The highest increase in load capacity occurs between contents of 38 and 51% and amounts to 22.5%. Further increasing the fibre content is not very effective as the load capacity is increased by as little as 0.6%, which makes sense if increasing the stiffness of the sample is sought, because its deflection decreases by 1.65 mm. In the case of samples cut perpendicularly to the direction of fibres, i.e. along direction 2, there is a very large drop in the load capacity of the sample. The load capacity drops from 10 times for samples with the lowest fibre content to up 15 times for those with the highest fibre content. The standard deviation of the load capacity (the highest value of the bending force transferred by the sample) for unidirectional samples was 5,1%, and for bidirectional orthogonal samples – 2,4%, while for bidirectional samples with an angle of 45 degrees, it was 4,3%. Comparative charts of the load capacity and deformability of 1-D samples are shown in ***Figure 5.a***.

The introduction of reinforcement also in the second orthogonal direction – 2 results in a significant improvement in properties with respect to the unidirectional composite. The properties of the bi-directional composite are comparable in both directions – 1 and 2. The bi-directional sample is also characterised by higher deformability. Comparative charts of the load capacity and deformability of bi-directional samples are shown in ***Figure 5.b***.

The load capacity of 2-D (bidirectional) samples cut at an angle of 45° was practically the same in both directions – 1 and 2. However, the value of the greatest force transferred by the sample was at least 50% lower than the highest load capacity of the remaining sample groups. The stiffness of the 2-D/45° samples was also the lowest compared to the remaining samples. The research conducted suggests that carbon composites show the best parameters when the main stresses coincide with the directions of carbon fibres. With the stress in a given element known, in particular the direction of the main stress isolines, one could hypothetically determine the optimal (the most advantageous) spatial system of a carbon fibre reinforcement. Given the possibilities offered by 3-D printing technology, the creation of such reinforcements made of carbon fibres seems to be feasible in the near future.

## Theoretical and numerical analyses

### Construction of models of samples based on classical TL and FEM

In order to describe the parameters of a laminate, it is necessary to know the technical parameters of its individual layers. The classical theory of laminates is based on the analyses of Pagano and as-

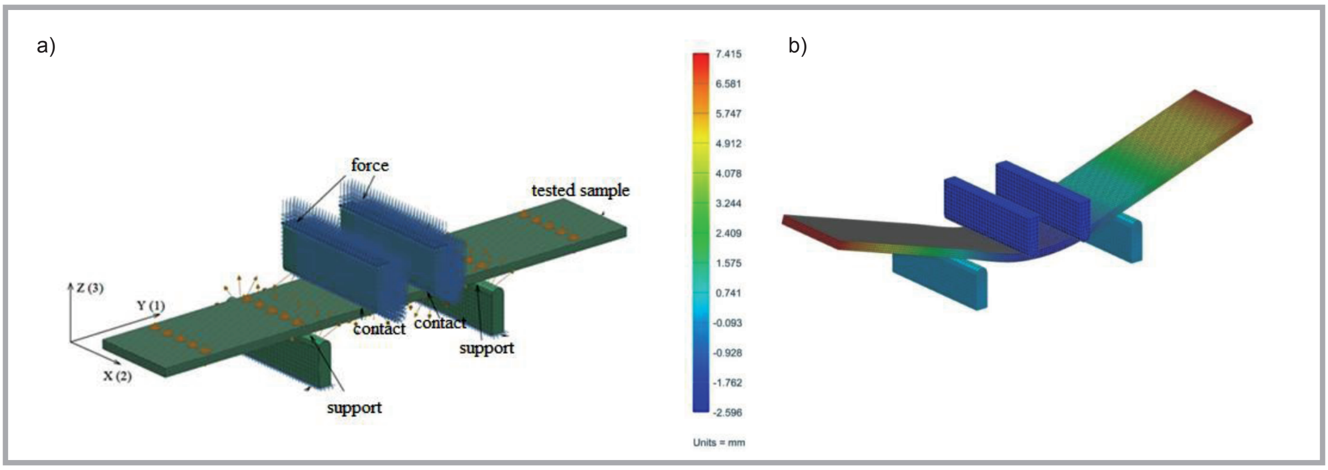


***Figure 6.*** *FEM model of a) discretisation & b) UY displacement for sample 2.2.*

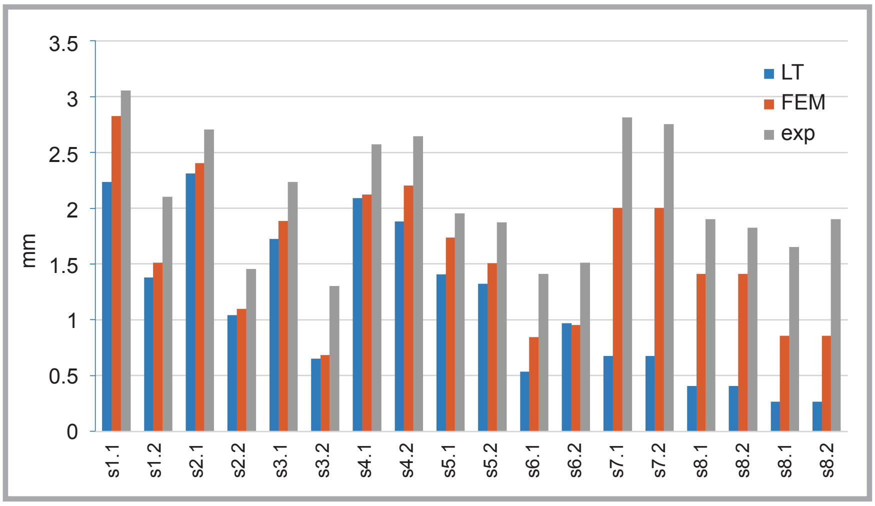


***Figure 7.*** *Comparative graph of displacements determined theoretically and experimentally*

sumes that the individual layers are permanently connected; the Kirchoff-Love theory applies here, providing for small displacements. Engineering constants for individual laminae were determined using the law of mixtures of the Halpina-Tsai compound. The transformation matrices were then determined and the susceptibility matrices were converted into stiffness matrices. In the next stage, the stiffness matrix for laminates was determined:

- Calculation of the stiffness matrix of the whole laminate,
- Determination of the strength of individual layers,
- Calculation of the strength of the laminates tested.

In the second analysis, an FEM model was designed and a numerical simulation of the 4-point bending of samples was performed, for which NX Nastran software codes were used. Three-dimensional models of supports/shores and a laminate beam were prepared (***Figure 6.a***). Based on the matrix and fibre data, the software calculated parameters of individual laminae using the finite element method. They were then used in simulations as the material from which the beam is made. All elements were covered with a hexahedral (cuboid) grid of finite elements. The boundary conditions of the task are fixed supports; the sample can move vertically, and the load is applied by setting the displacement value with the use of two punches. Between the punches and the top surface of the sample, the surface-to-surface contact was modelled. The technical constants and strengths of the layers calculated by the software using the finite element method and summary results of computer simulations of stresses in the layers, as well as beam displacements and the Strength Ratio (SR) parameter are presented in graphical and tabular form. One of the challenges in designing using composites is that due to the typical complexity of the composite part, the component design and simulation results may be difficult to visualise, and the selection of the correct design parameters required to correctly define the component is often unclear. A layer table is a simple way to understand the composite structure. ***Table 3*** shows how the composite is organised in terms of the number of layers (5), material and orientation.

***Table 3.*** *Comparison of results for individual laminate layers.*

| Layer no. | $\sigma_1$, MPa | | $\sigma_2$, MPa | | $\tau_{12}$, MPa | | Min. SR, – |
|---|---|---|---|---|---|---|---|
| | Max | Min | Max | Min | Max | Min | |
| 1 | 12.71 | -26.38 | 40.28 | -77.24 | 0.0462 | -0.0473 | 1.04 |
| 2 | 15.07 | -23.52 | 47.79 | -68.16 | 0.0350 | -0.0358 | 0.875 |
| 3 | 17.44 | -20.66 | 55.40 | -59.08 | 0.0444 | -00435 | 0.755 |
| 4 | 19.81 | -17.79 | 63.04 | -50.00 | 0.063 | -0.062 | 0.664 |
| 5 | 22.22 | -14.93 | 70.69 | -41.38 | 0.083 | -0.081 | 0.592 |

Parameter Strength Ratio values (SR) were determined, which allows identification of the destruction of the composite layer for the case where SR < 1.0 of the sample deflection calculation at this point. The parameter which is best verified experimentally in the first phase of failure of the sample load capacity is its deflection. Deflection results for, e.g. sample 2.2. are shown in ***Figure 6.b***.

As clearly shown by the chart of the largest displacements the sample can transfer during the test, for each case the highest values were obtained during the experiment. While lower values of displacements result from FEM, which correspond to the smaller loads at which the sample is destroyed. The test samples withstood the highest load when the fibre arrangement was parallel to the direction of the main stresses in the sample. The biggest discrepancies are between the experiment and the results obtained from the classical theory of lamination. It should be emphasised that the results obtained using the theory of lamination as well as FEM are always lower than the values achieved experimentally. Therefore these can be considered safe. However, more accurate results are provided by FEM.

The discrepancies between the simulation and calculation results and research results observed consist of many factors, the most important being the simplifications adopted in the calculations and modelling resulting from the complexity of the structure of the composites tested – the classical theory of lamination assumes that the layers are perfectly joined together, which is not actually the case. As the complexity of the sample's structure increases, the mechanisms of interactions and stresses in the material become more complicated, which leads to lower accuracy of results. This can be observed for samples reinforced at an angle of 45 degrees – with a relatively low load they undergo significant deformation, which was not predicted either by the software or by calculations.

The error increases due to an increase in fibre content in the laminate, and hence the number of layers is, in turn, related to the strength criterion selected – only the displacement and force at the moment of the first layer destruction (the so-called FPF – First Ply Failure) were determined numerically, and the first three layers – using FEM. As a rule, the laminate does not lose its load capacity with the destruction of the first layer, as the remaining ones still carry loads. The more layers in the sample, the less important for its load capacity is the destruction of the first layer.

In summary, composites as complex and anisotropic materials require advanced calculation methods, and any simplification may result in lower accuracy of results obtained. A correctly prepared and calibrated FEM model allows to significantly reduce the costs of the composite material design process.

## Conclusions

- load and displacement results obtained based on the classical theory of lamination and FEM numerical calculations are lower than experimental values,
- the stress in a given element, in particular the direction of the main stress isolines, determines the most advantageous spatial system of a carbon fibre reinforcement,
- given the possibilities offered by 3-D printing technology, the creation of such a reinforcement made of carbon fibres seems to be feasible in the near future,
- the classical theory of lamination does not take into account the spatial state of stresses and assumes a perfect connection between layers, which translates into significant discrepancies with experimental data,
- the accuracy of calculations is significantly reduced when the first layer (KTL numerical calculations) and the first three layers (FEM) are destroyed.

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