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DEFORMATION AND SAFETY FACTOR SIMULATIONS OF POLYMER-MATRIX STRUCTURES WITH SolidWorks SOFTWARE

This article deals with the possibility of simulating composite models in CAD software. The first part of the paper deals with information about composite material, the types of fabrics, types of laminates and the properties of layers. Then a suitable part was chosen and a model was created for the next analysis. The main reason for choosing carbon fiber as the material for the new part is due to its low density and high tensile strength. The weight of the part made from a carbon fiber composite is also smaller than from classic materials like aluminium. At the end of the paper, external loads are simulated on the composite model and the criteria of failure are defined.

Keywords: composite material, carbon fiber, simulation of composites, SolidWorks

SYMULACJE PROCESU ODKSZTAŁCENIA I WSPÓŁCZYNNIKA BEZPIECZEŃSTWA STRUKTUR KOMPOZYTOWYCH NA OSNOWIE POLIMEROWEJ ZA POMOCĄ OPROGRAMOWANIA SolidWorks

W artykule przedstawiono możliwości symulacji modeli kompozytowych z zastosowaniem oprogramowania CAD. Pierwszą część pracy poświęcono zagadnieniom dotyczącym materiałów kompozytowych, rodzajów włókien i laminatów oraz właściwości warstw. Do symulacji zastosowano model kompozytu z włóknami węglowymi, które wybrano ze względu na ich niską gęstość oraz wysokie własności wytrzymałościowe. Ciężar elementu z nowo powstałego kompozytu jest niższy od ciężaru takiego elementu wykonanego z klasycznych materiałów inżynierskich, jak np. aluminium. W ostatniej części pracy na stworzonym modelu przeprowadzono symulację obciążeń zewnętrznych oraz zdefiniowano kryteria zniszczenia kompozytu.

Słowa kluczowe: kompozyt, włókno węglowe, symulacja, SolidWorks

INTRODUCTION

Composite laminates have flexible use and a wide range of applications, from consumer goods to aviation and astronautics. These laminates consist of two completely different materials: thermoset resin and a suitable (glass-, carbon, aramid, boron etc.) fabric. The integration of both materials offers excellent mechanical properties compared to the individual materials used.

The design of composite parts in the past consisted of many trials, prototyping and testing, resulting in increased production costs. With the advances of technology and performance of personal computers came the analytical range of 3D CAD software to enable design and analysis in a virtual environment. This eliminates the tedious and expensive trial errors, which often limit the design process. Often the designer neglects the preparatory phase in order to reduce costs and propose overly-equipped components, which today is highly inappropriate.

COMPOSITE MATERIALS

Composite materials (composites for short) are made simultaneously with two or more materials with vastly different mechanical and/or chemical properties which remain separate and are clearly observable on a macroscopic or microscopic scale inside the finished part. There are two categories of materials involved: reinforcement and filler. At least one piece from each category must necessarily be present. The filler surrounds and supports the reinforcement to maintain a mutual relative position. The reinforcement adds its special mechanical properties in order to improve the mechanical properties of the filler. Synergy produces mechanical properties unattainable by the individual participating materials, and a wide range of fillers and reinforcement allows the designer to select the most appropriate product combination [1].

Laminates are composite materials consisting of fillers and reinforcements in the form of fibers/fabrics. Resins of different types are used as fillers, depending

on the application and desired properties. The most famous of them are polyester, vinyl ester, epoxy, phenol formaldehyde (PF), polyimide (PI), polyamide, polypropylene (PP) and polyether ether ketone (PEEK). They have different mechanical properties, different terms of use, thermal expansion and resistance. As reinforcement fabrics, woven cloth, twill or satin (Fig. 1) or single-shift and bi-axial or mat with a binder (powder, emulsion) are used. Additionally, separate bundles of fibers called rowing are also used for longitudinal reinforcement parts and the fabrication of pressure tanks. The fibers are mostly glass, carbon, aramid, and hybrid boron - using various types of weaves in order to obtain special properties [2].

TABLE 1. Comparison of mechanical properties of fibers [3]
TABELA 1. Porównanie własności mechanicznych włókien

Type of fiber	Density [g/cm]	Tensile strength [MPa]	Modulus [GPa]	Elongation [%]
Glass	2.54	3450	73	3÷4
Carbon ^{a)}	1.78÷1.81	3800÷6530	230÷400	1.78÷1.81
Aramid ^{a)}	1.44	3600÷4100	131	-

a) Values depend on type of fiber (standard, medium, high modulus)

Mutual arrangement of the warp and weave creates three basic types of bonds presented in Figures 1 and 2:

- **plain weave** is the most rigid and pliable to shape well when the source in the warp and weave are equally strong and equally distant; strand of weaving always passes over and under each strand of the warp (so-called balanced plain weave),
- **twill weave** is created by weaving crosses of at least two sources of warp and reverting to one or more sources of warp, in another place; the weaving moves right or left always to the nearest spring warp; fabric with a twill weave is more flexible, but only in a soft surface arrangement of fibers,
- **satin weave** is an integral textile in which a source of warp is covered by four or more strands weaving on the top and one strand from the bottom; the surface of the fabric is smooth and shiny, with long pads in which the fibers lie parallel to the surface [3].

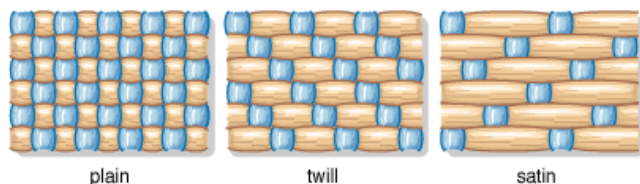


Fig. 1. Types of fabrics

Rys. 1. Rodzaje splotu



Fig. 2. Types of fabrics from side: a) plain, b) twill, c) satin

Rys. 2. Rodzaje splotu (przekrój poprzeczny): a) zwykły, b) diagonalny c) atlasowy

When selecting processing technologies, all the factors that affect the final properties of composites should be carefully considered. Technologies, which use unidirectional oriented fibers (winding, pulling) are suitable to prepare composites with a high fiber content and hence very good mechanical properties. Their drawback is the high anisotropy of their properties. Technology which uses flat or space-oriented fabrics show a lower degree of anisotropy of properties, but also have a lower fiber content and hence poorer mechanical properties [4].

COMPUTER DESIGN OF COMPOSITE MODELS IN SOLID WORKS

In the Dassault System's SolidWorks 2009 SP0 version, it is possible to propose and analyze composite models. The package is part of the SolidWorks Premium kit. The proposal consists of two parts: modeling using surfaces (surface modeling) and defining the properties of composites, which takes place in the superstructure, SolidWorks Simulation. For the design model, it is necessary to understand the basic principles of modeling using surfaces.

In SolidWorks, solids and surface elements are in principle almost the same. To understand the differences and similarities between them, exactly what constitutes a solid body (solid points) and body surface (surface points) should be known. Solid and surface bodies are made up of two types of information (entities) [5].

Geometry - Geometry describes the shape. There are different shapes - flat, wavy, straight or crooked. A point is a unique position in space.

Topology - Topology describes the relationship as:

- The interior and exterior of a solid is defined normal to the surface,
- Which edges meet in vertices,
- Which edges are boundary surfaces,
- Which edge forms the boundary of two adjacent surfaces.

The definition of composite material

When modeling using selected model surfaces, it is necessary to define the orientation of layers and composite structures. One layer consists of a unidirectional fabric and suitable thermosetting resin. A layer of orthotropic material - a material whose properties depend on direction. This layer has three main axes: the X-axis fiber direction, Y normal to the fiber direction and Z normal to the layer (Fig. 3). As expected, the material properties vary considerably in different directions and must be thoroughly characterized.

Composite structures are usually composed of two or more layers with different fiber orientation. To maintain optimum material properties for the application, the layers are composed of sequences depending on the desired properties. A laminate has a global coordinate

system where the Z axis is always normal to the surface model. Each layer is laid with a certain orientation, depending on the X axis [6].

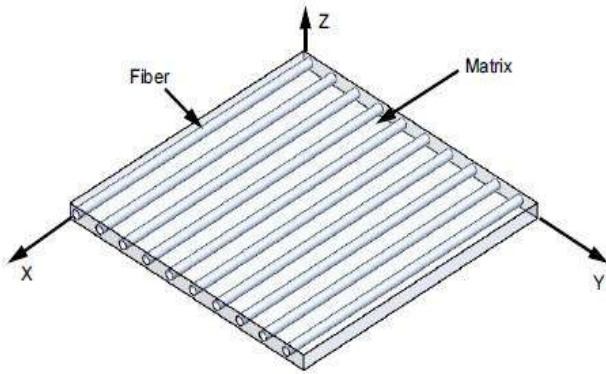


Fig. 3. Laminate layer and main axis [5]

Rys. 3. Warstwa laminatu z oznaczeniem głównych osi

In SolidWorks Simulation Premium from the 2009 version, it is possible to analyze composites with a thickness of up to 50 individual layers. The software assumes that the layers are perfectly bonded together with an absence of shear stress between the layers. The most common compositions of layers are:

Symmetric laminate - In this type (Fig. 4) the layers are distributed symmetrically in the median plane (layer) of the laminate. The layer thickness, fiber orientation and properties of the layers are the same for each of them.



Fig. 4. Symmetric laminate

Rys. 4. Laminat symetryczny

Asymmetric laminate - A laminate exhibiting no symmetry in the central reference plane (Fig. 5), the composition of the individual layers can vary.

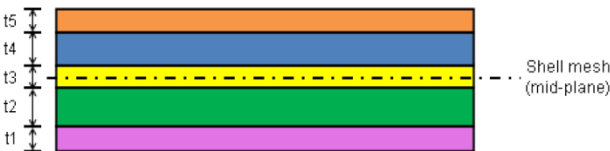


Fig. 5. Asymmetric laminate

Rys. 5. Laminat asymetryczny

Sandwich materials - a sandwich (Fig. 6) is a special case of a symmetric laminate with an odd number of layers. The central reference layer consists of a soft core material of a greater thickness, for example balsa and other layers are made up of conventional fiber and resin [7].

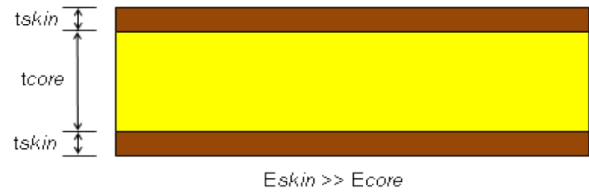


Fig. 6. Sandwich materials

Rys. 6. Materiały o strukturze typu sandwich

Layer properties

For complete characterization of orthotropic materials, nine material constants (Young's modulus E , Poisson's constant ν , shear G in all three axes X, Y, Z) are needed. To achieve these results, a large series of experiments is required. This method is probably the most accurate.

Another method is the so-called rule of materials ratio. If a layer of unidirectional fiberglass fibers is used, it can be considered as a transverse isotropic fiber and isotropic resin. In this case, we can calculate the approximate effective properties of the unidirectional layers. The defined terms are:

- The proportion of fibers V_f - the total ratio of volume of fibers in one layer of a laminate
- The ratio of resin V_m - the total ratio of volume of resin in a single layer of a laminate

If the laminate has no foreign elements, defects or bubbles, the sum of these two units is 1. Information about the proportion of fiber/resin can be obtained experimentally, by weighing the dry reinforcement before impregnation. Then the ratio of the components according to density can be recalculated. If we know the volume ratio of resin and fiber, the material properties can be calculated as follows [7]:

$$E_x: E_x = E_m \cdot V_m + E_{xf} \cdot V_f \tag{1}$$

$$E_y: E_y = \frac{E_m \cdot E_{yf}}{E_m \cdot V_f + E_{yf} \cdot V_m} \tag{2}$$

$$E_z: E_z = E_y \tag{3}$$

$$\nu_{xy}: \nu_{xy} = \nu_{xyf} \cdot V_f + \nu_m \cdot V_m \tag{4}$$

$$\nu_{yz}: \nu_{yz} = \frac{\nu_{yzf} \cdot V_m}{\nu_{yzf} \cdot V_m + \nu_f \cdot V_m} \tag{5}$$

$$\nu_{xz}: \nu_{xz} = \nu_{xy} \tag{6}$$

$$G_{xy}: G_{xy} = \frac{G_{xym} \cdot G_{xyf}}{G_{xym} \cdot V_f + G_{xyf} \cdot V_m} \tag{7}$$

$$G_{yz}: G_{yz} = \frac{E_y}{2 \cdot (1 + \nu_{yz})} \tag{8}$$

$$G_{xz}: G_{xz} = G_{xy} \tag{9}$$

This set of equations allows us to calculate more effective material properties of the laminate layers. This

rule can only be used for one-directional fibers. Research has shown that the ratio of materials rules out relatively accurate analytical results in the X axis (along the fibers). This rule is not sufficiently accurate for a lateral load (in Y axis). In our analysis, this rule is sufficient due to the nature of the load.

The company SolidWorks recommends entering a minimum of six material constants in the analysis of composites, namely: E_x , E_y , ν_{xy} , G_{xy} , G_{yz} , G_{xz} . If any of these parameters is unknown, SolidWorks Simulation applies the basic set of values, which may affect the results, depending on the load [8].

For complete characterization of orthotropic materials, it is necessary to define the following five parameters:

- Tensile strength in the X direction, F_{xt}
- Tensile strength in the Y direction, F_{yt} Compressive strength in the X direction F_{xc} Compressive strength in the Y direction, F_{yc} ,
- Shear strength in the XY plane, F_{xy} .

Layer possibilities and settings - The settings can be found in the "Composite properties manager" and we can define everything about the model: type of laminate (sandwich, symmetric, asymmetric), number of layers, layer thickness, orientation layers and layers of material. The graphics window shows the laminate coordinate system (red arrow is the X-axis) and also shows the direction of the individual layers with a gray arrow (Fig. 7). This coordinate system is not the same coordinate system as a model or assembly.

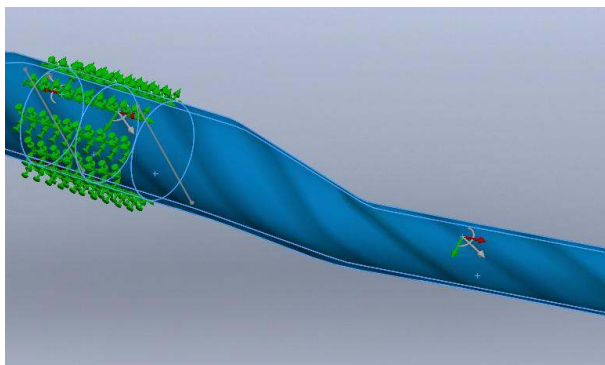


Fig. 7. Coordinate system of composite
Rys. 7. Układ współrzędnych kompozytu

In the Composite properties manager, there is also the possibility of setting the overall orientation of the composite. This allows the rotation or reversal of the coordination system of the composite. These settings affect only the currently marked area of the model. If the model has various surfaces, their orientation must be set in one direction. For studies with multiple composite shells, it is suitable to have all the normal surfaces oriented in one direction. In our case, it was after several experiments with different numbers and thicknesses that the number of layers was set to 8, each 0.4 mm thick, with an orientation to the X axis sequentially [0/30/0/-15/15/0/-30/0] [9].

ANALYSIS OF COMPOSITE MODEL IN SolidWorks

For this test, oversized handlebars for an Enduro mountain bike were proposed. For an FEA analysis model, we first need to define the material - either choose a suitable material from the library or define our own. The material is defined in the Composite properties manager - each layer can be defined and for each layer another material can be used. In our case, we used the same material for all the layers.

Then it was necessary to enter the material properties obtained by means of experiment and calculation. In our case, the ones we used are as follows [10]:

- Elastic modulus in x = $147e9 \text{ N/m}^2$
- Elastic modulus in y = $10.3e9 \text{ N/m}^2$
- Elastic modulus in z = $10.3e9 \text{ N/m}^2$
- Poisson's ratio in xy = 0.27
- Poisson's ratio in yz = 0.54
- Poisson's ratio in xz = 0.27
- Shear modulus in xy = $7e9 \text{ N/m}^2$
- Shear modulus in yz = $3.7e9 \text{ N/m}^2$
- Shear modulus in xz = $7e9 \text{ N/m}^2$
- Mass density = 1600 kg/m^3
- Tensile strength in x = $2280e6 \text{ N/m}^2$
- Tensile strength in y = $57e6 \text{ N/m}^2$
- Compressive strength in x = $1725e6 \text{ N/m}^2$
- Compressive strength in y = $228e6 \text{ N/m}^2$
- Shear strength in xy = $76e6 \text{ N/m}^2$

As handlebars are firmly attached by a locked connection to the bicycle stem, this gripping needs to be simulated. From the menu we select the Fixed Geometry Connections - the component has mountings in 0 degrees of freedom. In the editor we indicate/select the mounting surface where the model is fixed. A representation of a firm grip model is displayed in Figure 8.

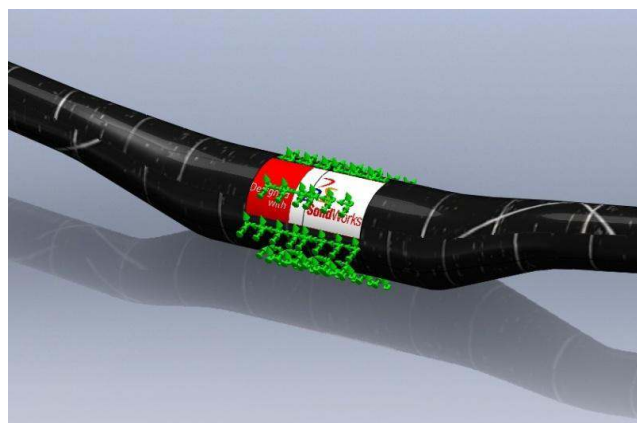


Fig. 8 Representation of firm grip model
Rys. 8. Przykładowy model uchwytu kierownicy

Definition of external load

Our goal is to simulate the load generated by the impact on the handlebars of a rider in a jump. We consider a rider weighing 85 kg, including clothing, bike weight of 15 kg and a jump from a height of 3 m with

negligible drive away called a "trial jump." On impact the rider has the speed:

$$v = \sqrt{2 \cdot g \cdot h} = \sqrt{2 \cdot 9.81 \cdot 3} = 7.672 \text{ ms}^{-1} \quad (10)$$

The rider has the kinetic energy on impact:

$$Ek = \frac{m \cdot v^2}{2} = \frac{85 \cdot 7.672^2}{2} = 2501.55 \text{ J} \quad (11)$$

The impact is suspended by front fork with a 150 mm stroke and the hands of the rider separated by a distance of 0.5 m with a total system stiffness and damping $k = 7883.416 \text{ Nm}^{-1}$.

The stopping distance is therefore:

$$s = \sqrt{\frac{2Ek}{k}} \quad (12)$$

The force that occurs due to the impact is unevenly distributed with a ratio of 40:60 on the hands F_h and feet F_f of the rider and it is defined by the equation:

$$F = \frac{Ek}{s} = \sqrt{\frac{1}{2} k \cdot Ek} = \sqrt{0.5 \cdot 7883.416 \cdot 2501.55} = 3140.124 \text{ N} \quad (13)$$

The handlebars thus are effected by the force:

$$F_h = 0.4 \cdot 3140.124 = 1256 \text{ N} \quad (14)$$

In the External Loads menu the force is selected and the area where the force is applied to the model (Fig. 9).

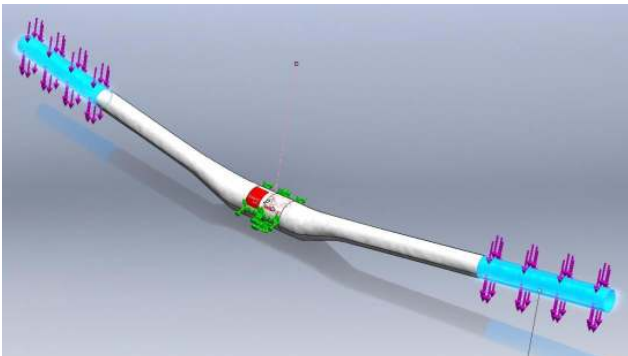


Fig. 9. Illustration of point of application and direction of forces

Rys. 9. Obszary i kierunki działania zadanych sił

Creating the mesh

During FEA model analysis, it is necessary to divide a finite number of elements. For this purpose, a mesh is created, the size and type of elements in the Mesh parameters menu is consequently defined. In our case, we chose the maximum element size of 4.1 and a 1.39 mm minimum. The mesh density depends on the time of its formation and also the calculation time of the analysis. Mesh control is used to refine the grid only in critical sections where we expect the greatest tension (Fig. 10). This procedure is much more effective than applying a fine mesh for the whole model.

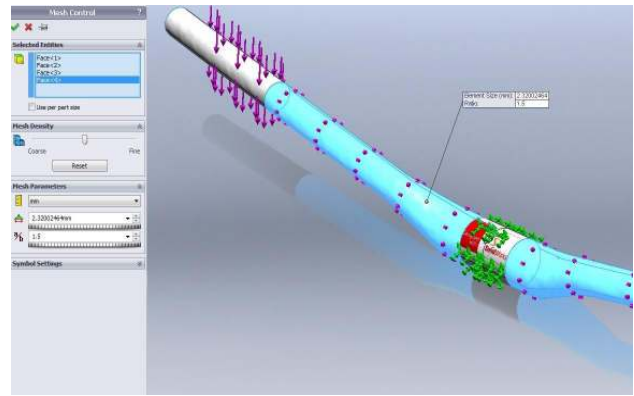


Fig. 10. Application of Mesh control - representation of fine grid

Rys. 10. Zastosowanie panelu kontroli rozmiarów siatki – przykład siatki drobnej

The criterion of failure

The failure criterion is defined by a factor of safety. The safety factor should be larger than 1. There are three different failure criteria for composites:

- **Criterion of maximum stress** - this theory is characterized by a failure if the stress in one of the main directions of the material is greater than the strength of the material in a given direction. This theory does not reflect the tension between the different components. The maximum stress criterion is suitable for fiber composite models which are primarily loaded in tension.
- **Tsai-Hill failure criterion** - also called the energy method - using the Von Mises theory and applying it to orthotropy composites. This theory takes into account the tension between the different components and distinguishes between tension and pressure, making it suitable for materials with equal tensile strength and pressure. Typically, this method is used for models whose fibers are primarily stressed by pressure.
- **Tsai-Wu failure criterion** - also called the interactive tensor polynome theory - is similar to the Tsai-Hill, but with more emphasis on accounting for the difference in tensile stress and pressure. It is therefore best suited for materials with different tensile strength and pressure.

Generally, for laminates with a dominant proportion of fibers, all three failure criteria can give reasonable results. For laminates with a dominant ratio of resin, the tensile stress and pressure have to be defined.

The rendered results are in a distorted state in the real scale factor. In our case, a shear far below the permitted stress was obtained. The total maximum stress was 386.5 MPa, displayed as the yellow area in Figure 11.

The minimum deflection was in the stem clamp of the value 0 mm (blue area in Fig. 12). The maximum deflection was at the edge of the handlebar in the red field (Fig. 12) of the value 6.126 mm.

The safety factor was defined using the Tsai-Wu Criterion as it is best suited for materials with different

tensile and pressure. It is also advisable to try different failure criteria and compare their results. When the safety factor is greater than 1, the model is safe. For certain components such as this, engineers tend to be close to the safety coefficient value of 1, which means a construction of less weight can be made. In our case, a safety factor of 1.22 was obtained (Fig. 13), which means the handlebars exceeded the safety criterion of 1 with a competitive weight of 205.71 g. Compared to aluminium handlebars with the same dimensions, the weight is 313 grams. The weight savings in our case is up to 34%.

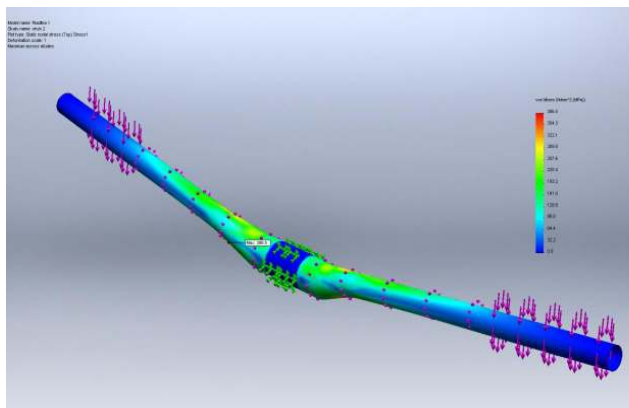


Fig. 11. Resultant maximum stress

Rys. 11. Naprężenia maksymalne otrzymane w wyniku symulacji

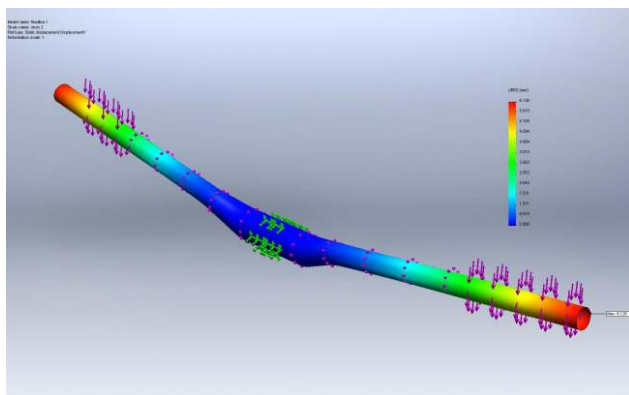


Fig. 12. Total deflection of handlebars loaded with force 1256 N

Rys. 12. Całkowite ugięcie kierownicy obciążonej siłą 1256 N

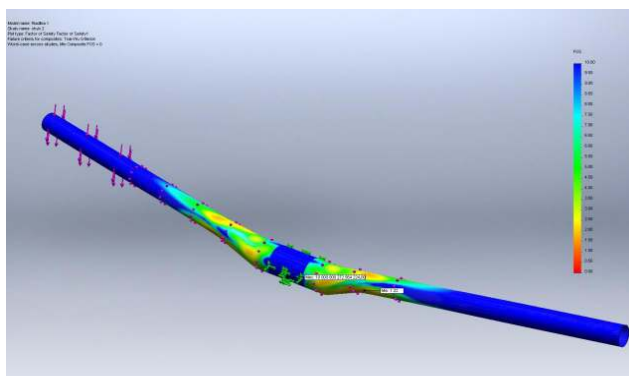


Fig. 13. Results of safety factor according to Tsai-Wu criterion

Rys. 13. Wyniki współczynnika bezpieczeństwa według kryterium Tsai-Wu

MAKING THE TEST MODEL

The test model was manufactured to prove the possibility of making handlebars from a carbon fibre composite. As the material for making the test model, woven carbon cloth (180 grams per square meter) was chosen as the fabric, MGS's L285 epoxy resin, 285 hardener for laminating and Styrofoam to make the core. After tracing the main dimensions reduced in diameter by 30%, a rough model was cut and sanded to the required quality. The pieces of carbon were wetted out and then the first layer on the foam core was added. While the first layer was still wet, the model was tightly wrapped with the first layer of carbon with electrical tape with the sticky side up to provide compaction during curing. Before wrapping, the tape was perforated with a pin over the whole surface. This squeezed out the excess resin after wrapping, displayed in Figure 14.



Fig. 14. Excess resin after wrapping

Rys. 14. Nadmiarowa żywica powstała podczas owijania

Approximately 20 minutes after the first layer was made, the tape was gently removed and another layer was added, and again wrapped with perforated tape.

After the resin dried (24 hours at 23°C), the excess carbon was cut and the entire surface was sanded. A few thin layers of wet epoxy were added, with sanding between each layer. The finished bars are presented in Figure 15. The whole surface was polished for a better (look Fig. 16).



Fig. 15. Finished handlebars

Rys. 15. Wykończona kierownica

The finished handlebars were heavier by 34 grams than the calculated ones. That could be explained by the additional layers of resin on the surface, added for deeper reflection.

The bars fits directly onto the bike stem and works as well as bars from traditional materials. After a few rides there are only some small cracks at the ends of the bars due to one crash and leaning the bike on a wall.

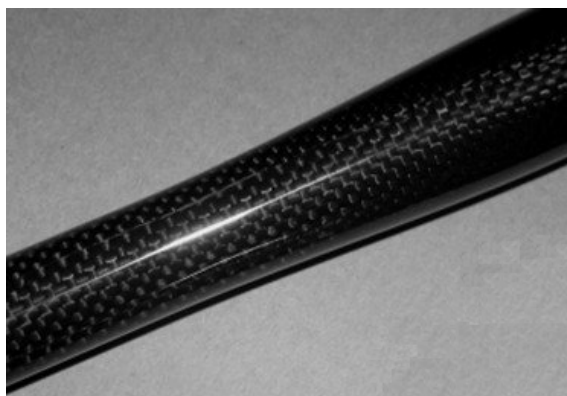


Fig. 16. Detail of polished surface

Rys. 16. Szczegóły wypolerowanej powierzchni

CONCLUSION

This paper describes the possibilities of using a carbon fiber composite in a wide range of applications. Carbon fiber composites, particularly those with polymeric matrices, have become the dominant advanced composite material for many industries due to their high strength and low density. As a tested model, bike handlebars were chosen and the calculations for a trial jump from 3 meters were performed. After the calculations of loads and forces, the simulation in Solid Works software was performed. With an applied calculated force of 1256 N, the maximum deflection was at the edge of the handlebar of the value 6.126 mm. The safety factor was defined using the Tsai-Wu Criterion and in our case a safety factor of 1.22 was obtained, which means the handlebars exceeded the safety criterion of 1. At the

end of the paper, the technique of production of the test model was described. The technique called core wrapping was used, where a core made of Styrofoam was wrapped with layers of carbon fiber and epoxy resin. The manufactured part weighed 239 grams, which is more than the calculated part, but much less than aluminum handlebars with the same dimensions, whose weight is 313 grams. The weight savings in our case is up to 34% compared to the simulation.

Acknowledgements

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