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Flexural testing of carbon FLP composite bars with annular and square cross section

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Abstract

Decrease of vehicle emissions require design changes already at the initial concept design. Use of fiber reinforced polymer (FRP) composites in design cause reduction of weight with increasing other properties. Paper presents the case study of proposal material for frame concept of special light vehicle design. The flexural test (basically three-point bending test) of carbon fiber reinforced polymer composite bars with annular and square cross section is presented. Experimental results were verified by numerical simulation finite element method (FEM). The permanent deformation of bar with annular cross section occurred at a force 2 280 N with deflection 4.22 mm. Model numerical simulation by FEM show same course of loading. For bar with square cross section the deformation occurred at a force 2 264 N, with deflection 7 mm. Model numerical simulation by FEM show different trend (under force 2264 N the deflection was 3.4 mm).

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1. Introduction

The development of the vehicles that do not produce any emissions due to their operation is the current trend in the automotive industry. This is visible in the development of special vehicles for rescue services, agriculture and forestry. These vehicles are used in the extreme terrain conditions and often in the protected landscape areas. To achieve the required characteristics of the vehicles such as slope accessibility, terrain permeability, range, load capacity with zero emissions, we can reach with sustainable design solution. It ensures necessary low weight, sufficient rigidity and strength of special vehicles. The use of fiber reinforced polymer composites in the design (Ashby, 2005; Miracle, 2001) of a special vehicle is essential for zero emissions achievement.

Fiber reinforced polymer composites reduce the weight of the shape while the required strength and rigidity is maintained. This material has well resistant to corrosion and allow creating components with a complex shape (Ashby, 2005; Miracle, 2001; Grand View Research, 2017). Due to production of components with a complex shape are the conventional materials such as steel or aluminums alloys unsatisfactory. Even natural fiber reinforced polymer have recently become attractive to researchers, engineers and scientists as an alternative reinforcement for fiber reinforced polymer composites (Ku et al., 2011). Fiber reinforced polymer composites are made with combination of resin and fibers. Conventional fibers are made from glass, carbon, aramid or basalt and others (Ashby, 2005; Grand View Research, 2017; Ku et al., 2011; Liptáková et al., 2012).

The most commonly used are glass fiber in composites is over 65% and the second commonly used fibers are carbon or over 40% (due to the higher price compared to price for glass fibers) then basalt, aramid and other (Grand View Research, 2017). More frequent use of the glass fiber reinforced polymer composites is due to their excellent ratio between price and mechanical properties. As it is mentioned in (Tekalur et al., 2008; Wonderly et al., 2005) the carbon composite showed higher tensile and compressive modulus. In-plane shear properties of both the composites were comparable and inter laminar shear properties of glass composites were observed to be better than the carbon composite, because of the better nesting between the glass fabric layers. According to experimental study in (Tekalur et al., 2008), the carbon fiber composites tend to achieve sudden destructive damage whereas glass fiber composites tend to sustain progressive damage, under dynamic loading. The composite materials made with a polymer matrix which consists of a polyester or vinyl ester resin reinforced with glass or carbon fiber are most commonly used (Liptáková et al., 2012). Appropriate design of the shape components or stocks (for example bar) made of a fiber reinforced polymer composite we can improve the weight to mechanical properties ratio. Disadvantage is higher price due to complex process of manufacturing (Liptáková et al., 2012).

The aim of this paper is present results of flexural test for two bars with different cross sections. The work was done as case study for special light vehicles frame design. 3D designs of frame for vehicle need to be designed and optimized in virtual reality. First, these processes have to be verified by experimental measurements. For model simulation a different numerical methods as finite element method (FEM), discrete element (DEM), boundary element method (BEM) or finite volume method (FVM) are available (Petrů, 2017). The comparison of experimental measurements results with FEM analysis will be presented in this paper. Full 3D frame design is not a matter of this paper.

2. Experimental material and methods

Experimental specimens are bars made of carbon fiber reinforced plastic composite. The bars have annular and square cross sections. Flexural tests were performed. To determine the properties of proposed bars, in this case study we have been chosen experiment conditions which imitate the nearly real loading of the frame.

The finite element method (FEM) was used for model simulation. The bars loading simulation was performed in Ansys Workbench 19 where the structure of the composite material was defined in ACP (Ansys Composite PrepPost).

2.1. Reinforcement and matrix

The carbon fibers tow 3K, from company Carbon Markers, UK was used for a production of carbon fiber reinforced composites bars. Carbon fibre tow 3K is the bundle (roving) of individual 3000 filaments. These 3K carbon fibers are made from carbon filaments Pyrofil TR30S 3K. One filament has a diameter 7 µm, weighs is 200 mg/m, a tensile strength is 4.41 GPa, modulus is 235 GPa and an elongation is 1.7%. Mentioned properties are according to producer Grafil INC.

The structural adhesive AcraLock SA-10-05-10-20A was used for matrix. The base is a methyl methacrylate adhesive (component A) mixed with an activator (component B). Working time for this adhesive is up to 20 minutes.

According to producer Engineered Bonding Solutions, LLC, FL USA, the properties of AcraLock are follow tensile strength is 19.3 MPa; modulus is 620 MPa; elongation is 80-120%; lap shear pultrusion is 20 MPa.

2.2. Manufacture of bars

Experimental specimens - bars were made by winding of carbon fibers on a core. The process of carbon fibers winding on the rotating core is shown in the next figure: Fig. 1. The Scheme of filament winding. More information about winding is possible find in (Miracle, 2001).

The fibers are impregnated with adhesive AcraLock SA-10-05-10-20A in a resin bath before being wound up on the core. The core rotates around the axis of the spindle. At the same time, the winder performs a second movement, namely a sliding rectilinear reciprocating one. The winding angle depends on the speed of rotation and the feed of the core.

After the cure process at room temperature for 24 hours, the carbon bars have been removed from the core.

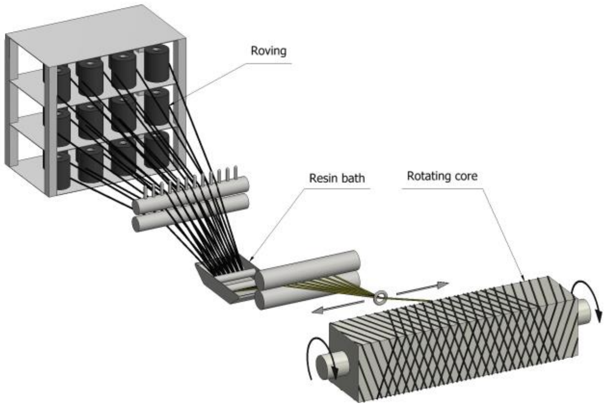

Fig. 1. The Scheme of filament winding

The first tested bar was with an annular cross section. The carbon fibers were wound up on a core with a diameter of 20 mm and a width of 240 mm. The impregnated carbon fibers were wound up in four layers. The layers were wound up at different angle of 25°, 75°, 33° and 45° from the inside to the surface. The thickness of one layer was 0.2 mm. The wall thickness of the bar was 0.8 mm. Steel pins with width of 20 mm were glued to the ends of the bar from each side. Steel pins glued to the bar ensured a suitable clamping of the specimen during the test (prevention from the walls deformation during clamping in jaws).

The second tested bar was with a square cross section. The core with square cross section had side length of 40 mm. The winding width was 440 mm. The impregnated carbon fibers were wound up in five layers, always at a different angle from the inside to the surface. The layers were wound up at an angle of 25°, 75°, 33°, 75° and 45°. The thickness of one layer was 0.2 mm, so the total wall thickness of the bar was 1 mm.

2.3. Flexural test

The flexural test is basically a three-point bending test. Test principle is about measuring the deflection under the middle loading mandrel with depending on loading at a constant feed rate, up to the moment of failure (Sohn et al., 1994, Miracle, 2001). The relative deflection in the direction parallel to the fibers can be calculated as a dependence on the applied load.

The experimental measurements were performed almost according to the requirements mentioned in EN standard EN

ISO 14125, 1998 Fibre reinforced plastic composites. Determination of flexural properties.

Tests were performed on the LabTest5-20 bursting test machine in the laboratory at the University of Žilina, Faculty of Mechanical Engineering, Department of Design and Mechanical Elements.

Flexural test conditions for the specimen with annular cross section:

- dimension of experimental specimen is mentioned above (Chapter 2. Experimental material and methods)
- in the middle of specimen, the ring with width 15 mm was stringed;
- specimen was placed on supports;
- distances between supports was 160 mm;
- perpendicular loading was placed to the ring and constant speed of loading was 10mm/min;
- during the test a deflection dependence on loading force [N] was directly displayed [mm].

Technical draw of specimen and its location is presented in the figure: Fig. 2. Location of specimen with annular cross section on the supports. Real view of flexural test is presented in the figure: Fig. 3. The Real image of flexural test, specimen with annular cross section.

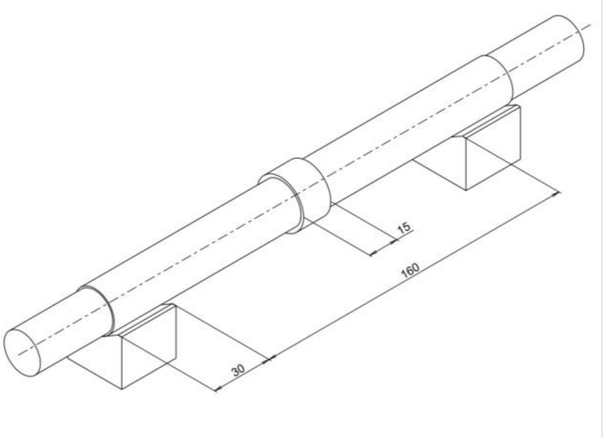

Fig. 2. Location of specimen with annular cross section on the supports

Flexural test conditions for the specimen with square cross section:

- dimension of experimental specimen is mentioned above (Chapter 2. Experimental material and methods);
- specimen was placed on supports;
- distances between supports was 320 mm;
- mandrel has prism shape, with width of 20 mm, length of 80 mm;
- perpendicular loading was placed to the ring and constant speed of loading was 10 mm/min;
- during the test a deflection dependence on loading force [N] was directly displayed [mm].

Technical draw of specimen and its location is presented in the figure: Fig. 4. Location of specimen with square cross section on the supports.

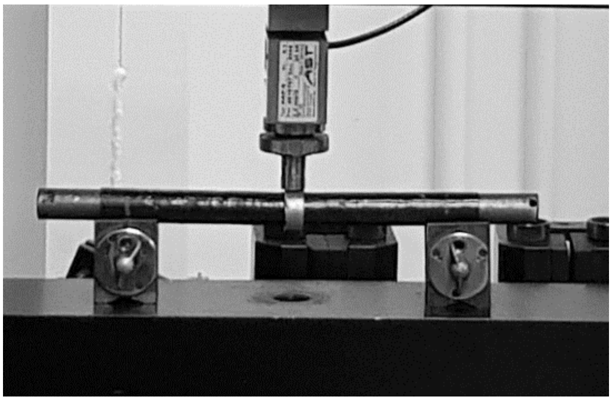

Fig. 3. The real image of flexural test, specimen with annular cross section

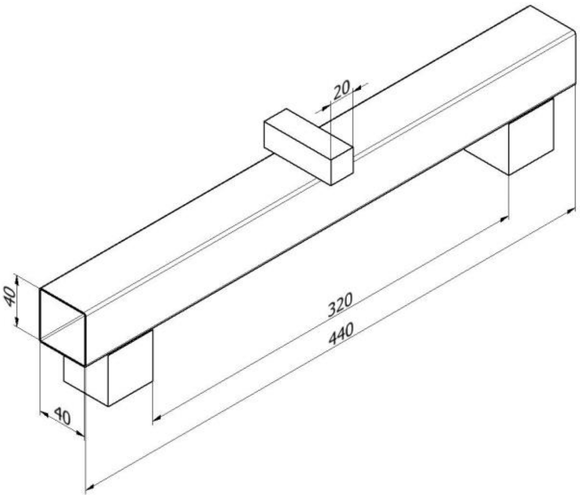

Fig. 4. Location of specimen with square cross section on the supports,

3. Results and discussion

The evaluation of the flexural test (three-point bending) for bar with an annular cross section was based on the values of force and deflection obtained by experimental measurement. Measured values of force and deflection are presented in Table 1. Values of force and deflection obtained during experiments and with FEM model simulation, annular cross section.

The values from Table 1 are graphically shown in figure: Fig.5. Comparison of experimental and FEM model simulation results for specimen with annular cross section.

In the graph, the blue straight curve represents the real course of the experimentally determined values. Values of FEM model simulation had same trend as values of real experiment. The permanent deformation occurred by breaking the carbon bar with annular cross section in the middle of its length, i.e. at the place of the greatest bending stress. This permanent deformation occurred at a force value of 2 280 N. The largest deflection value was 4.22 mm. After deformation indicated by noise the test was interrupted. Also changed trend of curve was visible on the graph recorded during experiment.

The results of the finite element method model simulation are also presented in Table 1. Values of force and deflection obtained during measurement and FEM model simulation, annular cross section are graphically shown in figure: Fig. 5.

Table 1. Measured values of force and deflection obtained during measurement and with FEM model simulation, annular cross section

Annular cross section		
Measured force [N]	Flexural deflection [mm]	FEM, Flexural deflection [mm]
0	0	0
300	0.59	0.53
600	1.15	1.07
900	1.66	1.6
1 200	2.17	2.14
1 500	2.67	2.68
1 800	3.21	3.21
2 100	3.82	3.75
2 280	4.22	4.07

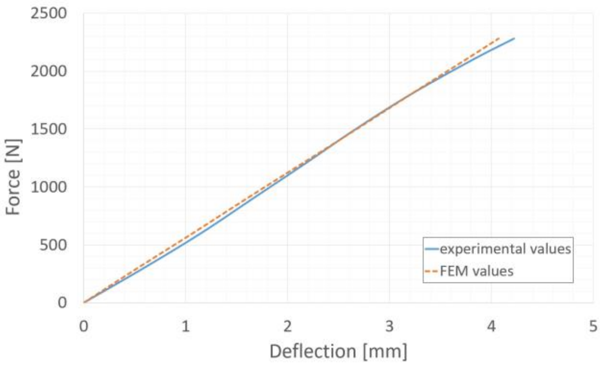

Fig. 5. Comparison of experimental and FEM model simulation results for specimen with annular cross section

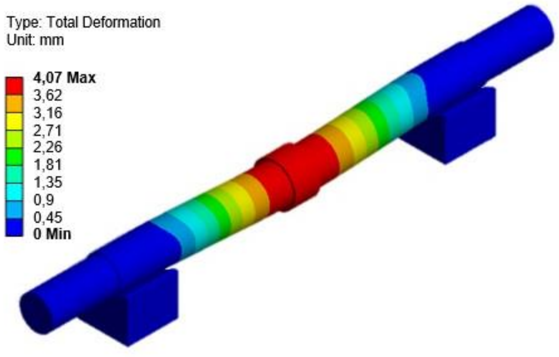

Fig. 6. FEM model simulation for bar with annular cross section, (deflection 4.7 mm, force 2 280 N)

Comparison of experimental and FEM model simulation of results for specimen with annular cross section. Values of finite element method simulation are indicated with the orange dashed curve. The simulation discovered a maximum deflection of 4.07 mm under a loading force of 2 280 N. Curves in figure: Fig.6. FEM model simulation for bar with annular cross section, (deflection 4.7 mm, force 2 280 N), have similar trend.

The example FEM simulation is presented for the bar with annular cross section in the figure: Fig.6. FEM model simulation for bar with annular cross section, (deflection 4.7 mm, force 2280 N). This model simulation presents the place width with loading force 2 280 N.

The evaluation of the flexural test of the bar with a square cross section was based on the values of force and deflection obtained with experimental measurement. The achieved values of force and deflection are presented in Table 2. Values of force and deflection obtained during measurement and with FEM model simulation, square cross section.

Table 2. Values of force and deflection obtained during measurement and with FEM model simulation, square cross section

Square cross section		
Measured force [N]	Flexural deflection [mm]	FEM, Flexural deflection [mm]
0	0	0
334	1	0.9
897	2	1.8
1 200	3	2.2
1 484	4	2.5
1 898	5	2.9
2 134	6	3.2
2 264	7	3.4

The values from the Table 2., are graphically shown in the figure: Fig.6. Comparison of experimental and FEM model simulation results for specimens with square cross section.

The blue dotted curve represents the real course of the experimentally determined values. The permanent deformation occurred by breaking the carbon composite bar in the middle of its length, i.e. at the place of the greatest bending stress. This deformation occurred at a force value of 2 264 N. The recorded largest deflection value was 7 mm.

At force 897 N, during the test a rupturing was indicated by noise. Test was not interrupted due to the increasing trend of the curve. Assumption is that one of the layers has been broken.

The values of results of the finite element method model simulation for specimen with square cross section are presented in Table 2 (above) and graphically shown in the figure: above, Fig. 7. Comparison of experimental and FEM model simulation results for specimens with square cross section. Orange dotted-dashed curve presents value of finite element method model simulation. Maximum deflection of 3.6 mm was determined under loading force of 2 350 N. The curves in figure: Fig. 6. FEM model simulation for bar with annular cross section, (deflection 4.7 mm, force 2 280 N), do not have similar trend. During the flexural test a visible deflection was observed, see figure: Fig.8.the real image of flexural test, specimen with square cross section. The assumptions of damages of layer or interconnection between composite components have been possible due to higher deflection in comparing FEM model simulation deflection. The bar did not bend under force about 1000 N, only the mandrel was pressed into the bar.

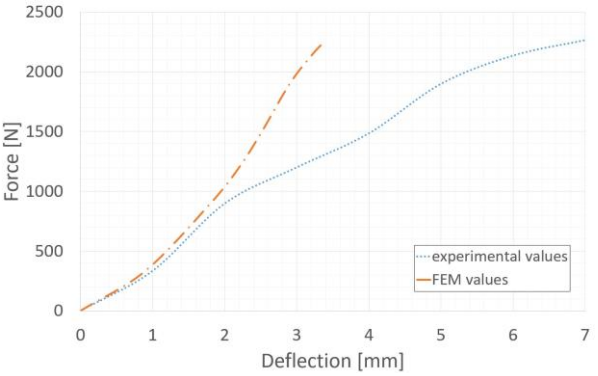

Fig. 7. Comparison of experimental and FEM model simulation results for specimens with square cross section

Fig. 8. The real image of flexural test, specimen with square cross section under loading

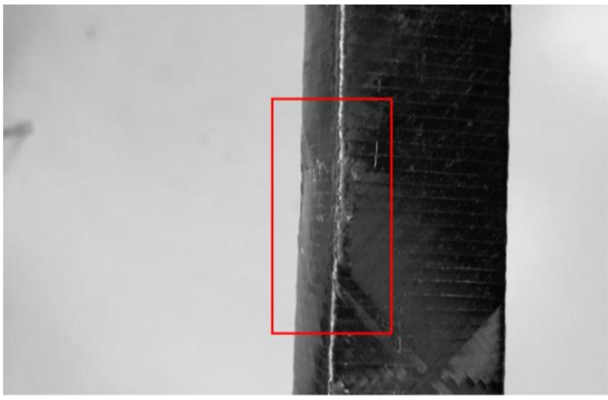

Fig. 9. The Specimen with square cross section after unloading

Square cross section bar returned to its original shape, after unloading, is presented in the figure: Fig.9. The specimen with square cross section after unloading.

Due to the unexpected reaction, the flexural test will be repeated and a structural analysis will be performed, additionally.

4. Summary and conclusion

The case study of experimental flexural test for two bars with different cross sections was done due to design frame for special light vehicle. Bars were manufactured from carbon fiber reinforcement and methyl methacrylate adhesive as matrix. Properties of carbon fibers are good known (Miracle, 2001). Methyl methacrylate adhesives have good properties and play a vital role in the engineering process of joining composites (Martin, 2020).

As was mentioned above, the experiment conditions which imitate the nearly real loading of the frame were chosen to verify properties in this case study. For model simulation a numerical method named finite element method (FEM) was used. The experimental results and results of FEM model simulation were presented and compared separately for bar with annular and square cross section.

Experimental studies of mechanical properties of fiber reinforced plastic composites are often focused on different experimental specimen shape. Due to this, is not possible to compare the results from this work with other case studies. The similar objective of experimental study of the square cross section profile is presented in (Czapski, 2020).

The mechanical loading of composite causes many different processes in the inner structure that varies with the actual deformation as is mentioned also in (Petrů, 2017). Therefore, it is necessary to simplify or neglect some characteristic features in modeling of such structures and determination of all unknown parameters is necessary.

The mechanical properties of composites depend not only on the properties of the individual components of the composite, but mainly on their interconnection. The stability of the mechanical properties of the composition is also determined by the firmly connected fibers with the matrix. When their connection was interrupted, mechanical properties will worsen as reported in (Sadeghian et al., 2006; Choi et al., 1999; Sohn et al., 1994).

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碳纤维 FLP 复合杆的弯曲测试

關鍵詞
碳纤维复合材料
弯曲试验
酒吧
环形方形截面
有限元模型仿真

摘要

减少车辆尾气排放需要在初始概念设计时就进行设计更改。在设计中使用纤维增强聚合物（FRP）复合材料可减轻重量，同时增加其他性能。本文介绍了特殊轻型车设计框架概念的提案材料的案例研究。提出了具有环形和正方形横截面的碳纤维增强聚合物复合杆的弯曲试验（基本上是三点弯曲试验）。通过数值模拟有限元方法（FEM）验证了实验结果。环形截面钢筋的永久变形发生在力为 2 280 N，变形量为 4.22mm 的情况下。 有限元模型的数值模拟表明了相同的加载过程。对于具有正方形横截面的钢筋，变形发生在 2 264 N 的力下，挠度为 7 mm。有限元模型数值模拟显示了不同的趋势（在 2264 N 的力作用下，挠度为 3.4 mm）。这项研究得到了斯洛伐克研究与发展局根据合同 No. APVV-18-0457，从非常规材料到恶劣条件和地形-LEV。