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COMPUTATIONAL AND EXPERIMENTAL STUDY OF THE STRENGTH OF A COMPOSITE DRIVE SHAFT

Summary. This computational and experimental work is dedicated to the development of promising designs of vehicle drive shafts made of polymer composite materials. This paper analyzes the existing models of drive shafts of “Formula Student” class vehicles and substantiates the use of a carbon-fiber drive shaft with titanium tips. A manufacturing technology for such a product is also presented. Evaluation of structure performance under the action of ultimate loads was carried out by the finite element method. Prototypes of composite drive shafts were produced for further laboratory and field tests. The author proposed a new design of composite drive shafts and a method for calculating the strength of the proposed design; the results were verified by bench laboratory and field tests. From the results of this work, conclusions about the performance of the developed structures and their applicability to racing cars were drawn.

1. INTRODUCTION

At present, composite materials are widely used as structural materials in vehicle units. In particular, the use of modern composite materials in the transmission elements of the car, i.e., axle shafts or drive shafts, allows to significantly improve the performance of the wheeled vehicle by reducing the full and unsprung weight and reducing the moment of inertia of the transmission. Among modern composite materials, it is possible to distinguish polymeric composite materials with carbon fiber as a reinforcing element. This type of fiber has low density, and the best combination of a high level of strength properties and manufacturability of the product.

The most widespread structural materials used in the manufacture of drive shafts are steel, titanium, glass fiber-reinforced polymers (GFRPs) and carbon fiber-reinforced polymers (CFRPs) [1]. Drive shafts made of steel are the most common. Steel shafts have more predictable properties than composite ones; they have a minimum price and great manufacturability, but they have a large mass.

The following requirements have to be fulfilled for the drive shaft:
- it must transmit torque from the transmission to the wheel;
- it must be capable of rotating at required vehicle speeds; and
- it must operate under torque application in both directions [2].

Since mass is an important factor affecting the dynamics of the vehicle, it is necessary to reduce the mass of the car and reduce the moment of inertia of the transmission as much as possible. The reduction in mass is of utmost importance in sports cars. Shafts made of titanium are the most expensive and difficult to produce because of the need for complex technologies, such as friction welding, in the manufacture of the product. Products made of GFRPs have a low specific strength in comparison with products made of CFRPs. The use of carbon fiber in the design of the drive shaft allows to reduce the weight of the product by 30% compared with the steel analog [3, 4]. Thus, to maximally reduce the weight of the drive shaft while maintaining its performance, it was decided to design a carbon-fiber drive shaft with titanium spline tips.

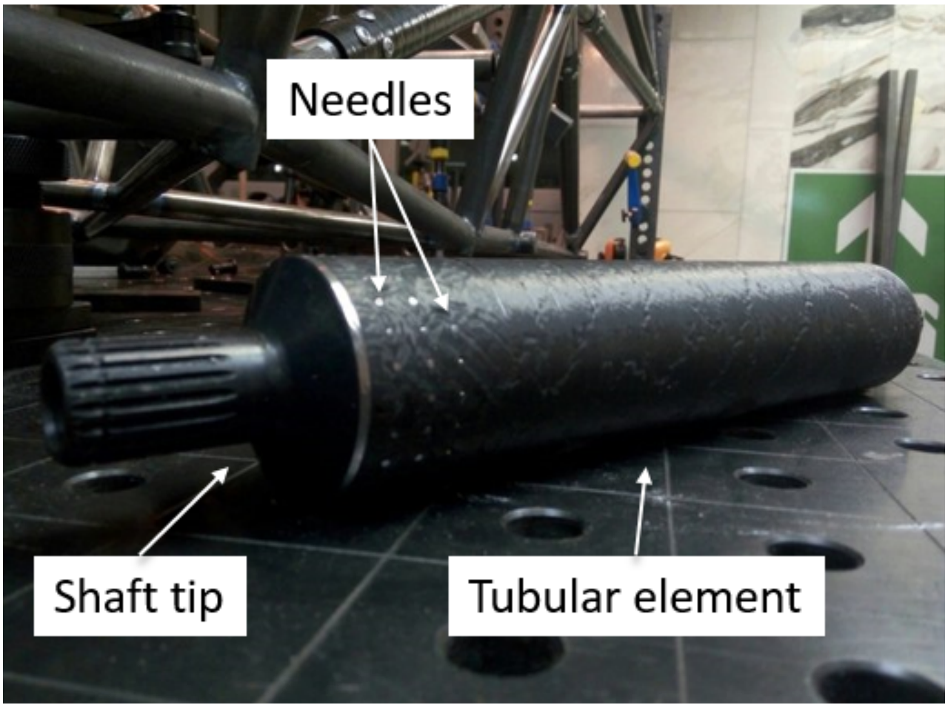

Fig. 1. General view of the composite drive shaft

To date, reliable transmission of torque by a spline connection remains a difficult task if one component is made of a CFRP and the other is made of metal. In view of this, the problem encountered in the manufacture of a composite drive shaft instead of a metal one is the connection of the composite shaft body and a metal tip. One of the easiest ways to ensure this connection is adhesive bonding [5, 6]. However, this method has several disadvantages such as high dependence of adhesive bonding on its production technology, low fatigue strength and high sensitivity to vibration loads. In this case, mechanical connection has greater reliability [7, 8].

This paper proposes the design of a drive shaft consisting of two titanium alloy tips mechanically connected by means of a carbon-fiber tubular element. The tip has splines, on which tripods are mounted. Tripods are fixed on the splines by means of two lock washers; the general view of the composite shaft is shown in Fig. 1.

The shaft tips are positioned relative to each other with a thin-walled technological composite tube with a certain length, which is glued to special collars on the ends. Further, the carbon fiber is wound onto the workpiece. The fiber is placed on the tip portion with needles and envelopes it, providing a mechanical connection between the metal and the composite.

2. DETERMINATION OF BOUNDARY CONDITIONS

Determination of the stress–strain state of the drive shaft made of a composite material is a non-trivial task due to the anisotropy of the properties of reinforced plastic. The main difficulties arise as a result of taking into account the features of the material structure, such as the direction of reinforcement and the number of layers of reinforcing material. The following assumptions are made:

- the shaft has an annular cross section of constant thickness;
- inertial loads are neglected; and
- damping and nonlinear effects are excluded.

The maximum torque on the drive shafts occurs in the breakaway and engine braking modes. The breakaway mode at the maximum moment realized by the grip is the most critical mode. In race cars, when using race tires, the coefficient of grip can reach 1.7-1.8; in calculations of the moment, the value of 1.7 is used [9].

$$M_{fr} = r_{\mathrm{k}} \cdot k_{\mathrm{bl}} \cdot \varphi \cdot M \cdot g \cdot 0.7 = 1140\ \mathrm{N \cdot m}, \quad (1)$$

where M = 270 kg, which is the vehicle gross weight; r_{k}= 0.261 m, which is the wheel rolling radius; k_{bl} = 1.25, which is the coefficient of the differential lock; φ = 1.7, which is the coefficient of grip; and M_{fr} is the maximum torque [10].

3. FINITE ELEMENT ANALYSIS

To evaluate the performance of the structure under the action of extreme loads, a finite element software complex with built-in modules is usually used to prepare the finite element model (FEM), taking into account the anisotropic properties of the reinforced materials [11 - 13]. As a solver, the OptiStruct was chosen for the HyperWorks software package.

At this stage, no calculations were performed for the buckling of a thin-walled drive shaft from compressive forces during a suspension operation [14, 15], since these forces are insignificant in comparison with the torque, which transfers the drive shafts from the differential to the hub of the drive wheels.

Within the framework of the study, a three-dimensional finite element imitation model of the drive shaft is created (Fig. 2) that consists of 11611 «shell» finite elements.

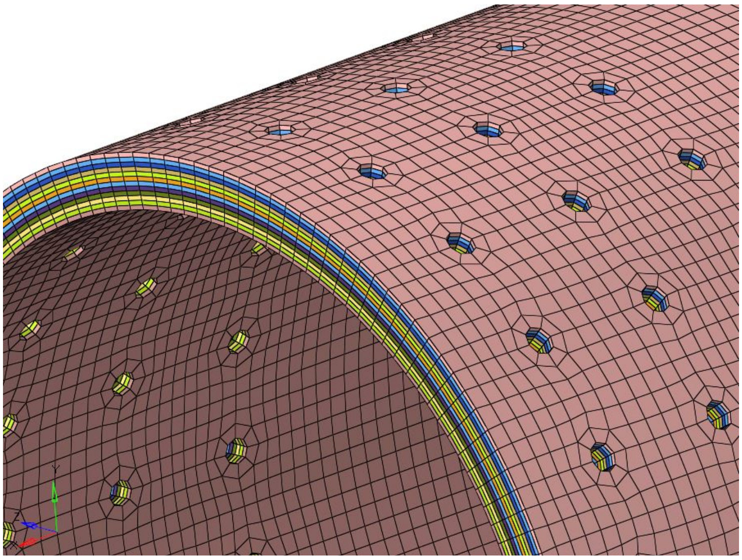

Fig. 2. Finite element model of a drive shaft

In the dialog box shown in Fig. 3 the material parameters such as Young's modulus (MPa), Poisson's Ratio and shear modulus (MPa) in three orthogonal directions are set. Next, the number and thickness (mm) of layers and the direction of reinforcement of the composite material are set. The layers alternate with winding angles of + 54° and - 54° [17, 18].

Next, boundary conditions are set. The shaft end assembly with needles is modeled in a simple manner with the help of "rigid"-type elements. On one side of the drive shaft, the previously calculated torque is applied, which is maximally realized by the clutch, and on the other, movements are limited.

For a correct evaluation of the drive shaft strength, it is necessary to use failure criteria that take into account the anisotropic properties and types of composite material failure. The finite element software complex allows evaluation of the strength of a part taking into account the simultaneous analysis of several failure criteria. It is possible to use maximum deformation, maximum stress, Tsai-Hill, Puk and other criteria [19]. In each layer of the composite, strength evaluation is carried out according to the listed criteria. Based on this evaluation, critical layers in which the values of one or more criteria reach a maximum are determined.

Card Image	MAT8
User Comments	Hide In Menu/Export
E1	140000.0
E2	7500.0
NU12	0.3
G12	4000.0
G1Z	
G2Z	
RHO	1.5e-009
A1	
A2	
TREF	
Xt	1500.0
Xc	900.0
Yt	58.0
Yc	170.0
S	80.0

Name	Id	Color	Material	Thickness	Orientation	IP	Result
ply1	1		CFRP	0.25000	54.0	3	yes
ply2	2		CFRP	0.25000	-54.0	3	yes
ply3	3		CFRP	0.25000	54.0	3	yes
ply4	4		CFRP	0.25000	-54.0	3	yes
ply5	5		CFRP	0.25000	54.0	3	yes
ply6	6		CFRP	0.25000	-54.0	3	yes
ply7	7		CFRP	0.25000	54.0	3	yes
ply8	8		CFRP	0.25000	54.0	3	yes
ply9	9		CFRP	0.25000	-54.0	3	yes
ply10	10		CFRP	0.25000	54.0	3	yes
ply11	11		CFRP	0.25000	-54.0	3	yes
ply12	12		CFRP	0.25000	54.0	3	yes

Fig. 3. Material parameters and laminate of the CF drive shaft

In Fig. 4, the most loaded layer of the composite material is given. Maximum stress is concentrated in a row of needles rearmost to the edge of the composite pipe. In the same region, the maximum values of the failure criteria are fixed. In the local zones of individual layers, the material can undergo destruction during extreme loads, but such zones are negligible. These zones are present only in some layers and do not affect reliability; hence, it can be concluded that the composite part is sufficiently strong.

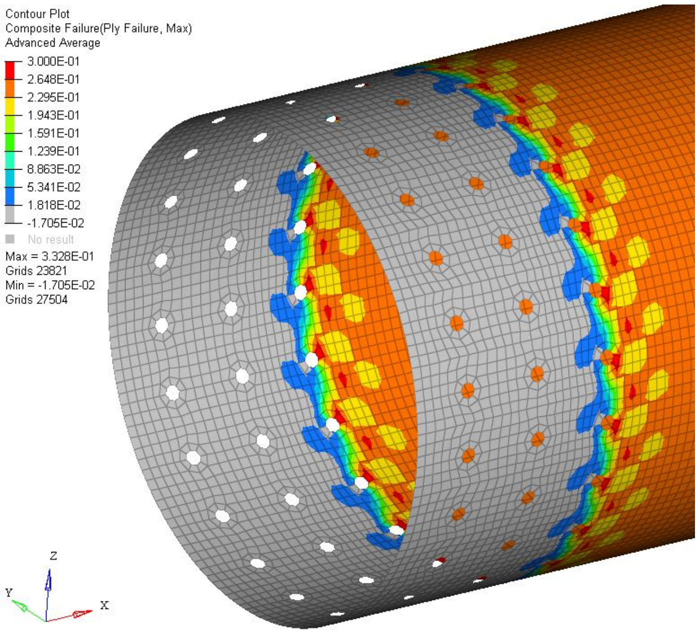

Fig. 4 Torque loading result

The tip is modeled with 125259 elements of the «tetra» type, and the needles are modeled with 13824 elements of the «solid» type. To speed up the calculation time, only one side of the drive shaft is reproduced. The shaft is modeled by 269404 elements of the «tetra» type. The connection of the needles with the shaft and the tip is carried out using a “tie” contact. FEM and the design scheme of a tip with needles are shown in Fig. 5. The boundary conditions are set as follows: displacements are limited on one side of the splines, simulating the inverse splined part on the tripod; the moment is applied to the shaft through the elements of the "rigid" type. The torque is distributed over all the holes and needles.

The results of the calculation of shaft tips and needles are shown in Fig. 6 and Fig. 7.

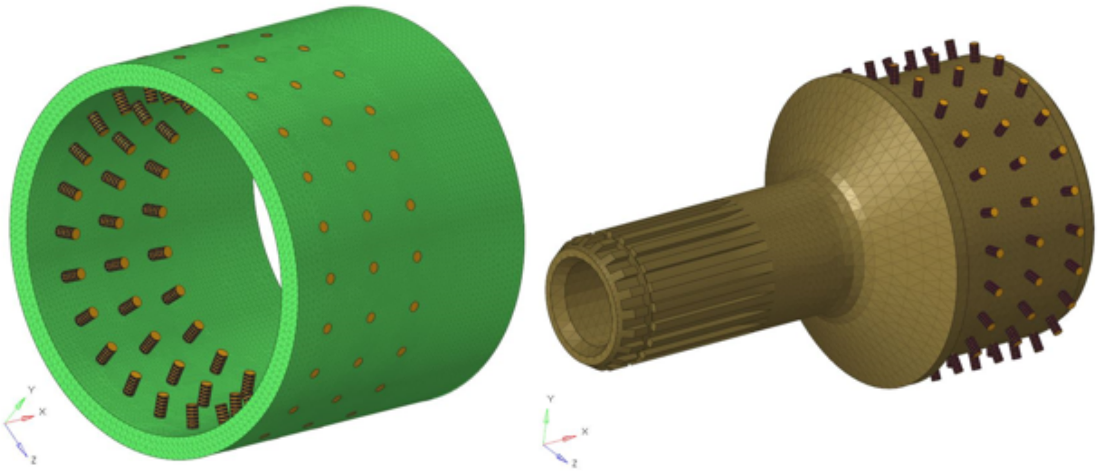

Fig. 5. FEM of the drive shaft tips with needles

The calculation shows high contact stresses at the bottom of the needles. This can be ascribed to the fact that the calculation does not take into account the adhesion of the carbon fiber and the shaft tip, which occurs while filament winding is applied to the work piece and, consequently, redistribution of the load occurs on the needles.

4. LABORATORY TESTS

Based on the results of structural calculations under the action of extreme loads, it is possible to draw conclusions about the efficiency of the design of composite drive shafts.

The next part of this work is dedicated to laboratory tests of the experimental sample of the drive shaft. For laboratory strength tests, a test stand, depicted in Fig. 8, is manufactured.

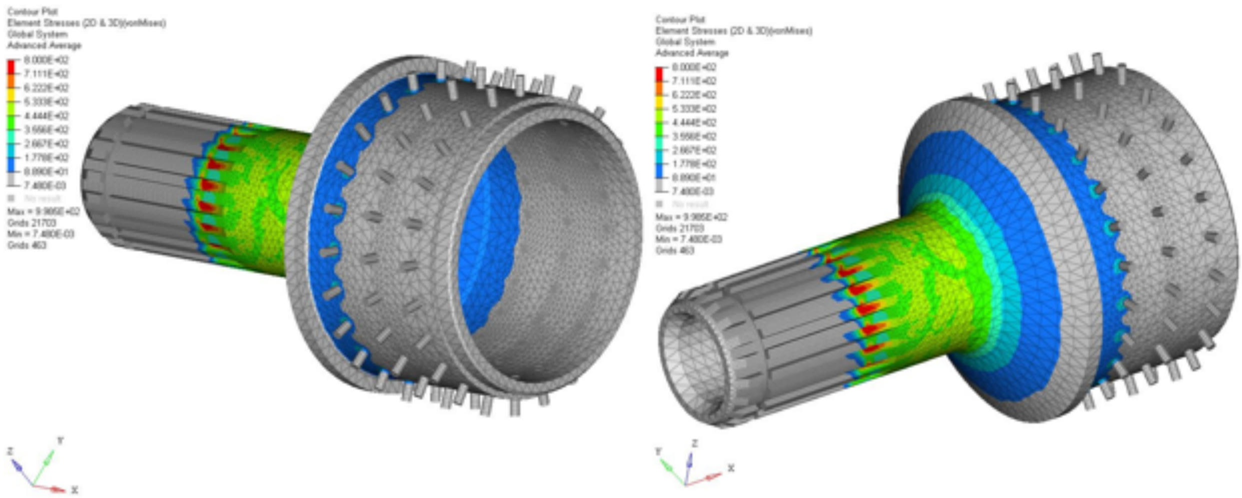

Fig. 6. Result of calculation of shaft tips

The plate (5) is mounted on the corner tool (4) and fixed to the welding table (2) by a bolt connection. The drive shaft is rigidly fixed on one side. On the other side, it is allowed to rotate relative to the plate (5) at the point of attachment of the lever (1).

The drive composite shaft is torsion tested under the action of a lever powered by means of a tightening device (3). The load value is recorded by the load cell (1). The magnitude of the torque is calculated as the product of the force, applied to the arm and its length. The magnitude of the angular displacement is measured by the dial indicator head (2). Failure occurs in the area of the splines of the titanium tip when the torque reaches the value of 1179 N·m (Fig. 10).

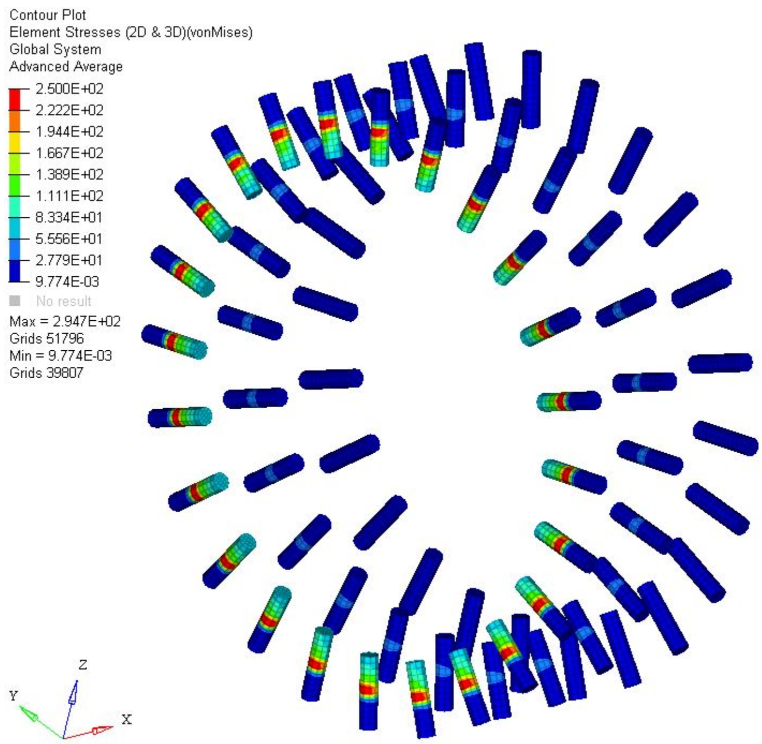

Fig. 7. Result of calculation of needles

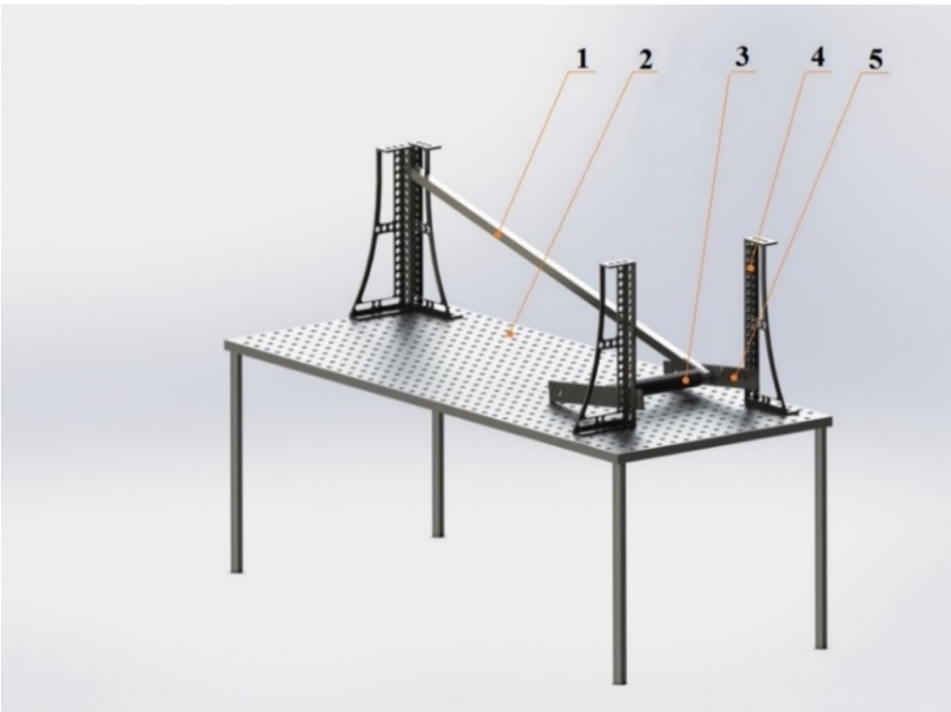

Fig. 8. Test fixture model

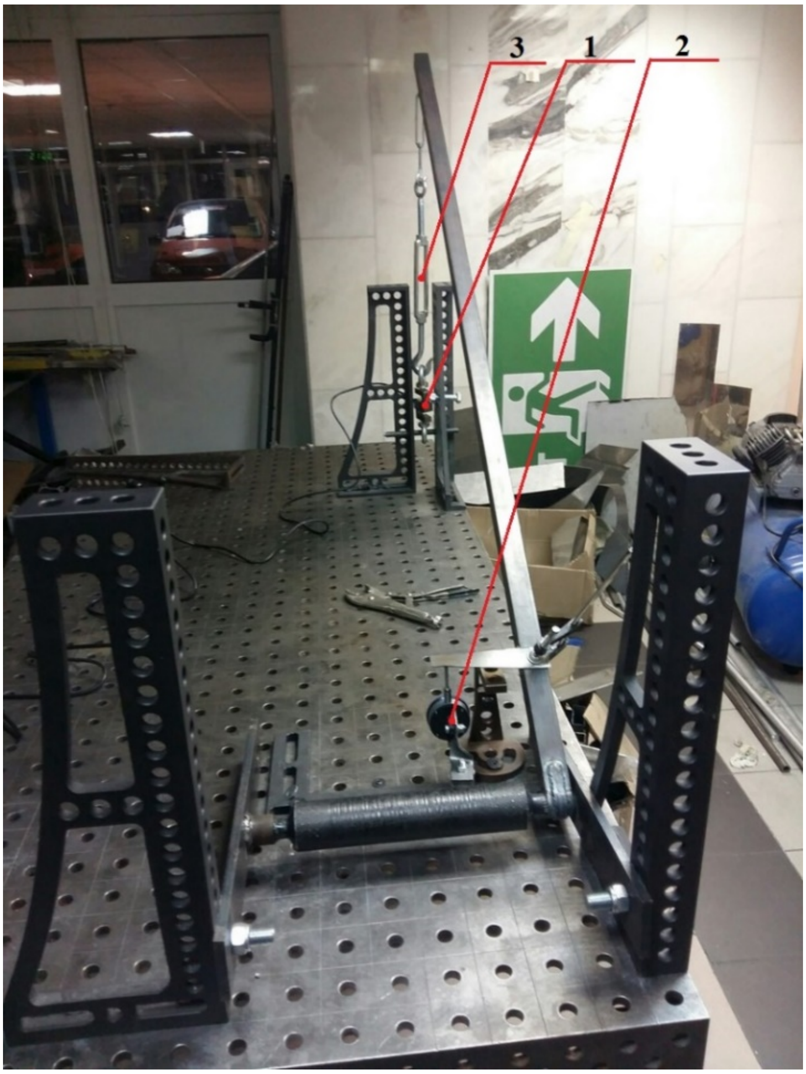

Fig. 9. Test fixture: 1 - strain gauge, 2 - dial indicator head, and 3 - tightening device

5. FULL-SCALE TESTS

This design of composite drive shafts, according to test results, sustains a greater torque than the calculated one. Therefore, a decision was made to make shafts and install them on a Formula Student car for carrying out field tests.

From the analysis of telemetry data, it was established that in full-scale tests, the car was operated under various conditions, such as standing start, engine braking, cornering, sudden acceleration and braking. During the operation of the car, no external defects either on the splines, or in the area of the titanium tip and composite pipe attachment, or on the composite pipe itself, were observed. At a run of about 30 km, all the needles fixing the titanium tip were destroyed (Fig. 12) [20].

During the operation of the car, there were no loads exceeding 60% of the calculated ones; therefore, the main cause of failure is fatigue failure of the needles. Fatigue failure could occur due to dynamic loads caused by unbalanced engine performance [12].

The test vehicle is equipped with a single-cylinder motorcycle engine Yamaha WR450f. Motors of this type have high-amplitude torsional vibrations of the engine–transmission–wheel system. The causes of the imbalance of the engine are the inertia forces of the reciprocating motion of masses and their moments, periodically changing magnitude and direction. Therefore, unevenness of the transmitted torque arises, causing high cyclic dynamic loads and rapid development of fatigue cracks in the shaft connection elements, significantly reducing the life of the part. To increase the durability of the drive shafts manufactured by the described procedure, it is necessary to reduce the stress concentration in the metal and composite joint elements, and to use materials with a higher fatigue endurance limit.

Fig. 10. Tip failure

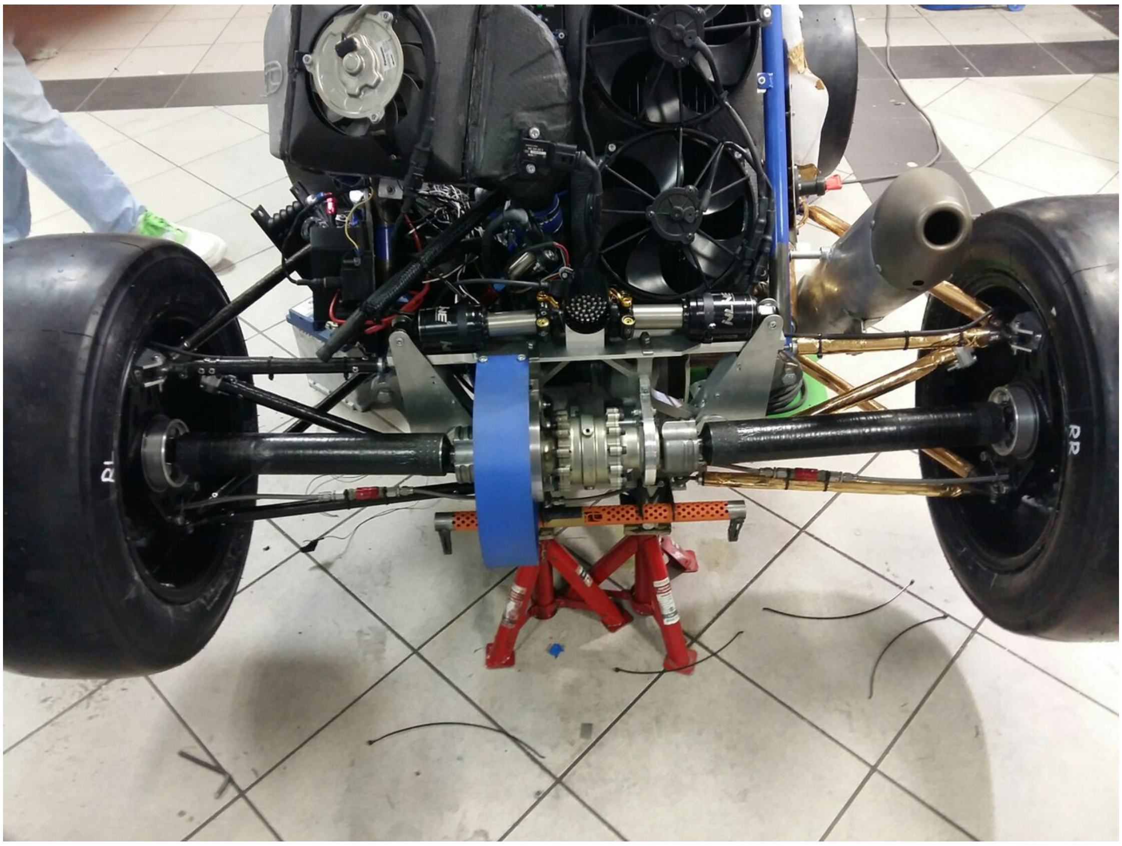

Fig. 11. Formula student car with composite drive shafts installed

Fig. 12. Composite drive shaft failure

Table 1

Mass of drive shafts

Drive shaft type	Mass
Steel drive shaft	1729 g
Composite drive shaft with needles	1138 g
Composite drive shaft with monolithic tips	985 g

6. DEVELOPMENT AND TESTING OF A NEW DRIVE SHAFT DESIGN

Due to the fact that the developed drive shaft did not have sufficient reliability, it was decided to develop a new design, without this disadvantage. Insofar as the weak point of the original design turned out to be a stress concentrator at the junction between inserts and the drive shaft tip, it was decided to develop and manufacture monolithic tips. In addition, it was decided to increase the strength of the connecting elements by increasing their cross-sectional area to increase the shear strength.

However, manufacture of inserts conjoint with the shaft is a difficult challenge in terms of technology. In addition, an increase in the diameter of the elements leads to the appearance of gaps between the composite material and the needle when the fiber is wound. To eliminate these gaps and simultaneously increase the cross-sectional area as well as improve the manufacturability of the product, it was decided to manufacture shaft tips with lozenge-shaped joint elements (Fig. 13). The faces of the lozenge-shaped elements are inclined at a winding angle to exclude gaps between them and the filament tow during winding. The production of such a part is not technologically challenging when using a 4-axis CNC machine tool. Due to the fact that the previous design of the shaft has already shown sufficient strength when tested by static load, a new design that is obviously more durable does not need static load tests.

It was decided to manufacture the proposed design and conduct field tests under real operating conditions. The tests were carried out on a Formula Student class vehicle and consisted of conducting test runs on typical routes of the competition. The modes of maximum acceleration and engine braking were implemented during the tests. During the test, failure did not occur and a visual inspection of the shafts revealed no structural defects.

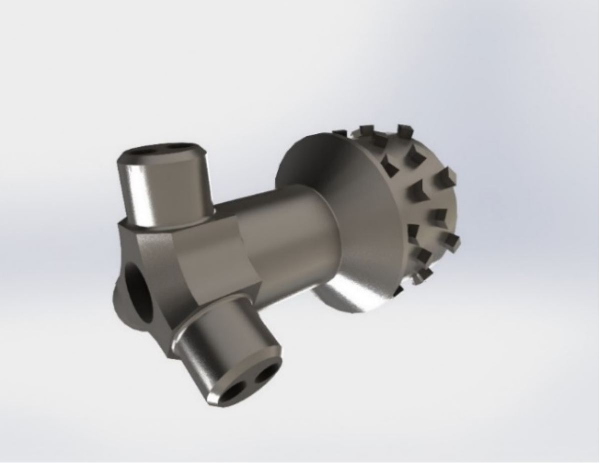

Fig. 13. Shaft tips with lozenge-shaped joint elements

Fig. 14. Formula student car with new design composite drive shafts installed

7. RESULTS AND CONCLUSIONS

As a result of the computational and experimental work, various designs of CFRP drive shafts as well as their manufacturing technology were developed. The assessment of the strength of the product under development was carried out taking into account the anisotropy of the properties of CFRPs in the HyperWorks software package based on such criteria as the maximum deformation, the maximum stress, the Tsai-Hill and the Puk criteria. Using the proposed technology, prototypes of drive shafts were manufactured.

To test the performance of both designs of drive shafts, full-scale samples were created to perform laboratory static tests and dynamic field tests. As a result of field tests, the drive shaft, made of tips with connecting needles, was destroyed. Analysis of the results of laboratory and field tests allows us to conclude that the connecting needles began to crack in the area of the outer surface of the tip due to fatigue failure. A composite drive shaft with a monolithic titanium tip was designed, manufactured and successfully tested. The developed design of the composite drive shaft with a monolithic titanium tip is 43% lighter than the metal counterpart and has the same reliability.

Future work could focus on the study and analysis of the effect of the unbalance of torsional vibrations of the engine on the reliability of composite drive shafts and the accumulation of fatigue cracks in them.

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