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ANALYSIS OF STRENGHT PROPERTIES OF CARBON FIBRE-REINFORCED COMPOSITES

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Abstract

Tensile tests were carried out on three series of composite samples according to the ASTM (American Society for Testing and Materials). The materials tested were characterised by using the same manufacturing method. The specimens were hand-laminated using MGS L285/H285 epoxy resin. The feature that differentiates the structure of each laminate series is the type of reinforcement. A biaxial fabric IMS65 CTLX with a 0/90 arrangement was used to reinforce the C-series composite specimens; for the D-series, a symmetrical fabric Interglass 02037 with a 0/90 weave was used, and for the E-series specimens, a modular fabric IMS65 with a 45 weave was used. The share of composites in the manufacture of construction products is steadily increasing. This is due to the development of new technologies for manufacturing composite elements and composites, with properties that are more and more in line with the requirements of the industry resulting from technological progress. Composite products have to meet many performance requirements. Tensile testing is used to determine some of the key mechanical properties of laminates. Fibre-reinforced polymer (FRP) composites have been used in various engineering structures for many decades. Their unique physical and mechanical properties make them a well-known, most produced and most widely used type of composite materials. In the case of fibre composites, it is the fibres that take over the basic stresses and are responsible for achieving the appropriate stiffness and strength, while the matrix ensures optimum use of the properties of the fibres and gives shape to the manufactured element. The mechanical properties of the composite and its failure process are fundamentally dependent on the high strength of the fibres, the stiffness of the matrix and the strength of the fibre-matrix interface.

Keywords: polymer composites; fibre composites; static tensile testing; carbon fibres; fibre-matrix interface

Type of the work: research article

1. INTRODUCTION

The development and search for solutions to obtain new materials with properties superior to those of materials traditionally used in engineering (metal alloys, wood, building ceramics, etc.) has led to the creation of a group of plastics called composites [1]. The main feature of this new pattern is the ability to combine properties in any way. The result of the use of these advanced materials is a new integration of structure and function, which is the fundamental basis for the emerging material-based industrial revolution [2].

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A composite is a material resulting from the close combination of two or more materials with completely different chemical and physical properties in such a way that, despite a clear separation line between them, the components are well and continuously bonded and the reinforcing phase is distributed as evenly as possible in the matrix. The reinforcement of the composite, also called the filler, is the element on which the properties of the whole material depend. The matrix of the composite has the task of bonding the reinforcement and giving the component the desired shape [3,4,5]. As a result of this combination, the different properties of the reinforcing phase and the matrix complement each other and thus making it possible to obtain a material with additional and/or much more enhanced characteristics than each component separately [6,7].

A composite material consists in the general case of one or more discontinuous phases arranged in a continuous phase. In the case of several discontinuous phases of different nature, the composite is referred to as a hybrid. The continuous phase is called the matrix and the discontinuous phase the reinforcement or reinforcing material [8,9].

The classification of composite materials is mainly based on the type of matrix and reinforcement phase [10].

The reinforcement used determines the tensile strength of the composite in the longitudinal direction, while other properties, such as tensile strength in the transverse direction, shear strength, compressive strength, heat resistance and environment are related to the matrix used [11].

Composite materials are well designed to meet the challenges of high-performance materials for engineering and structural applications. The ability of composite materials to absorb stress and dissipate strain energy is much higher than that of other materials such as polymers and ceramics, and therefore, they offer many mechanical, thermal, chemical and damage resistance advantages with limited drawbacks such as brittleness [12]. Nowadays, composites are widely used. They have started to become a dominant group of structural materials due to their excellent strength properties [13,14]. Multifunctional fibre-reinforced polymer laminates are the primary structure for structural load bearing [15].

The greatest advantage of composite materials is strength and stiffness combined with lightness [1,3,4]. The combination of a polymer matrix and reinforcing fibres results in high-performance materials, which offer weight reductions of over 50% compared to the weight of aluminium and steel [16,17]. Weight saving is one of the main reasons for using composite materials, instead of conventional materials. Although composites are lighter, they are also stronger than other materials [4,18]. The low weight/strength ratio is one of the characteristic properties that is common to most composites. This feature is the reason for their wide application in biomedicine, automotive and aerospace industries [19,20]. A unique feature of composite materials is that they can be tailored to specific applications. In general, composites are designed to have predetermined load carrying capacity and other properties superior to other materials [19].

Despite the many benefits of composite materials, there are also some defects in them. Composites are susceptible to structural damage such as delamination, discontinuities or cracking [3]. With regard to the damage mechanisms in layered composites, two groups can be distinguished: inter- and intralaminar damage. Delamination is an intralaminar damage mechanism, which is defined as the initiation and propagation of an interlaminar matrix crack, which leads to the separation of two laminates and significantly degrades the out-of-plane and flexural properties of the composite structure. Intralaminar damage mechanisms refer to damage within the lamina, that is matrix cracking, fibre cracking, fibre/matrix delamination and fibre pull-out. The sequence of damage accumulation depends on many variables such as the material properties of the composite components, exact arrangement of the layers, defects created during manufacturing, the loading profile and the environmental conditions under which the structure operates [21,22]. Intrinsic defects in composites can arise during manufacturing and service [23]. On the one hand, random porosity or undesirable material may appear in composite structures during the manufacturing process. On the other hand, external impacts may cause delamination or rupture of the structure during its operation [24]. Significant reductions in the mechanical properties and fatigue resistance of composite structures can occur even from low-energy impacts, such as barely visible impact damage, because the excellent mechanical properties of laminated composites come at the expense of through-thickness properties. Impact damage often results in a complex network of cracks and delaminations of the matrix inside or on the back surface, without modifying the upper surface of the structure. A feature of such damage is that it is invisible on the surface and in most cases cannot be easily detected by visual inspection. In addition to impact damage, other internal defect mechanisms such as porosity, voids (or resin coverage area) and inclusions can contribute to the failure of the composite structure [23].

In composite materials, components with complementary physical and mechanical properties are combined. The introduction of reinforcements with good tensile strength, with very high moduli, into the polymer matrix allows for improved mechanical and thermal properties. The advantage of polymer matrix composites, compared to metals, is the manufacturing process, which allows the production of parts with complex shapes, including their lower density and thus lower fuel consumption (in aviation and automotive), higher speed in high-performance sports or greater range of missiles and higher payload (in transport) [8].

As mentioned earlier, composites are structural materials that consist of two or more constituent materials with large discrepancies in their physical, chemical and mechanical properties. The characteristic properties of these composites result from the individual properties of their constituent parts and their respective volume shares and distribution in the material system. Depending on the intended application, composites can be designed to meet specific geometrical, structural, mechanical, chemical and sometimes aesthetic requirements [19]. Therefore, the use of composite materials in various advanced applications is constantly increasing. The aerospace and defence industry was the first to discover the beneficial properties of composite structures [25].

Composite materials have been used in aviation since the mid-20th century [26]. In 1944, glass fibre-reinforced plastics (GFRPs) were used for the first time in the fuselage skin of the Vultee BT-15 training aircraft [27]. Highly favourable mechanical properties of composite materials at their low weight enable the construction of strong yet lightweight aircraft structures, which, in turn, affect the reduction of aircraft operating costs [3,26]. Fibre-reinforced polymers also offer exceptional lightweight potential. Products made from FRPs can be made lighter, thereby increasing resource efficiency and reducing emissions during use [28,29]. For example, Boeing's '787 Dreamliner' became the most fuel-efficient mid-size aircraft when it introduced lightweight composite structures, which account for about 50% of the aircraft weight [15]. Therefore, FRPs could play a key role in the transition to a sustainable and CO_2-neutral society. This objective is becoming increasingly important at a time when the effects of climate change are becoming more pronounced [28,30].

Polymeric fibre composites are predominantly used in the aerospace industry. The reinforcing phase of these composites are different types of fibres. The most common types of reinforcement used in fibre composites are glass G (glass), carbon C (carbon) and aramid A (aramid) fibres [5,31]. The functions of the fibres include carrying most of the tensile or compressive load applied to the FRP specimen, as well as bridging cracks in the matrix and mitigating crack growth by dissipating energy near the crack tip [27]. The matrices in fibre composites are metallic or, more commonly, polymer resins [5,31]. The function of the polymer matrix in FRP composites is to hold the reinforcements together, transfer loads, distribute them uniformly, transfer interlaminar shear and prevent direct contact between fibres and different environmental conditions [27]. Carbon fibre-reinforced plastic (CFRP) polymer composites have high mechanical properties, which make them exemplary engineering materials for load and stress transfer [16]. They have become a mainstay of the aerospace industry. For example, the fuselages of the Boeing 787 and Airbus A350 XWB aircraft are composed of 50% and 52% CFRP, respectively [32]. Carbon fibre-reinforced polymers in the aerospace industry are used in wing flaps, sandwich panels and fuselages. Glass fibre-reinforced polymers are used in thicker composites such as helicopter rotor structures as well as pipelines and storage tanks in the petrochemical industry [33].

Due to their unique physical-mechanical properties, composite materials have gained popularity in recent years in many high-tech and engineering applications. They were initially used as fairings/reinforcements for various structures, but their use has recently shifted from general purpose structures to primary and secondary support structures where structural failures could cause catastrophic safety consequences [33]. Unwanted vibrations in the system induce residual stresses in the structure, which reduces its service life [25]. The process of gradual development of microcracks and other material damage contributes to the phenomenon of slow changes in the values of elastic coefficients, strength indices, vibration damping characteristics and other material properties [34,35]. These changes in the case of composites subjected to long-term static and fatigue loads may amount to 10–50% [34]. Recent studies indicate that the more complex a composite is, the more likely it is that damage will occur in it. Furthermore, the integrity and life cycle of the structure cannot be guaranteed under different loading conditions. Given that composite structures are intrinsically complex and their behaviour under fatigue loading and fracture mechanism are poorly understood (i.e., compared to their metallic predecessors), continuous investigation of their structural integrity and interlaminar strength is of paramount importance [33].

The interface between the fibre and the polymer matrix is critical to the short- and long-term properties of fibre-reinforced polymer composites due to the transfer of shear stress from the matrix to the fibre through their interface. The interface in FRP is the common boundary between the fibres and the polymer matrix through which the load can be transferred from the matrix to the fibres based on strain compatibility. If the interface fails prematurely, the deformation (or stress) of the matrix is not compatible with the deformation of the fibre, with the result that the load cannot be transferred from the weak component (matrix) to the strong component (fibre). In other words, the reinforcing effect of the fibres on the polymer matrix cannot be achieved [27].

Strength tests are carried out to determine the properties of materials and to determine its basic parameters. One of the most important mechanical properties of a material is its tensile strength. It is the value of stress at which a material sample is damaged and consequently breaks. Tensile testing is carried out in testing machines equipped with appropriate jaws allowing to securely fix the tested specimen, a dynamometer allowing to measure the force F acting on the specimen and a displacement sensor recording the elongation ΔL in relation to the initial length of the specimen [36].

Carbon fibre composites are a unique material with exceptional mechanical properties. For this reason, they are widely used for structural applications in the aerospace, automotive, and wind energy industries. The most basic mechanical properties important for the design and application of such materials are stiffness and strength. These mechanical properties are obtained by static tensile testing of monofilament composites [37].

The ASTM static tensile test is used to determine the force required to break a composite specimen and the extent to which the specimen will stretch or elongate to failure. In the test process, the specimen to be tested is placed in the grips of the testing machine. The load is applied and gradually increased. The specimen is elongated during the testing process. This process continues until the specimen breaks. During the test, the relationship between the elongation of the test piece in relation to the applied force is recorded. The tensile test produces a graph showing the tensile stress as a function of the linear deformation of the material. Based on the results recorded during the test, it is possible to determine a number of parameters describing the properties of the tested material: tensile strength, value of breaking stress, explicit yield strength, conventional yield strength, relative elongation, relative constriction and material constants in the form of Poisson's ratio modulus and Young's modulus [36,38].

For the behaviour of fibre-reinforced composites under tensile loading, the stress–strain relationship is dependent on the direction of loading relative to the longitudinal axis of the fibre. This only applies to composites with continuous and aligned fibres. Discontinuous and linearly oriented fibres behave differently. The failure strength (stiffness) of the fibre material is usually an order of magnitude higher than that of the matrix. However, the matrix has a higher ductility and therefore a higher failure stress than the fibre. For this reason, the failure strength and strain of fibre-reinforced composites are between the failure strength and strain of the respective fibres and matrices [19].

2. TEST OBJECT

Composite specimens were tested for tensile strength. The test object was made using the hand lamination method, also known as the contact method.

Laminating is a technique for producing composite systems with increased strength, stability and appearance by using two or more materials in multiple layers.

The entire laminate production process begins with the application of a resin layer, using MGS L285/H285 epoxy resin. The resin applied to the laminate permeates the material and penetrates deep into its structure. Applying eight layers of fabric with an arrangement (45 and 0/90) was intended to further strengthen the samples. The next stage is the application of a flexible bag, pressed with special clamps around the edges of the mould. Excess resin and air are extracted using a spigot and vacuum pump. Curing of the laminate takes place at an atmospheric pressure of 0.9 atm. The resulting laminates are placed at 60C for 8 h. Specimens are cut from the resulting sheet with the appropriate dimensions specified in the ASTM standard. To protect the specimens from damage while they are placed in the grips of the testing machine, the final composite specimens are covered with glass–epoxy composite overlays.

The following types of fabric were used for the different series:

- C series—biaxial fabric IMS65 CTLX with 0/90 weave,
- D series—Interglass 02037 symmetric fabric with 0/90 weave,
- E series—Modular fabric IMS65 with 45 twill.

ASTM is a test method for determining the in-plane tensile properties of high-modulus fibre-reinforced composite materials with a polymer matrix. This method enables the determination of tensile properties for material specification, research and development, quality assurance, and structural design and analysis. Factors influencing the tensile test include material, material preparation and lay-up methods, specimen lay-up sequence, specimen preparation, geometric dimensions and test time.

Table 1 shows the parameters of fabrics used to reinforce the composite specimens.

Table 1. Parameters of fabrics used as reinforcements of composites [39].

Parameter	**Biaxial fabric IMS65 CTLX**	**Symmetric Interglass 02037**	**Modular fabric IMS65**
Density of fabric sheet [g/m^2]	6,8	47,5	27,2
Thickness [mm]	0,19	0,21	0,21
Tensile strength [MPa]	513	443	1450

From the resulting composite sheet, reinforced with IMS65 CTLX biaxial fabric, flat bars were cut, the dimensions of which are shown in Table 2.

Table 2. Geometrical parameters of C-series specimens [op. cit.]

Designation	**Width [mm]**	**Thickness [mm]**	**Length [mm]**
1C	25	2	250
2C	25	2	250
3C	25	2	250
4C	25	2	250
5C	25	2	250
6C	25	2	250
7C	25	2	250
8C	25	2	250
9C	25	2	250

C-series, with specimen designations from 1C to 9C, is characterised by the same geometric dimensions and fabrication.

From the resulting composite sheet, reinforced with Interglass 02037 symmetric fabric, rectangles were cut in accordance with ASTM, the dimensions of which are shown in Table 3.

Table 3. Geometrical parameters of D-series specimens [op. cit.]

Designation	**Width [mm]**	**Thickness [mm]**	**Length [mm]**
1D	26	2	250
2D	26	2	250
3D	26	2	250
4D	26	2	250
5D	26	2	250
6D	26	2	250
7D	26	2	250
8D	26	2	250
9D	26	2	250

D-series, with designations from 1D to 9D, is characterised by identical geometric dimensions and the same method of specimen fabrication.

Following the ASTM standard, flat bars were cut from the IMS65 modular fabric reinforced board obtained during the hand lamination process, and their geometric dimensions are listed in Table 4.

Table 4. Geometrical parameters of E-series specimens [op. cit.]

Designation	**Width [mm]**	**Thickness [mm]**	**Length [mm]**
1E	26	2	250
2E	26	2	250
3E	26	2	248
4E	26	2	250
5E	26	2	250
6E	26	2	250
7E	26	2	250
8E	26	2	250

The E-series, with designations from 1E to 8E, shows little difference in the geometric dimensions of the samples. Plate E3 differs from the other samples only in terms of length. All flat bars are characterised by the same preparation method.

3. TEST BENCH

Composite specimens tested for tensile strength in accordance with the required ASTM standard are rectangular in shape with a constant cross-section. They look like flat bars. There are several specimens in each batch that have been prepared in the same way and have the same layout.

Tensile testing is a destructive process. The specimens are damaged during the experiment.

The tests were carried out using an Instron testing machine, model ZWICK Z100 (Figure 1). This machine is designed to perform static tensile tests. Any material can be tested in different temperature ranges. The experiment was performed at a constant strain rate.

Figure 1. Instron ZWICK Z100 testing machine [op. cit.]

The Instron ZWICK Z100 testing machine can be used for static tensile testing of any material at room temperature and at temperatures up to 1,200C. The machine is equipped with tools that make it easy to test round, bolted, M8 to M16 head diameter and flat bars up to 8 mm thickness. The elongation of the specimen is measured by a macro extensometer (ambient temperature), a MAYTEC HT thermal extensometer operating up to 1,500C and the machine crosshead. The use of two furnaces for heating the specimens increases the testing capacity by 50%. The individual technical parameters of the machine are presented in Table 5 [40].

Table 5. Technical parameters of the Instron ZWICK Z100 testing machine [40].

Maximum test force F_N (tension, compression)	100 kN
Test temperature	Room up to 1,200°C
Number of furnaces	2
Temperature control	Three thermocouples in furnace chamber Three thermocouples next to sample
Traverse speed	0.0005 do 750 mm/min
Accuracy of set rate	0.003% V_{nom}
Measurement of force in the range from 0.4% to 100% F_{nom}	Class 1
Measurement of force in the range from 2% to 100% F_{nom}	Class 0.5
Initial measurement length of extensometer	11–50 mm

The data obtained during the test are automatically transferred to a specialised program that creates a document with the results and saves it as a file. The test control program testXpert provides a graphical representation of the results in a coordinate system of any configuration, and the elongation can be presented in mm or % [13].

The automatic closing and opening of the extensometers makes the machine easy to use, easy and efficient. Additional advantages of the Instron tensile testing machine include an alternative for determining the modulus of elasticity, an innovative control system that allows swapping parameters during the test and having two workspaces.

The force is recorded at each range, within 5% and with a very high accuracy.

The tensile test is one of the most important test methods for characterising or obtaining material parameters. The tensile test determines, for example, what load a material can withstand until it begins to deform plastically (yield strength) or under what maximum load the material breaks (tensile strength). The tensile test can also be used to determine the elongation at break (rupture strain) in order to obtain information about the strength of the material.

Although the tensile test examines the behaviour of the material under pure tensile loading, conclusions can be drawn about the behaviour of the material under other types of loading. The tensile test therefore plays a key role in mechanical engineering.

In a tensile test, a material sample with a standardised geometry (tensile test specimen) is subjected to a tensile load. The standardisation of the geometry is intended to achieve comparability of the material parameters obtained, as the characteristic values also depend on the geometry of the specimen.

In the tensile test, the specimen is subjected to a quasi-static load with an increasing (uniaxial) tensile load until the specimen breaks. For this, the tensile test specimen is clamped in a universal testing machine, and the elongation ΔL is measured as a function of the tensile force F. The measured values obtained in this process are plotted on a stress–strain diagram. From this, the characteristic values of yield strength, tensile strength and elongation at break are determined.

The static tensile test was carried out using an Instron ZWICK Z100 testing machine. A flat section of material with a constant, rectangular cross-section is clamped in the grips of the testing machine (Figure 2) and subjected to a continuous, monotonic tensile test with simultaneous recording of the load. The ends of the strain gauges are soldered to the soldering points to connect the strain gauges to the wires of the testing machine (Figure 3). The tensile strength of the material can be determined from the maximum load carried before failure. The incremental elongation of the specimen for each force value is recorded by the extensometers. The relative deformation is determined by measuring the actual length of the laminate as the load increases. The stress value is determined from the instantaneous tensile force divided by the initial cross-sectional area of the specimen.

Figure 4 and Figure 5 show the appearance of the composite specimens after the static tensile test.

The test control program TestXpert produces a stress–strain diagram based on the results obtained, which is also called a conventional tensile diagram (Figure 6).

Based on the results obtained from the tensile tests carried out, it is possible to determine the tensile modulus, Poisson's modulus, tensile modulus and tensile modulus.

Figure 2. Sample in the machine's grips [op. cit.]

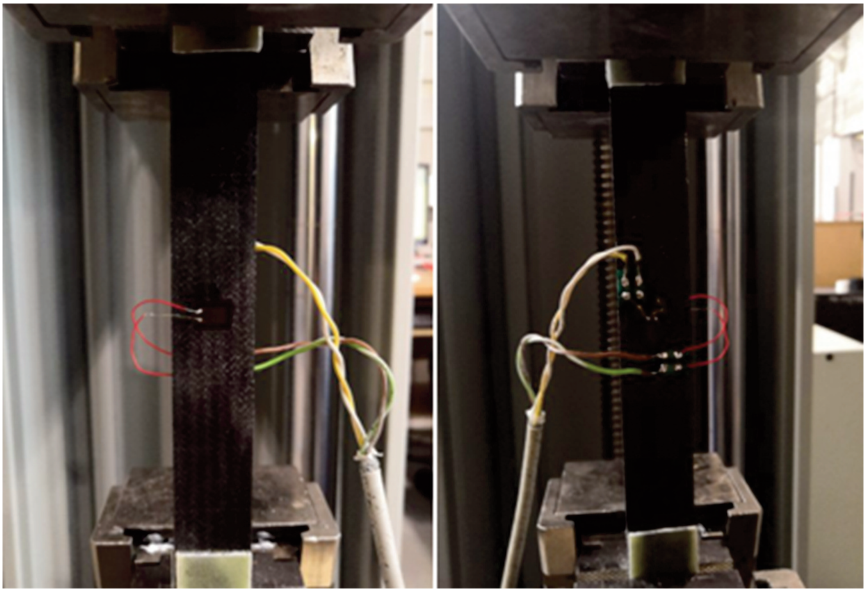

Figure 3. Machine wires connected to the strain gauges [op. cit.]

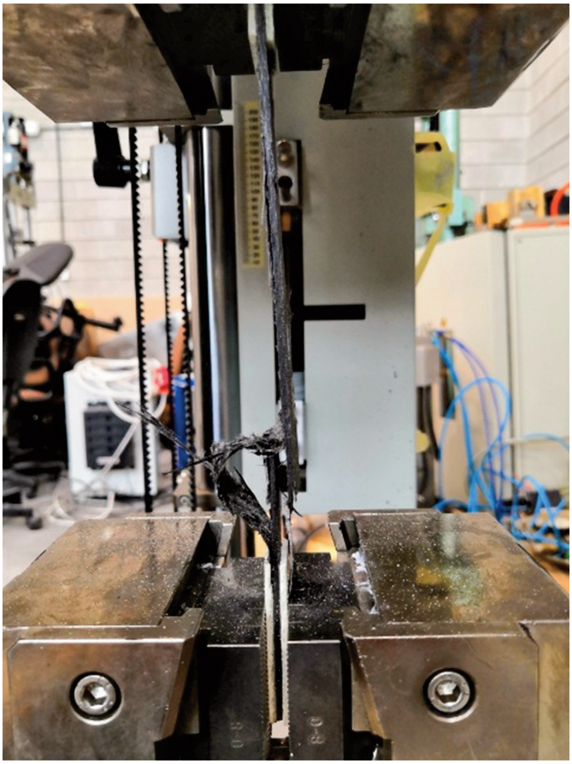

Figure 4. Composite specimen after tensile strength testing [op. cit.]

Figure 5. D-series composite specimen after tensile strength tests [op. cit.]

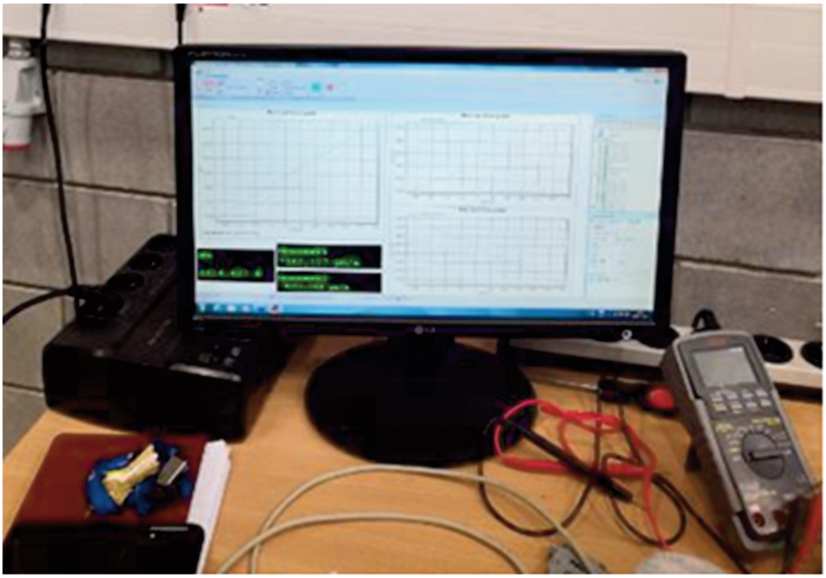

Figure 6. TestXpert test control program [op. cit.]

4. RESULTS OF TENSILE TESTS

Tensile testing provides detailed information about the mechanical properties of a material in tension. These properties can be represented on a graph as a stress–strain curve. According to Eq. (4.1), to obtain the stress, the force measurements are divided by the initial cross-sectional area of the specimen.

$$\sigma = F/S_0 \text{ [MP]} \tag{4.1}$$

where F is the tensile force [N] and S_0 is the cross-sectional area of the specimen [mm^2].

Strain measurements are obtained, according to the relation (4.2), by dividing the change in length by the initial specimen length.

$$\varepsilon = l/l_0 \tag{4.2}$$

where l is the length increment [mm] and l_0 is the initial sample length [mm].

The incremental elongation of the specimen l is recorded by using extensometers as the load increases for each value of the tensile force F.

From the maximum tensile force Fm, the tensile strength Rm is determined according to the relation (4.3):

$$Rm = Fm/S_0 \text{ [MPa]} \tag{4.3}$$

where Fm is the maximum tensile force [N] and S_0 is the cross-sectional area of the specimen [mm^2].

Tensile tests were carried out according to the ASTM standard. The values of tensile stress and corresponding linear strain, tensile force, ultimate tensile strength and Poisson's ratio were recorded and determined during the tensile tests. The values obtained during the tests were collected and presented in a table and graphically.

Tensile testing was carried out on D-series specimens with specimen designations sequentially from D1 to D9. D-series composite laminates were formed using MGS L285/H285 epoxy resin and were additionally reinforced with Interglass 02037 symmetrical fabric with 0/90 weave. Table 6. presents the results obtained during bench tensile tests for D-series specimens, designated successively from D1 to D6. The test results for composite laminates designated D7 to D9 were discarded due to specimen breakage beyond the gauge length. The maximum tensile force during loading ranged from 14.555 kN to 40.040 kN. These values correspond to a tensile strength ranging from 291.109 MPa to 800.795 MPa.

Table 6. Summary results of strength tests of D-series composite laminate [op. cit.]

Designation	**Section area S_0 [mm^2]**	**Maximum tensile force Fm [kN]**	**Tensile strength limit Rm [MPa]**
D1	50	16.950	339.009
D2	50	40.040	800.795
D3	50	36.356	727.115
D4	50	26.894	537.885
D5	50	33.539	670.782
D6	50	14.555	291.109

Table 7 lists 30 consecutive authoritative results obtained during tensile testing of specimen D1.

Table 7. Results of strength tests of specimen D1 [op. cit.]

Lp.	**Time t [s]**	**Force F [kN]**	**Tension σ [MPa]**	**Tensometer 1**	**Tensometer 2**	**Poisson's ratio [-]**
1	44	0.308	6.152	120.776	4.623	-0.038
2	44.2	0.310	6.202	121.518	4.547	-0.037
3	44.4	0.312	6.242	122.241	4.585	-0.038
4	44.6	0.314	6.287	123.060	4.585	-0.037
5	44.8	0.316	6.328	123.859	4.585	-0.037
6	45	0.318	6.362	124.563	4.566	-0.037
7	45.2	0.320	6.402	125.400	4.642	-0.037
8	45.4	0.322	6.449	126.275	4.642	-0.037
9	45.6	0.324	6.489	126.846	4.566	-0.036
10	45.8	0.327	6.532	127.455	4.623	-0.036
11	46	0.328	6.559	128.101	4.452	-0.035
12	46.2	0.330	6.600	129.053	4.566	-0.035
13	46.4	0.332	6.639	129.757	4.623	-0.036
14	46.6	0.334	6.685	130.308	4.604	-0.035
15	46.8	0.337	6.734	130.955	4.490	-0.034
16	47	0.339	6.774	131.526	4.414	-0.034
17	47.2	0.341	6.814	132.287	4.262	-0.032
18	47.4	0.343	6.858	133.200	4.224	-0.032
19	47.6	0.345	6.894	133.847	4.319	-0.032
20	47.8	0.347	6.935	134.437	4.414	-0.033
21	48	0.349	6.981	135.331	4.585	-0.034
22	48.2	0.351	7.026	136.302	4.776	-0.035
23	48.4	0.354	7.076	137.234	4.699	-0.034
24	48.6	0.357	7.131	138.261	4.776	-0.035
25	48.8	0.358	7.167	139.060	4.699	-0.034
26	49	0.361	7.211	139.917	4.604	-0.033
27	49.2	0.363	7.266	140.830	4.433	-0.031
28	49.4	0.366	7.312	141.705	4.528	-0.032
29	49.6	0.368	7.356	142.599	4.661	-0.033
30	49.8	0.370	7.401	143.551	4.680	-0.033

Based on the data obtained, a tensile diagram of specimen D1 was made, showing the relation between the load and the corresponding deformation (Figure 7).

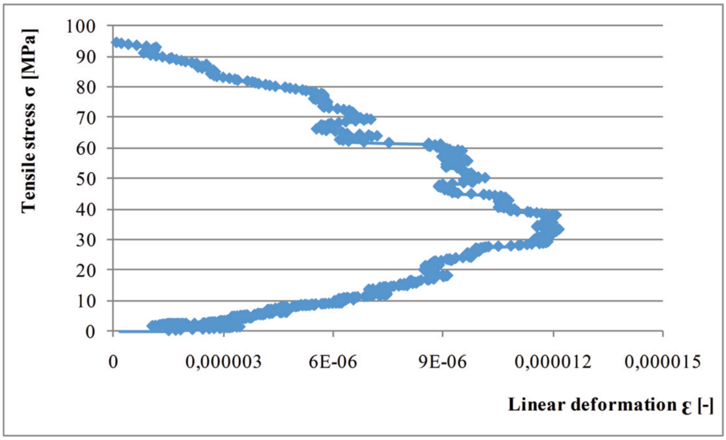

Figure 7: Characteristics of tensile stresses as a function of linear deformation for specimen D1 [op. cit.]

Characteristics of the course of the stress parameter as a function of the linear deformation of specimen D1 show difficult readings of the parameter values, which is due to defects in the measuring system.

The course of tensile force acting on specimen D1 during strength tests is presented in Figure 8.

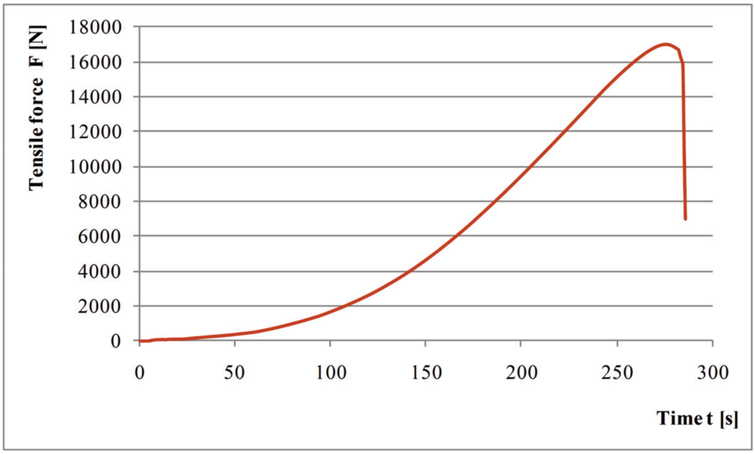

Figure 8: Tensile force characteristics of specimen D1 as a function of time [op. cit.]

The tensile test for the E-series laminate was carried out on specimens designated sequentially from E1 to E8. The E-series composite specimens were created by the hand lamination method using MGS L285/H285 epoxy resin. Modular fabric IMS65 with a 45 diagonal arrangement was used to reinforce the E-series composite specimens. Table 8 shows the results obtained during the bench tensile test for the E-series specimens designated E1, E2, E4 and E5. The test results for specimens designated E3 and E6 to E8 were invalidated due to their rupture beyond the gauge length. The maximum tensile force during loading ranged from 9.995 kN to 21.414 kN. These values correspond to a tensile strength ranging from 199.897 MPa to 428.278 MPa.

Table 8: Summary results of strength tests of the E series composite laminate [op. cit.]

Designation	**Section area S_0 [mm²]**	**Maximum tensile force Fm [kN]**	**Tensile strength limit Rm [MPa]**
E1	50	18.425	368.501
E2	50	21.414	428.278
E4	50	9.995	199.897
E5	50	13.102	262.031

The data obtained during testing of specimen E1 are presented graphically in the form of a plot of tensile stress versus linear strain (Figure 9).

In the final phase of the strength test, a clear decrease in strength is noticeable. This phenomenon is characteristic for delamination of individual laminate layers.

The course of the force applied to specimen E1 for the tensile strength tests is shown in Figure 10.

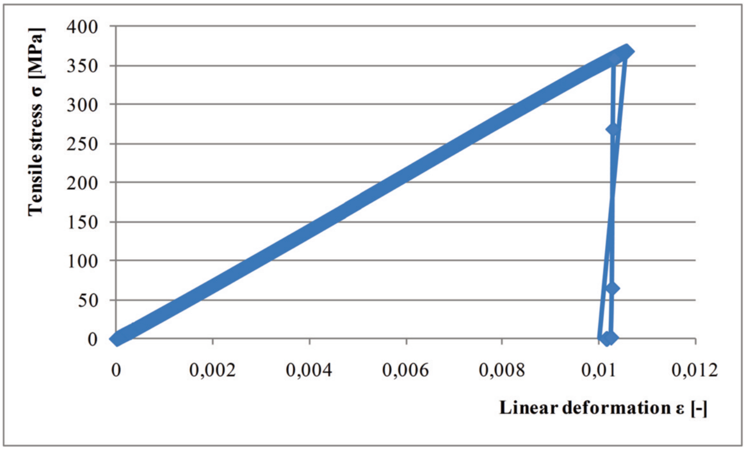

Figure 9: Characteristics of tensile stresses as a function of linear deformation for specimen E1 [op. cit.]

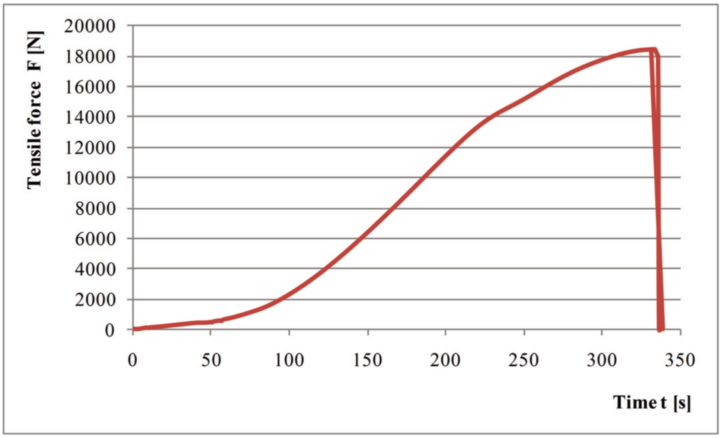

Figure 10: Tensile force characteristic of specimen E1 as a function of time [op. cit.]

Based on the data recorded during the static tensile test, a plot was made showing the relationship between stress and linear strain of specimen E2 (Figure 11).

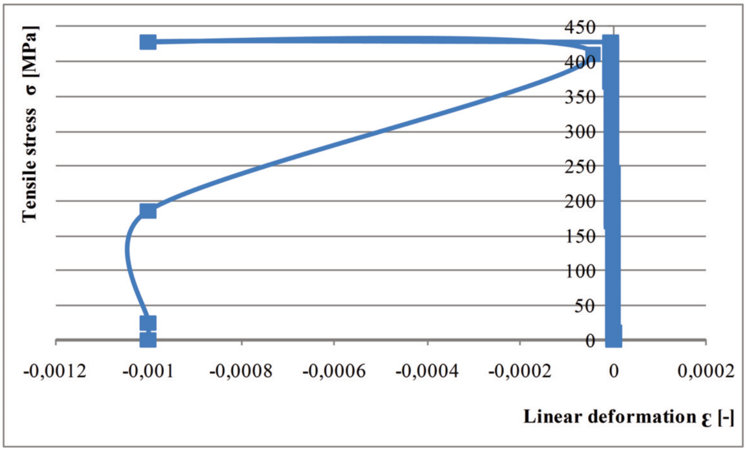

Figure 11. Characteristics of tensile stresses as a function of linear deformation for specimen E2 [op. cit.]

The anomalies in the measured values of the stress parameter as a function of linear deformation are a result of damage to the strain gauge systems of specimen E2.

Figure 12 shows the course of the tensile force acting on specimen E2 during testing.

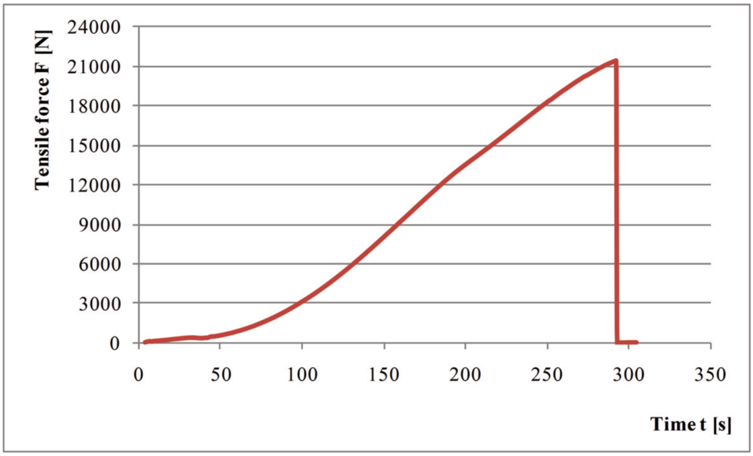

Figure 12. Tensile force characteristic of specimen E2 as a function of time [op. cit.]

The results obtained during the strength tests of specimen E4 are presented graphically as the characteristics of tensile stress as a function of linear strain (Figure 13).

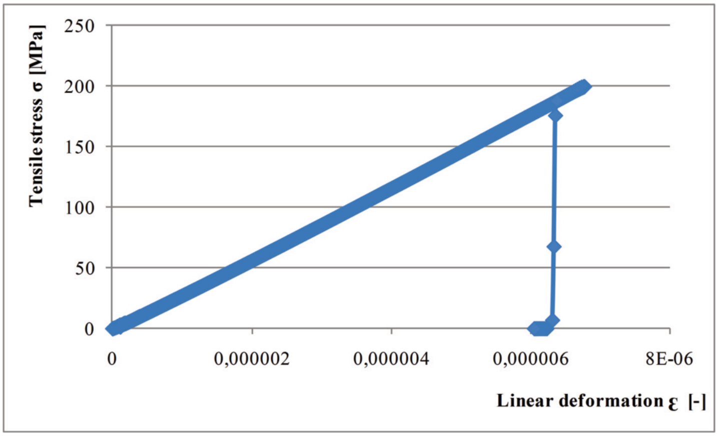

Figure 13. Characteristics of tensile stresses as a function of linear deformation for specimen E4 [op. cit.]

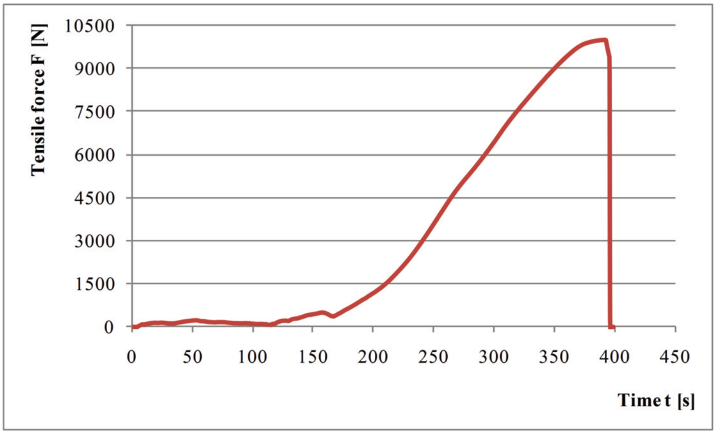

Figure 14. Tensile force characteristic of specimen E4 as a function of time [op. cit.]

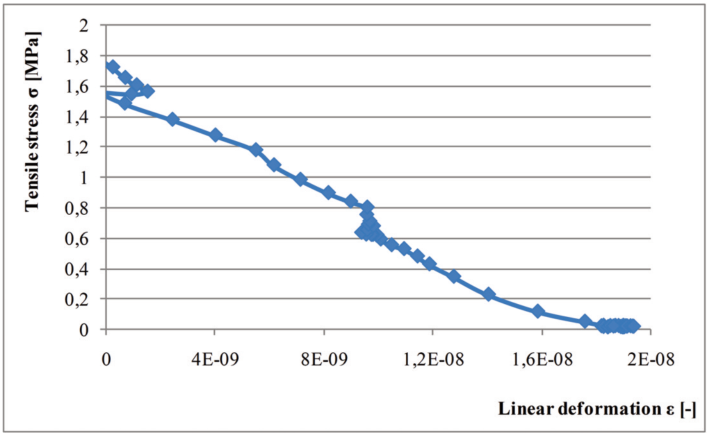

Figure 15. Characteristics of tensile stresses as a function of linear deformation for specimen E5 [op. cit.]

The sudden drop in force observed at the end of the tensile test indicates the delamination of the individual laminate layers.

The course of the force acting on specimen E4 during the static tensile test is shown in Figure 14.

Figure 15 shows a tensile plot of specimen E5 made from the data obtained during the strength tests.

Difficulties with readings of the stress parameter as a function of linear deformation are related to damage to the strain gauge systems of specimen E5.

The tensile force waveform recorded during testing of specimen E5 is shown in Figure 16.

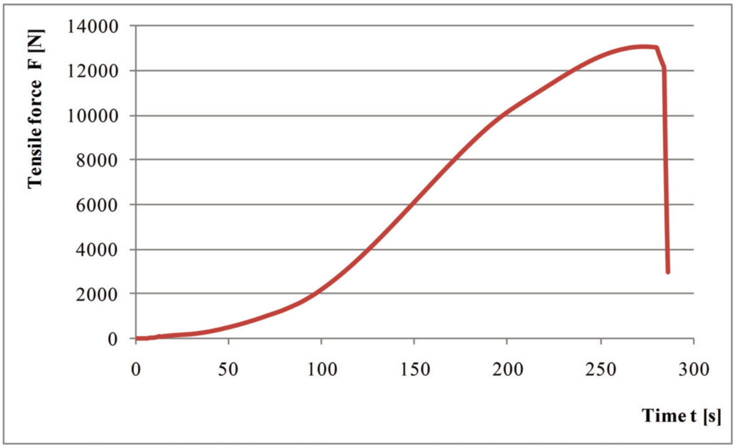

Figure 16. Tensile force characteristic of specimen E5 as a function of time [op. cit.]

Tensile testing is commonly used for selecting a material for application, quality control and predicting how a material will react to different types of forces. The ASTM standard carefully regulates the exact procedure for tensile testing. This test method enables the determination of the in-plane tensile properties of polymer matrix composite materials reinforced with high-modulus fibres. The forms of composite materials are limited to composites reinforced with continuous or discontinuous fibres, in which the laminate is balanced and symmetrical with respect to the test direction.

This test method has been developed to obtain tensile property data for material specifications, research and development, quality assurance and structural design and analysis. Factors influencing the tensile response and therefore requiring reporting are: material, material preparation and placement methods, specimen placement sequence, specimen preparation, specimen conditioning, test environment, specimen placement and gripping, test speed, time at temperature, void content and volume percentage of reinforcement. Properties that can be obtained from this test method are tensile strength, tensile strain, tensile modulus of chord, Poisson’s ratio and transient strain.

ASTM D3039 is specific to particle- or short-fibre-reinforced plastics and is one of the most basic tests used to characterise, qualify and certify the tensile properties of these materials. However, a wide range of other tests are required to fully characterise the many different mechanical properties of anisotropic and heterogeneous composite materials.

5. SUMMARY AND CONCLUSIONS

Composite products are successfully used in various fields of industry and technology. The properties they obtain often significantly exceed the parameters characterising classical materials. A special feature of composites is the ability to shape their structure in order to obtain the expected properties. In order to ensure the wide use of composites in modern technology, they must be subjected to a wide range of requirements concerning their functional properties. Tensile tests are used to demonstrate some of the most important mechanical properties of laminates.

Tensile tests were performed in accordance with the ASTM standard. Only D-series specimens and E-series specimens were tested. The C-series specimens experienced problems with the static tensile test. The test specimens were fabricated by hand lamination using MGS L285/H285 epoxy resin. The laminates produced in this way differ in the type of reinforcement for each series. Interglass 02037 symmetrical fabric with a 0/90 weave was used to reinforce the D-series composite specimens, while IMS65 modular fabric with a 45 twill pattern was used for the E-series specimens.

The static tensile test of the laminates was carried out on an Instron model ZWICK Z100 testing machine. In connection with the tensile test, parameters such as maximum tensile force and tensile strength limit were obtained. The averaged tensile test results for individual specimens are shown in Table 9.

Table 9. Averaged results of strength tests [op. cit.]

Parameter	**D-series**	**E-series**
Maximum tensile force Fm [kN]	28.056	15.734
Tensile strength limit Rm [MPa]	561.116	314.677

Based on the test results obtained, it can be concluded that the lowest averaged values of maximum tensile force and ultimate tensile strength are characterised by the E-series. The values of these parameters are 15.734 kN and 314.677 MPa, respectively. It is worth noting that during the tensile tests, the D-series obtained almost twice as high results as the E-series. The average value of the maximum tensile force of the D-series is 28.056 kN, while the average value of the limit tensile strength is at the level of 561.116 MPa.

Figure 17 compares the course of tensile stress in relation to the corresponding linear strain for specimens D2, D5, D6, E1 and E4. Samples D1, D3, D4, E2 and E5 showed irregularities and difficulties in the readings of the tested parameters due to damaged measuring systems and peeling off of the strain gauges.

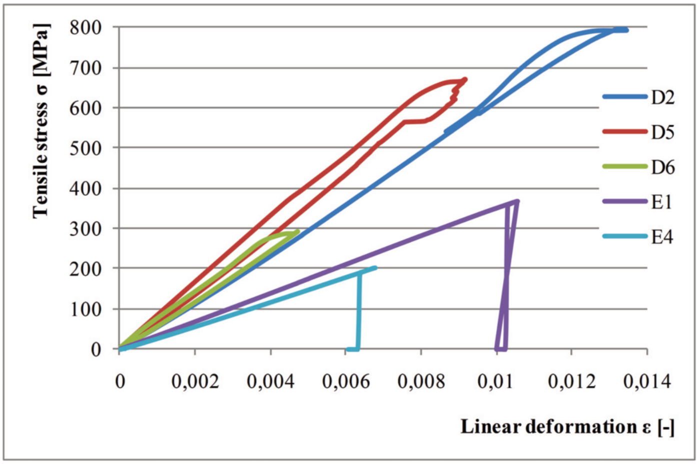

Figure 17. Comparative characteristics of tensile stresses as a function of deformation linear deformation [op. cit.]

Figure 18 shows the course of the tensile force acting on the individual laminates during the tensile test of specimens D2, D5, D6, E1 and E4.

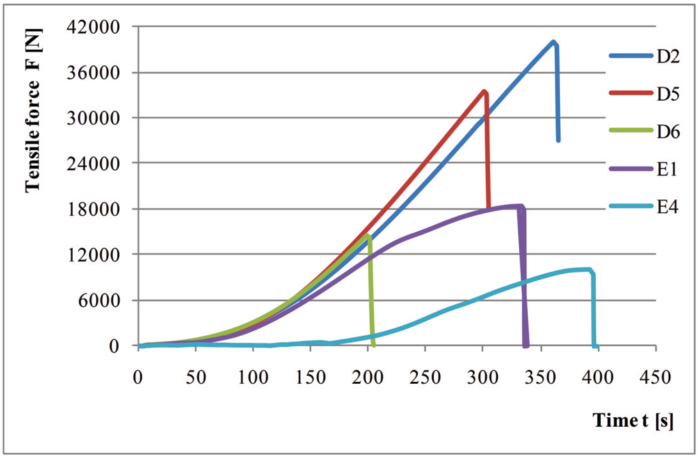

Figure 18. Comparative characteristics of tensile force as a function of time [op. cit.]

For E-series specimens, there is a sharp drop in strength at the end of the test, indicating delamination of the individual layers of material. D-series specimens, on the contrary, show a linear increase in the stress-strain relationship, indicating that the material behaves as a brittle material during tensile testing. The research was used to investigate new materials used in the gyrocopter's support structure.

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