TOMSK POLYTECHNIC UNIVERSITY
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Министерство науки и высшего образования Российской Федерации
федеральное государственное автономное
образовательное учреждение высшего образования
«Национальный исследовательский Томский политехнический университет» (ТПУ)

School Engineering school of novel manufacturing technologies
Specialization Material science and technology of materials
School division Division for materials science

Master thesis

Research subject
Investigation of SWCNT addition on the fracture toughness of hybrid carbon fiber reinforced polymers (Исследование влияния углеродных нанотрубок на трещинностойкость углепластиков)

UDK: 678.5.067:620.19

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Group	Name	Signature	Date
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ADMIT THESIS FOR DEFENSE:

Head of study plan	Name	Degree	Signature	Date
Material science and technology of materials	Panin S.V.	PhD		

Tomsk – 2021

Expected learning outcomes on 22.04.01 Materials Science and Technology of Materials (MSc)

Code of result	The result of study
P1	Осуществлять сбор и критический анализ информации, включая научные публикации, патенты, маркетинговые исследования в области материаловедения и технологии материалов
P2	Управлять научно-исследовательским и производственным проектом, включая критический анализ проблемных ситуаций, оценки потенциала коллектива и самооценки
P3	Способен представлять и защищать результаты своей работы и деятельности коллектива, включая планы научно-исследовательских работ, производственных проектов, научные публикации и доклады с использованием современных коммуникативных технологий, в том числе на иностранном языке.
P4	Руководить коллективом в сфере своей профессиональной деятельности, толерантно воспринимая социальные, этнические, конфессиональные и культурные различия
P5	Ориентироваться в современных технологиях новых материалов с учетом экономичности, требований готовой продукции и интеллектуального потенциала предприятия, производства или научной группы
P6	Внедрять в производство технологии получения керамических, металлических наноматериалов и изделий, включая эксплуатацию соответствующего оборудования.
P7	Эксплуатировать оборудование и обрабатывать экспериментальные результаты с целью изучения структуры и свойств материалов, диагностики их эксплуатационных характеристик
P8	Разрабатывать новые и модернизировать существующие технологии получения керамических, металлических материалов и изделий, в том числе наноматериалов

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School Engineering school of novel manufacturing technologies
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APPROVED:
Head of study plan
_______ S.V. Panin
(signature) (date)

TASK
for research work of master degree

Type of work:

Master thesis

Student:

Group	Name
4BM9I	Abdullah bin Firoz

Topic of the work:

Investigation of SWCNT addition on the fracture toughness of hybrid carbon fiber reinforced polymers	
Approved by the Director of School of NMTУ	Order №62-46c 03.03.2021

Completion date for the work:	

TECHNICAL TASK:

Initial data for work	Carbon fiber fabrics, epoxy binder and dry single wall carbon nanotubes. Testing standards for fracture toughness evaluation. Testing machines, personal computers for data capturing and analysis. Scientific papers on the subject.

The list of task for research, design and development	Perform an analytic review on following subjects: composite materials, their properties and manufacturing technologies; investigation of fracture toughness of laminate composites. Prepare initial and modified my SWCNT CFRP blanks. Establish the sizes of the specimens for Mode I and II fracture toughness testing. Cut specimens and prepare loading blocks. Test specimens according to ASTM standards recording the deformation data: load and extension. Process the data to obtain the fracture toughness values. Analyze the impact of SWCNT on fracture toughness of carbon fiber reinforced polymers.
List of graphic material	

Advisers on sections of the work

Раздел	Консультант
Financial management, resource efficiency and resource saving	*Menshikova E.V., Associate professor*
Social responsibility	*Antonevich O.A., Associate professor*
Research technique and results	*Burkov M.V., Associate professor*

The section titles, which must be written in Russian and foreign languages:

All section must be written in English

Completion date on a calendar plan:	

Task is issued by scientific adviser:

Position	Name	Degree	Signature	Date
Associate professor	Burkov M.V.	PhD		

Task is accepted by student:

Group	Name	Signature	Date
4BM9I	Abdullah bin Firoz		

Abbreviations and definitions

ILFT	Interlaminar fracture toughness
CNT	Carbon nanotubes
SWCNT	Single-wall carbon nanotubes
DWCNT	Double-wall carbon nanotubes
PEI	Poly ether imide
PBT	Poly butylene terephthalate
MWCNT	Multi-walled carbon nanotubes
G_{IC}	Mode I strain energy release rate
G_{IIC}	Mode II strain energy release rate
ASTM	Society for testing and materials
ENF	End notched flexure
DCB	Double cantilever beam
CNC	Computer numerical control
PAN	Polyacrylonitrile
CF	Carbon fibers
FC-CNT	Face centered carbon nanotubes
CVD	Chemical vapor deposition
PC	Pre-cracked
NPC	Non pre-cracked
MBT	Modified beam theory
MCC	Modified calibration calculation/calibration
CC	Calculation/calibration compliance

Abstract

Master thesis consists of 85 p., 34 fig., 31 tables, 39 references, 1 appendix.

Keywords: CFRP, CNTs, Hybrid composites, Fracture toughness, Delamination

Subject of research: investigation the fracture toughness of carbon fiber reinforced polymers hybridized with single-wall carbon nanotubes.

Aim of study: investigate Mode I and II fracture toughness of carbon fiber reinforced polymers and analyze the impact of single wall carbon nanotubes on improvement of delamination resistance

During the research the following has been done: literature review of CFRP and CNTs, their manufacturing methods, and approaches for improvement of the fracture toughness. Using raw materials the blanks of non-modified CFRPs and modified by CNTs were manufactured. The standards for both Mode I & II interlaminar fracture toughness testing were analyzed and the technique for performing the test was established. The specimens were prepared and tested. After performing the tests the data was processed and fracture toughness values were calculated. After the analysis of the results obtained the strengthening mechanisms were discussed and the conclusions on effectiveness of the technique for preparation of modified hybrid composites were made.

Main technological, technical and operational parameters: the fracture toughness Mode I and II of non-modified CFRP were estimated as 909 and 600 J/m^2 correspondingly. Tensile and flexural strength are 682 and 649 MPa, correspondingly.

After the research the following results were obtained: it was found that Mode I fracture toughness decreased with increasing the concentration from 0.1-0.5 wt% of CNT by 25.7% but it remain consistent for 0.1 wt% of CNT. Mode II fracture toughness was seen to be improved by 17.7% for 0.1 wt% of CNT and by 36% for

0.5 wt% of CNT which is the highest result. When analyzing other mechanical properties like tensile and flexural behavior it is shown that SWCNTs improve the strength within the range of 4-14%. It is concluded that SWCNT have a positive effect on mechanical properties in wide range of SWCNT content but if the Mode I fracture toughness is important the SWCNT content is limited to 0.1 wt%.

The degree of implementation: the technique for CFRP preparation is a laboratory type. In order to use it in manufacturing is should be redesigned for a larger manufacturing equipment.

Application area for results: the results obtained in the present work can be utilized by engineers involved in designing of structures based on CFRPs. The positive influence of SWCNT on mechanical properties can reduce the weight of the structures while saving the same load bearing capacity and safety.

Cost-effectiveness/value of work: One of the demanded applications of CFRP is aerospace industry and using of the composites with better mechanical properties allow reducing weight and improving fuel economy.

Future plans: investigation of CFRPs based on thermoplastic binder with nanoscale additives.

Contents

Introduction

Composite materials are made up of two or more distinct constituent materials that together form a product with different characteristics than that of their individual components. Fiber reinforced polymers (FRPs) are based on polymer matrices and high performance fibers. They are unique in a way that they can offer superior mechanical properties and are much lighter than typical metals and alloys. This makes them very valuable for industries such as the aerospace industry. Aircrafts that are constructed using carbon-fiber composite are more lightweight and burn less amount of fuel allowing to save funds and reduce emissions making them more environmentally friendly. Although fiber reinforced composites exhibit excellent in-plane properties, they are highly vulnerable to out of plane impacts due to the onset of delamination. In composites, the strength is heavily reduced due to delamination between plies. Delamination induced failure is normally a result of a combination of compressive and bending stresses caused by the delamination plies as they buckle out of plane. The resistance to delamination growth depends on interlaminar toughness of the composite material. In a common FRP these properties are defined by the binder and its adhesion to the fibers. One of the approaches allowing to improve the fracture toughness is associated with the use of nanoparticels as a secondary reinforcement. The resulting composites can be classified as “hybrid composites”.

In this research CFRPs hybridized with SWCNTs with different content from 0.1-0.5 wt% were manufactured and tested. Mode I & Mode II interlaminar fracture toughness were obtained and analyzed. In addition with the results of different mechanical properties assessment the strengthening mechanisms were analyzed in order to evaluate the effectiveness of the proposed hybrid composite manufacturing technique.

1 Literature Review

1.1 Carbon Fiber Composites: Properties and Manufacturing Methods

CFRPs are composite engineered materials consisting of carbon fibers (CFs) as reinforcements and an organic epoxy resin as a matrix, a combination that renders the materials extremely strong but also lightweight. These features, along with their unique electrical conductivity, thermal stability, good resistance to corrosion, and high rigidity, have led to CFRPs being widely used in the aerospace, vehicle, wind power generation, and construction industries since the 1970s.

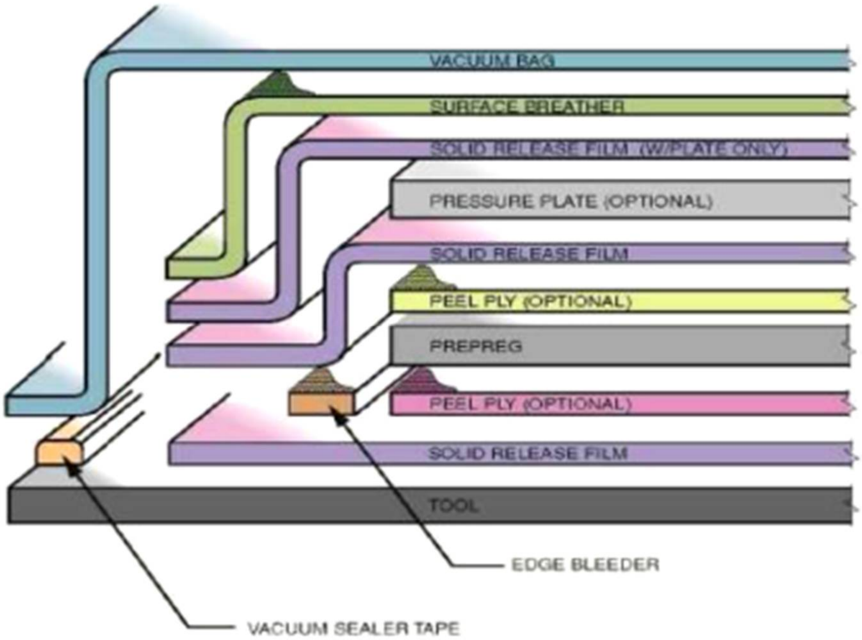

Figure 1. Typical prepreg laminate layup/ bagging [1]

There are a number of different manufacturing techniques used to produce high quality carbon fiber composites. One of the more commonly used methods involves the use of prepreg fibers to construct a laminate. Prepreg fibers are sheets of carbon fiber that contain the matrix material prior to curing (Figure 1). Prepregs are commonly cured using an autoclave oven to ensure that the high temperature and pressure conditions are uniform throughout the curing process. One drawback of this method is that autoclaves are very expensive to operate and most carbon fiber composites require long curing cycles. For flat parts, a heat press can also be used for curing of prepegs. It is important that air is not trapped in between piles of the laminate before it is cured in order to avoid the formation of voids, or air pockets, in the cured composite. Prepegs fibers must be kept refrigerated before they are cured or else the resin will expire.

Other method of manufacturing carbon fiber composites involves liquid of resin while the laminated is being heated. Resin Transfer Molding (RTM) is a technique that involves placing dry fibers into an old and infusing them with the resin by application of pressure.

Vacuum Assisted Resin Transfer Molding (VARTM) is a modified version of RTM that is becoming more popular as a liquid resin infusion due to its low cost of manufacturing and versatility in parts can be made. VARTM uses the vacuum pressure to draw the resin in, while the laminate is being heated. The piles are pressed against one side of a mold before curing takes place and are held under vacuum pressure while curing. Though this method is cheaper than prepreg methods, but it does not match the quality parts of that an autoclave and prepreg create [2]

1.2 Failure Modes of Composites

When metals are subjected to high levels of stress, they deform elastically until reaching their elastic limit. Metals undergo permanent deformation. Deformation distributes the stress before fracture. Unlike metals, carbon fiber composites are not ductile, so they don’t go under plastic deformation. CFRP are anisotropic materials, and their mechanical properties behave differently depending on the direction. They also have a number of different possible failure modes, making it difficult to accurately define a failure criterion. The primary modes of failure in a composite laminate are fiber buckling, fiber breakage, matrix cracking, and delamination as shown in Figure 2 [3].

Fiber buckling is the most common failure mode when a composite is loaded under compression in the fiber direction [4]. Buckling does not always result in failure of the composite because the fibers are supported by the matrix [3]. The compressive strength lost die to fiber buckling is dependent on the properties of the fiber as well as matrix.

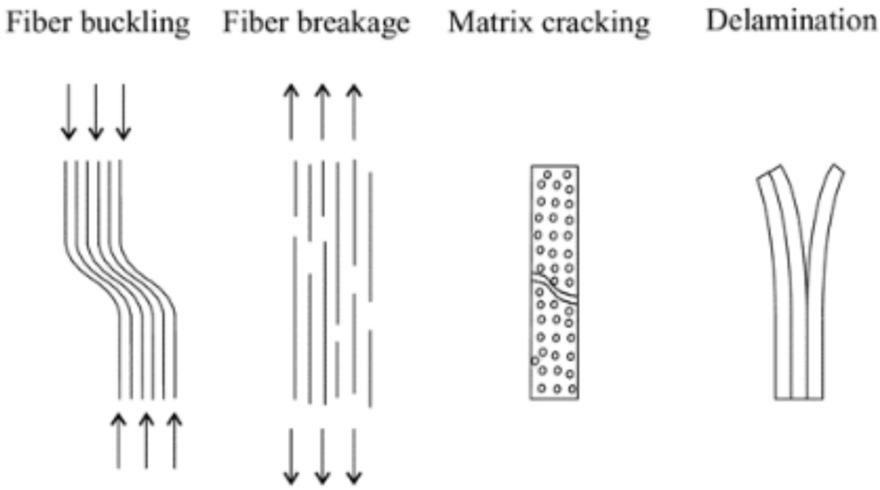

Figure 2. Failure modes of Composites [3]

Fiber breakage is when some of the fibers in the laminate break, resulting in them no longer being able to carry tensile load. Fiber breakage is caused by low velocity impacts which induce shear force and high bending stresses [5]. When fibers in composites break, the load that the broken fibers were carrying is distributed to adjacent fibers through the matrix. This process is called fiber bridging, and allows for the fibers to carry more load than they could if they were not embedded in a matrix [3].

Matrix cracking is first damage mode that occurs, and it is most common in composites. The most serious damage that can occur from cracking is the initiation of delamination.

Delamination is critical mode in composites. It is caused by high interlaminar stresses with the very low through-thickness strength. This happens because fibers lying in the plane of a laminate do not provide reinforcement through the thickness, and so the composite relies on the relatively weak matrix to carry loads in that direction. This is compounded by the fact that matrix resins are brittle [6].

In-plane failure of composites is driven by energy released as fibers are unloaded. This happens in two: by fracture of the fibers, or by delamination and matrix cracks together sum up to produce a fracture surface, without breaking fibers. Figure 3 shows laminate that has failed in tension by pull-out failure. Specimens with continuous fibers comes under load the delamination can still produce large reduction in strength, also when plies of the same orientation are placed together.

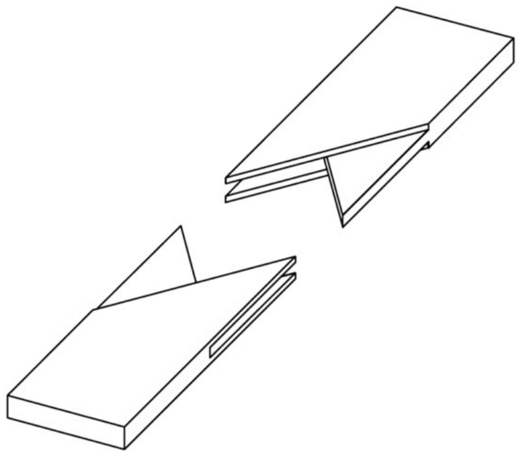

Figure 3. Schematic of pull-out failure of (45/-45) laminate with no fiber fracture

1.3 Hybrid Composites

Lightweight design is becoming important in various industries, mostly in aerospace, wind energy and automotive applications. Fiber-reinforced composites are attracting more interest for these weight-sensitive applications as their t stiffness and strength are combined with a low density. But, the high stiffness and strength of these composites are having limited toughness. Like most materials, fiber-reinforced composites also face the strength versus toughness perplexity. So with drawback of toughening strategies and the need of material, which is light weight, with good toughness, hybridization helps to overcome these drawbacks. The term hybridization is generally used to describe a matrix containing at least two types of reinforcements. The need of improving the properties of CFRP can be done by hybridizing with carbon Nanotubes (CNT) [7]. CNTs were first described by Ijima in 1991 [8], and since their discovery, they have generated much interest in the fields of physics, chemistry, materials science, and engineering. CNTs are chosen as reinforcement for improving the properties of CFRP because of their own extraordinary mechanical and physical properties. Also CNT posse's good thermal properties such as thermal conductivity and thermal stability [7].

Carbon Nanotubes are long cylinders composed of carbon atoms that have excellent mechanical, electrical, and thermal properties. CNTs have been identified as excellent reinforcements to FRP laminates due to their very high surface are to volume ratio. There are lots of method to incorporate CNTs into fiber, interleaving methods, spraying methods and others. An approach to CFRP hybridization with long and continuous CNT fibers is proposed [9]. CNTs are of low density and excellent mechanical properties also good thermal stability. So they can be used as a potential hybridization with carbon fiber reinforced composites. In hybrid composite structures, it has been shown that CNTs can be grown onto the surface of carbon fiber, introduced through sizing agent. The tensile test for the hybridized CFRP with aligned FC-CNT and CNT films, for double notched hybrid specimen showed 9% increase in failure stress without affecting the composite stiffness [9]. The increase in the strain failure was reported 15%. This concludes that addition of CNT fiber results in toughening effect.

CFRP are mainly used in civil aviation industry for manufacturing parts of airplane, fuselage is the principal structure, due to electrical leakage in the cables and wires, a large potential difference is created which leads to localized heating of these structures, and this can be reduced by addition of CFRPs which is electrically insulating. The integration of Nano fillers, in particular carbon nanotubes (CNTs), in the polymer resin or at the fiber/matrix interface, can improve the overall electrical resistance of the material [10]. One of the methods to introduce CNTs to carbon fiber is through CVD (chemical vapor deposition). Also specimens are coated with silver layer on top and bottom surfaces. Following with test which takes place in the assembly composed of the sample that is positioned between two electrodes made up of polished copper plates. So this experiment results show that there is significant impact of adding CNTs on the conductivity. The electrical conductivity in the direction of thickness was reported with and without CNT samples as σ_{TH}=1.0

(±0.25) , σ_{TH}=0.016 (±0.3×10^{-3}) respectively. The difference between electrical conductivity can be seen and also a significant impact of adding CNTs [10].

There are various types of CNTs, like single-wall CNTs (SWCNT), double-wall CNTs (DWCNT) or multi-wall CNTs (MWCNTs). Each type of nanocomposites produced exhibit enhanced strength and stiffness also it increases fracture toughness. The surface of nanotubes provides a good surface stress transfer, but also has strong attractive forces between themselves, leading to agglomeration nature. The specific surface area (SSA) which is diameter dependent, SWCNTs have the largest aspect ratio compared to CNTs consisting of multiple layers, so this can be reduced SNWCTs forms aggregates of bonded and aligned CNT bundles called Nano-ropes. These ropes consist of hundreds of individual tubes that are difficult to separate. Liao et al [10] found the influence of SWCNTs on the thermo-mechanical properties of epoxy based nanocomposites. These composites were produced by using sonication. It is the most commonly used method. Relative improve in mechanical properties was observed. A correlation was found in between provided surface area and dispersibility. It turned out to be more difficult, the larger the SSA of CNT. So functionalization with amino-groups improved the dispersibility and improved reagglomeration [11]. The most significant improvements of strength (+10%), stiffness (+15%), and fracture toughness by (+43%) were obtained with amino-functionalised DWCNTs at 0.5wt% filler content [11].

1.4 Improving Interlaminar Fracture Toughness

Various researchers have explored wide range of methods to improve interlaminar fracture toughness (ILFT) of fiber reinforced polymers composites. The toughness of a material is ability of the material to absorb energy before fracture, and interlaminar fracture toughness describes the energy needed to propagate a crack in the interface of matrix surface of composites. The ILFT values for composites are important because they show the resistant properties to delamination. Method such as modifying the surface geometry of the composite, stitching, and z-pinning are available though they show negative effects on in-plane mechanical properties [12, 13]. Stitching in the interlayer can act as a grain boundary by hindering the crack propagation, these solutions does not definitely stop the fracture, but they do help to stop crack growth. So surface treatment of interface has shown influence to ILFT significantly.

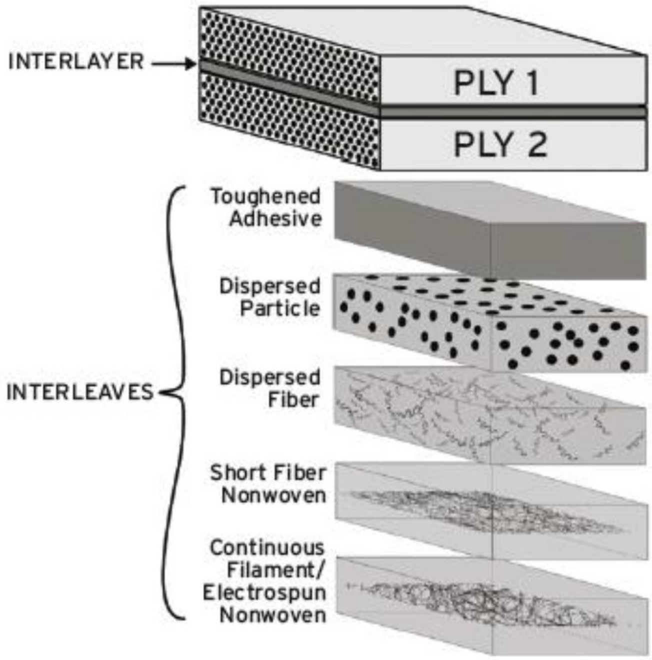

Figure 4. Types of interlayer toughening material [14]

A study showed that the individual inclusion of up to 1.5 wt% of three types of thermoplastics, poly (ether imide) (PEI), polycarbonate, and poly (butylene terephthalate) (PBT), increased the impact strength of epoxy/fiber composites [15]. The study also showed evidence that the PEI and polycarbonate thermoplastics helped prevent micro-cracking in the composites. Inclusions of thermoplastics in an epoxy matrix have also shown to increase the mode I strain energy release rate of fiber reinforced composites [16].

Another method of increasing interest involves the interleaving of toughening material in between the plies of fiber composites. Interleaving methods are advantageous because they do not affect the properties of the matrix, however the choice of toughening material is crucial because it must be compatible with the matrix. Ideally, the interleaf will not add much weight and thickness to the composite. Figure 4 shows the types of interlayer toughening materials. A study investigated pristine and functionalized SWCNTs effect on mode I ILFT in woven in woven composites [17]. Two different solutions were mixed with ethanol and sprayed onto carbon fiber plies before VARTM process was used to cure the laminates. This study found out both types of SWCNTs had little effect on the G_{IC} in the beginning; however the samples containing functionalized CNTs showed more stable crack growth.

CNTs have been investigated for using it as material to strengthen composites against impact forces. A study was performed which used the CNTs in dispersed form in epoxy matrix to increase the residual compressive strength and mode II ILFT in woven fiber composites [18]. This study found the incorporation of CNTs was successful in increasing the residual compressive strength and mode II ILFT

2 Materials and technique

2.1 Carbon fiber reinforced polymers specification and manufacturing technique

CFRP blanks were prepared by the method of hand lay-up of dry fabrics and impregnation of modified binder with subsequent hot press molding. The layup was balanced and unidirectional $[0]_{10s}$. CBX300 biaxial fabrics made up of PAN carbon fiber Mitshubishi Pyrofil TR505 12K was used along with R&G Epoxy L and GL2 hardener (Figure 5) to prepare blanks. SWCNTs used as secondary reinforcement were TUBALL™ (Figure 6), having mean diameter of 1.6±0.4 nm and length of >5 µm. Four different types of specimens were made with different concentration (0.1, 0.2, 0.3, 0.5 wt %) and non-modified CFRP blank was manufactured providing the baseline data. All specimens were manufactured with a preimplanted non-adhesive Teflon film insert.

a b

Figure 5. Raw materials: (a) epoxy resin L and GL2 hardener; (b) dry carbon fabrics

The modified epoxy preparation procedure includes the following steps. Firstly the additives were put into the GL2 hardener and mixed for 30 minutes. During the mixing temperature inevitably rises to 40-50°C but there is no necessity for cooling. This increase in temperature reduces the viscosity, which result in more homogeneous SWCNTs distribution. Second step is mixing the hardener with epoxy resin after it was cooled down at room temperature. To reduce the overheating and uncontrolled binder curing the tank was immersed in cold water. High rotation velocities and long mixing will result in ultimately curing, and this process should be controlled with attention.

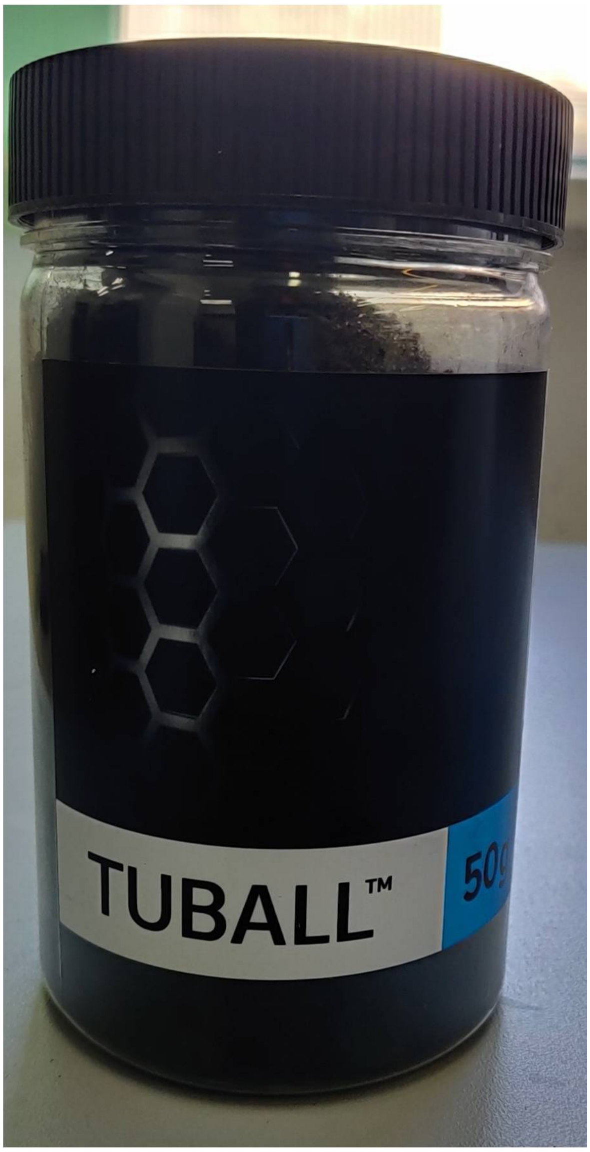

Figure 6. SWCNT TUBALL

Blank manufacturing involved hand lay-up and impregnation thus the amount of prepared epoxy binder was much higher than it was needed for a composite with 70/30 fiber to-binder ratio predicted to be obtained after hot press molding. After the preparation of the layup the stack was placed between the thermal press Gotech 7014 (Figure 7) and subjected to the pressure of 0.7MPa and temperature of 70°C. The dwell time was 2 hours. During pressing the excess of binder was removed to the breather ply perpendicularly to the lay-up and to the sides where the additional absorbing fabrics was placed. In addition, it was found that in the specimen modified with SWCNTs the binder excess absorbed by the side breather was free of SWCNT that is a result of the filtering phenomena described in the literature [19–22].

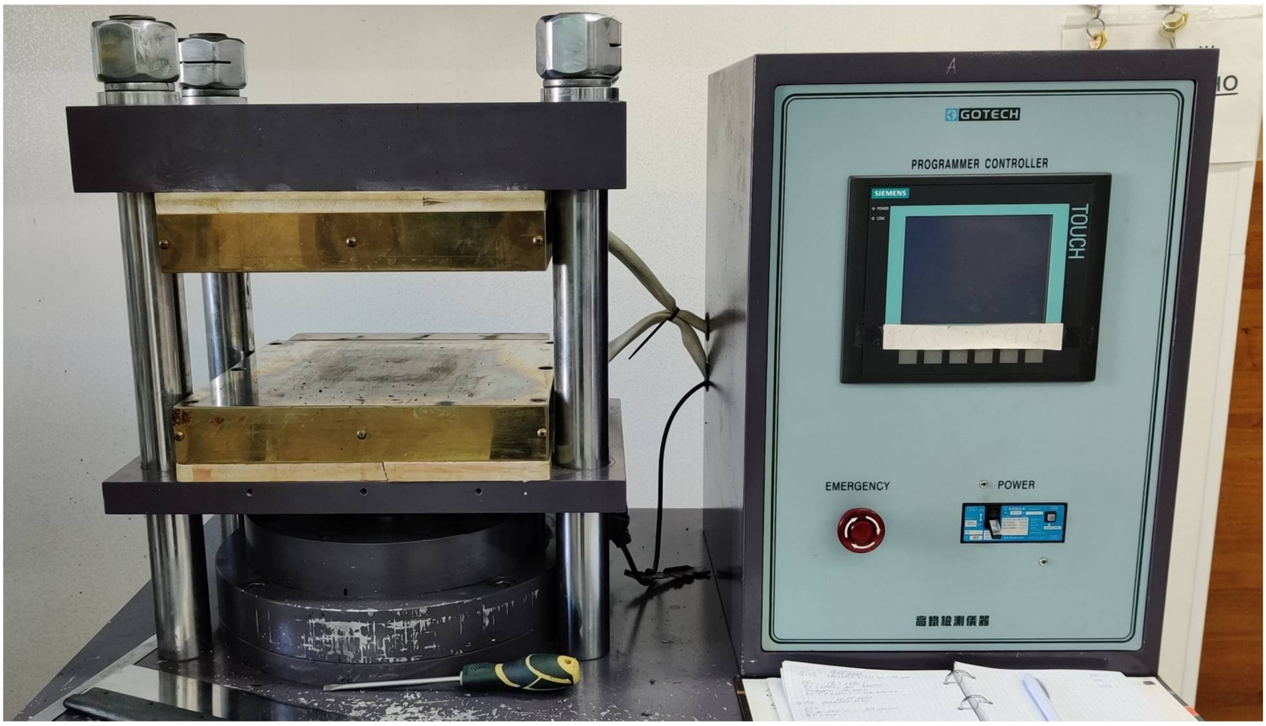

Figure 7. Thermal press Gotech 7014

After hot pressing the preliminary cured stack was taken off, the release films and breather were removed, and the blank was put into the heating chamber with a temperature of 70°C for 24 hour to finalize all curing process. The example of the resulting blank can be seen in Figure 8. After the post-curing, the blanks were cut on a CNC milling machine with water-cooling to obtain the specimens for testing described below.

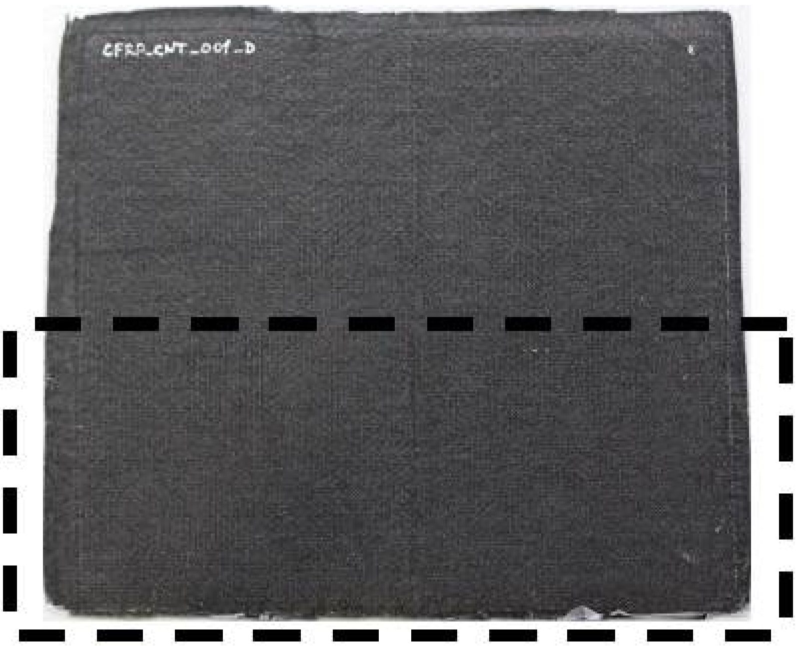

Figure 8. Manufactured CFRP blank. Dashed area shows the position of the Teflon insert

2.2 Double Cantilever Beam Testing Technique (Fracture Toughness Mode I)

The double cantilever beam (DCB) is utilized in this research and is used to determine the ILFT of composite under the opening failure mode, of continuous fiber-reinforced composites material using DCB specimen [23].

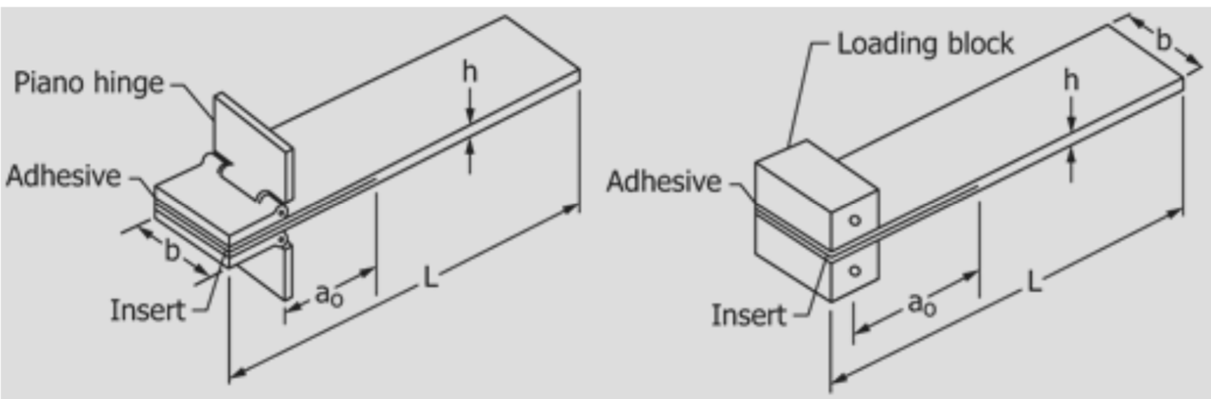

Figure 9. DCB test specimen bonded with piano hinges and loading blocks [23]

The DCB test involves the propagation of a pre-crack in the mid-plane of a composite laminate and uses the force vs displacement data along the crack length to determine the mode I ILFT, also known as G_{IC}. This test method has great significance, it can be used to compare quantitatively the relative values of G_{IC} for composite materials with different constituents, and it can be used to develop delamination failure criteria for composite damage tolerance and durability analyses. Opening forces are applied to two hinges bonded to the surface of the composite, resulting in crack propagation. Figure 9 shows a sketch of mode I specimen bonded with piano hinges and loading blocks.

There are three different methods for calculating G_{IC}, the modified beam theory method, the compliance calculation, and the modified compliance calculation method. The G_{IC_VIS} at initiation is taken as the first calculated G_{IC} value where fracture first occurs from the pre-crack, and the G_{IC} propagation is the average of all other G_{IC} values calculated during DCB test. The test procedure is defined in ASTM D5528-13 [23] and all the procedure was followed to perform the DCB test.

2.3 End Notched Flexure Testing Technique (Fracture Toughness Mode II)

The end notched flexure (ENF) test is utilized in this research and is used to calculate the mode II ILFT (G_{IIC}) in composites for the shear failure mode. This method is similar to the DCB test, and it is used for unidirectional fiber-reinforced polymer matrix composites [24].

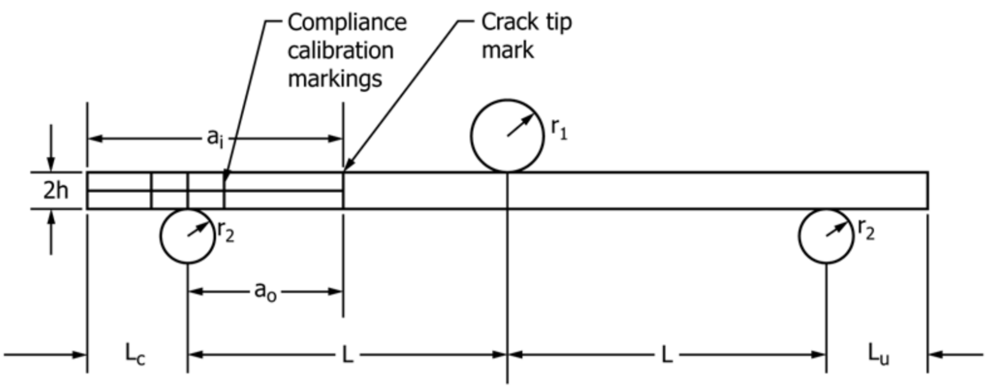

Figure 10. ENF specimen, fixture, and dimensions [24]

The G_{IIC} values that are calculated during the ENF test represent the critical value of strain energy rate for delamination to grow. The fracture is due to an in-plane shear force that is perpendicular to the initial delamination. The test is performed to find G_{IIC} at insert, called initiation, and the G_{IC} at propagation. The test is performed on rectangular specimens made with a non-adhesive insert in the mid-plane to initiate delamination. Compressive force is applied in the out of plane direction to initiate delamination, and the force displacement curves are recorded. G_{IIC} is obtained for both non-precracked and pre-cracked specimens, based on maximum load point. The sketch can be seen in Figure 10. The test procedure is defined in ASTM D7905/7905M [24] and all the procedure was followed to perform the ENF test. The test involves 3 point flexural testing of the specimen with a delamination.

2.4 Mechanical properties of CFRPs

The results of testing of different mechanical properties of hybrid CFRPs modified by the addition of SWCNT are reported in [XX]. It is concluded that SWCNT addition allowed improving different mechanical and physical properties. Below there is data on static tensile strength (Table 1, Figure 11) and flexural strength (Table 2, Figure 12) [25]. Single-wall CNTs provide a significant impact on static strength reaching 9% improvement for 0.3wt% of CNTs (Figure 11).

Table 1. Results of tensile testing.

Material	Tensile strength, MPa		Elastic modulus, GPa		Strain at break, %	
NM CFRP	682±13	+0.0%	58.8±0.2	+0.0%	1.20±0.05	+0.0%
0.1 wt% CNT	706±18	+3.5%	58.5±1.4	-0.5%	1.25±0.05	+3.6%
0.2 wt% CNT	732±13	+7.3%	57.9±1.2	-1.5%	1.29±0.03	+7.4%
0.3 wt% CNT	741±31	+8.6%	55.7±1.9	-5.2%	1.32±0.06	+9.3%
0.5 wt% CNT	735±27	+7.8%	54.1±2.8	-8.0%	1.33±0.02	+10.7%

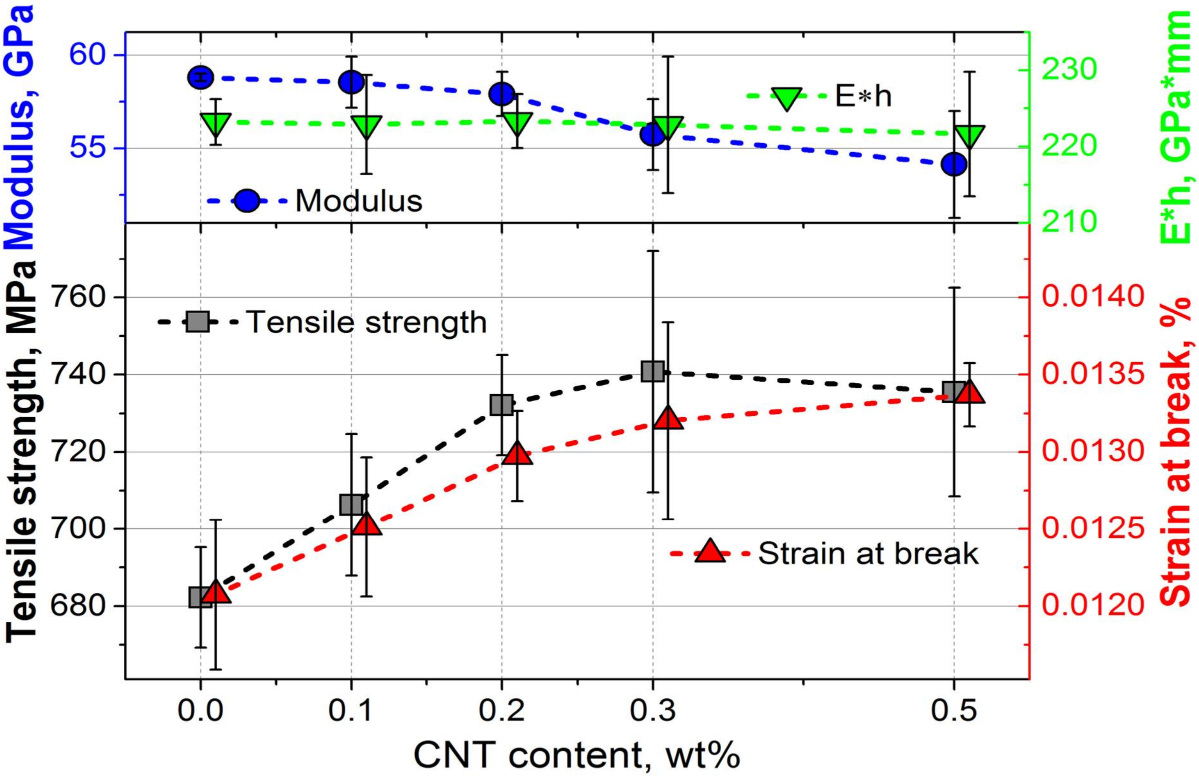

Figure 11. Results of tensile testing of CNT specimens

The flexural properties obtained for CNT specimens are similar to the tensile ones. Flexural modulus demonstrates a slight decrease while strength and strain at break increase non-linearly. The results of flexural testing are summarized in Table 2. The highest improvement of flexural strength is achieved for 0.3 and 0.5 wt% of CNTs reaching ~14%.

Table 2. Results of flexural testing.

Material	Flexural strength, MPa		Flexural modulus, GPa		Strain at break, %	
NM CFRP	649±34	+0.0%	53.5±2.1	+0.0%	1.30±0.1	+0.0%
0.1 wt% CNT	693±42	+6.7%	51.8±0.7	-3.1%	1.48±0.03	+13.4%
0.2 wt% CNT	714±26	+10.0%	52.8±3.5	-2.4%	1.47±0.13	+12.8%
0.3 wt% CNT	740±41	+14.0%	52.2±3.4	-2.5%	1.55±0.14	+19.2%
0.5 wt% CNT	742±16	+14.3%	50.6±2.5	-5.4%	1.59±0.16	+22.0%

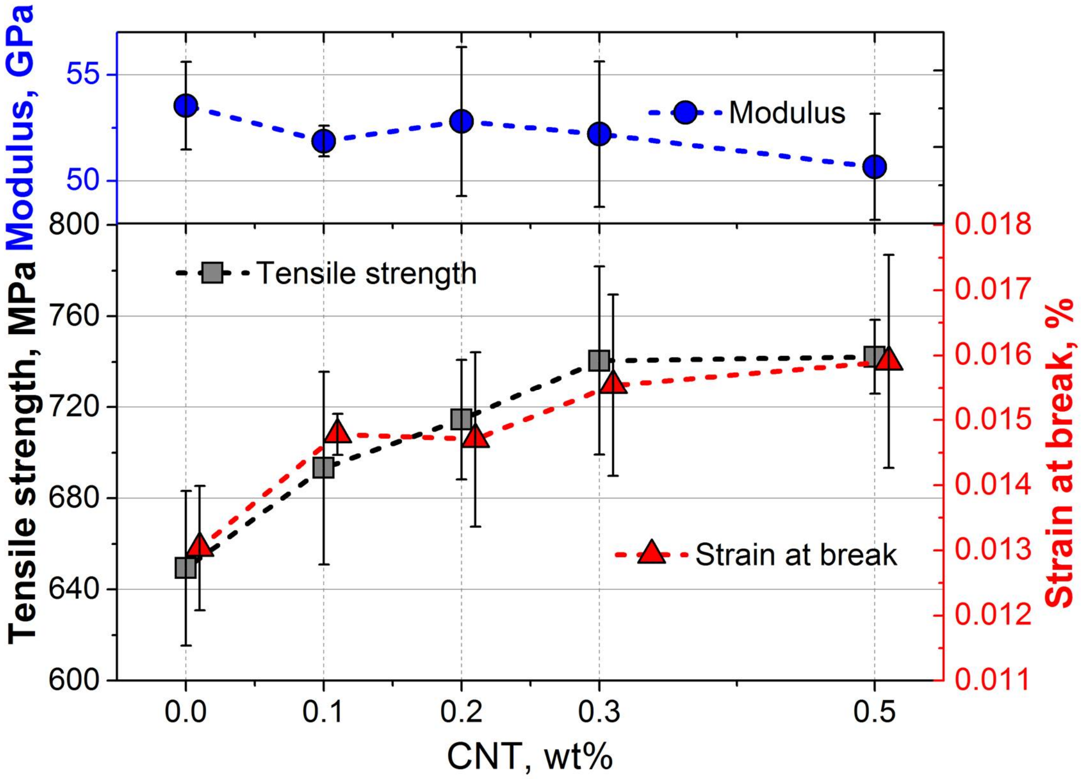

Figure 12. Results of flexural testing of CNT specimens.

The results above were obtained by the testing of hybrid CFRPs beyond the scopes of the present master research and are provided here for comparison in order to evaluate the impact of SWCNTs on fracture toughness and overall improvement of materials performance. It is concluded that CFRP containing 0.3 wt% of SWCNT demonstrate the best set of properties, particular tensile, flexural and short beam (shear) strength which are correspondingly 8.6%, 14% and 18% higher than the baseline values of non-modified CFRP.

TASK FOR SECTION
«FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING»

Student:

Group	Name
4BM9I	Abdullah Bin Firoz

Institute	ISHNTP	**Department**	Division for materials science
Level of education	Master	**Specialty**	22.04.01 Material science and technology of materials

Subject of research: « Investigation of SWCNT addition on the fracture toughness of hybrid carbon fiber reinforced polymers »

Background to the section «Financial management, resource efficiency and resource saving»:	
The cost of resources for the research: logistics, energy, financial, information and human	Scientific and technological research is carried out in the laboratory of mechanics of polymer composites ISPMS SB RAS, the project involves 3 workers: scientific adviser, student and researcher
Norms and standards for resource consumption	In accordance with GOST 14.322-83 "Rational consumption of materials" and GOST 51541-99 "Energy. Energy efficiency"
The used system of taxation, tax rates, deductions, discounting and lending	Deductions of insurance contributions - 30% of payroll
The list of subjects for the study, design and development:	
Assessment of commercial potential, prospects and alternatives of research from the perspective of the resource efficiency	- Potential consumers of research results; - SWOT-analysis of the project
Development of the statute of scientific and technical research	Not required
Planning of research management process: the structure and schedule of the budget and the procurement organization	- Planning research studies (purpose and result of epy research, a list of works, complexity of work and schedule) - Estimated costs for research
Determination of the resource, financial, budgetary, social and economic efficiency of the project	- Analysis and evaluation of the scientific and technical level of the project; - Evaluation of risks
List of graphic material:	
SWOT Matrix The schedule of estimated costs Gantt chart Evaluation of the resource, financial and economic efficiency	

Date of reference for this section on a line graph	

Task is issued by a consultant:,

Position	Name	Degree	Signature	Date
Associate Professor	Menshikova E.V.	PhD		

Task is accepted by a student:

Group	Name	Signature	Date
4BM9I	Abdullah Bin Firoz		

5 Financial management, resource efficiency and resource saving

The purpose of this section discusses the issues of competitiveness, resource efficiency and resource saving, as well as financial costs regarding the object of study of Master's thesis. Competitiveness analysis is carried out for this purpose. SWOT analysis helps to identify strengths, weaknesses, opportunities and threats associated with the project, and give an idea of working with them in each particular case. For the development of the project requires funds that go to the salaries of project participants and the necessary equipment, a complete list is given in the relevant section. The calculation of the resource efficiency indicator helps to make a final assessment of the technical decision on individual criteria and in general.

5.1 Competitiveness analysis of technical solutions

In order to find sources of financing for the project, it is necessary, first, to determine the commercial value of the work. Analysis of competitive technical solutions in terms of resource efficiency and resource saving allows to evaluate the comparative effectiveness of scientific development. This analysis is advisable to carry out using an evaluation card.

First of all, it is necessary to analyze possible technical solutions and choose the best one based on the considered technical and economic criteria.

Evaluation map analysis presented in Table 1. The position of your research and competitors is evaluated for each indicator by you on a five-point scale, where 1 is the weakest position and 5 is the strongest. The weights of indicators determined by you in the amount should be 1. Analysis of competitive technical solutions is determined by the formula:

$$C = \sum W_i.P_i \qquad (1)$$

C - the competitiveness of research or a competitor; Wi– criterion weight; Pi – point of i-th criteria. P1= CFRP (Carbon Fiber Reinforced Polymer) P2=GFRP (Glass Fiber Reinforced Polymer) P3= AFRP (Aramid Fiber Reinforced Polymer).

Table 1. Evaluation card for comparison of competitive technical solutions

Evaluation criteria *example*	**Criterion weight**	**Points**			**Competitiveness Taking into account weight coefficients**		
		P_f	P_{i1}	P_{i2}	C_f	C_{i1}	C_{i2}
1	2	3	4	5	6	7	8
Technical criteria for evaluating resource efficiency							
1. Density	0.15	5	4	3	0.75	0.60	0.45
2 .Tensile Strength	0.10	4	3	5	0.40	0.30	0.50
3. Elongation	0.10	3	4	5	0.30	0.40	0.50
4. Stiffness	0.15	5	4	3	0.75	0.60	0.45
Economic criteria for performance evaluation							
1. Development cost	0.15	3	4	4	0.45	0.60	0.60
2. Market penetration rate	0.15	3	5	3	0.45	0.75	0.45
3. Expected lifecycle	0.10	5	4	4	0.50	0.40	0.40
4. Recyclability	0.10	5	4	3	0.50	0.40	0.30
Total	1	33	32	30	4.1	4.05	3.65

So according to this analysis we can conclude that CFRPs have better mechanical and economical performance when compared to other composites. And our scientific work is focused on the manufacturing and testing of CFRPs

5.2 SWOT analysis

Complex analysis solution with the greatest competitiveness is carried out with the method of the SWOT analysis: Strengths, Weaknesses, Opportunities and Threats. The analysis has several stages. The first stage consists of describing the strengths and weaknesses of the project, identifying opportunities and threats to the project that have emerged or may appear in its external environment. The second stage consists of identifying the compatibility of the strengths and weaknesses of the project with the external environmental conditions. This compatibility or incompatibility should help to identify what strategic changes are needed.

Table 2. SWOT analysis

	Strengths: S1. High stiffness and strength S2. Chemical resistivity S3. Corrosion resistance	**Weaknesses:** W1. The high cost associated with CFRP has limited its usage W2. Demonstration of cost-effective recycling/recovery and repair methods W3. Time-Consuming Manufacture
Opportunities: O1. Weight reduction being the key factor for emission control O2. Investors are increasingly interested in companies that incorporate sustainability strategies O3. Low bending, high-speed operation, vibration suppression, space saving	High strength to weight ratio for CFRP has made it popular in the aerospace & defense industry. CFRP is popularly used in military planes and helicopters, owing to its ability to reduce a weight of an object to a large extent.	Many of the technical hurdles that can reduce material cost and enable recycling are under development and their prospects are encouraging
Threats: T1. The lack of integration between product and corporate CF could be the main threat. T2. Economic and financial crises are an obstacle for companies investing in CF implementation and environmental protection in general	More reliable structures based on newly developed material	Lack of demand of a new material; Closing machine-building enterprises in Russia.

5.3 Project Initiation

The initiation process group consists of processes that are performed to define a new project or a new phase of an existing one. In the initiation processes, the initial purpose and content are determined and the initial financial resources are fixed. The internal and external stakeholders of the project who will interact and influence the overall result of the research project are determined.

Table 3. Stakeholders of the project

Project stakeholders	**Stakeholder expectations**
Russian scientific fund	Obtaining novel relevant results in CFRP manufacturing and testing.

Table 4. Purpose and results of the project

Purpose of project:	Investigation of the possibility of improvement of fracture toughness Mode I and Mode II of carbon fiber reinforced polymers by addition of single wall carbon nanotubes.
Expected results of the project:	Improvement of fracture toughness by the effect of nanotube bridging.
Criteria for acceptance of the project result:	Fracture toughness increase by 10%
Requirements for the project result:	More than 3 specimens for one measurement point
	Coefficient of variation of the key property not more than 50%

5.3.1 The organizational structure of the project

It is necessary to solve the some questions: who will be part of the working group of this project, determine the role of each participant in this project, and prescribe the functions of the participants and their number of labor hours in the project shown in Table 5.

Table 5. Structure of the project

№	Participant	Role in the project	Functions	Labor time, hours (working days (from table 7) × 6 hours)
1	Abdullah Bin Firoz (Student TPU)	Student, researcher	Participating in specimens testing; Processing of raw data; preparation of report	168
2	Burkov M.V. (Assistant Professor)	Scientific adviser	Designing experiment; Conducting experiments; Establishing of data processing techniques	210
3	Eremin A.V. (Assistant Professor)	Researcher	Conducting experiments	180

5.3.2 Project limitations

Project limitations are all factors that can be as a restriction on the degree of freedom of the project team members shown in Table 6.

Table 6. Project limitations

Factors	Limitations / Assumptions
3.1. Project's budget	273522.9
3.1.1. Source of financing	Russian scientific fund
3.2. Project timeline:	02.2021 -04.2021
3.2.1. Date of approval of plan of project	July 2020
3.2.2. Completion date	June 2021

5.3.3 Project Schedule

A project schedule is a timetable that organizes project tasks, activity durations, calendar start and end dates, and sets overall project milestones on a timeline. Project schedules also define the team members and resources needed to complete tasks. Project scheduling is fundamental for planning and control in project management. Table 7 shows the project schedule with the tasks assigned and completion of the tasks.

Table 7. Project Schedule

Job title	**Duration, working days**	**Start date**	**Date of completion**	**Participants**
Manufacturing the specimens	12	Feb 10	Feb 24	Burkov Eremin
Cutting the specimens	2	March 9	March 10	Burkov, Abdullah
Preparation of loading blocks	3	May 13	May 16	Burkov
Adhesive bonding of loading blocks	2	May 17	May 18	Burkov
Marking of specimens	2	May 19	May 20	Burkov
Testing of FT Mode 1	3	June 2	June 5	Burkov, Eremin Abdullah
Testing of FT Mode 2	5	April 5	April 10	Burkov, Eremin Abdullah
Result preparation for mode I	10	June 7	June 18	Burkov, Eremin Abdullah
Result preparation for mode I	17	April 12	April 30	Burkov, Abdullah

A Gantt chart, or harmonogram, is a type of bar chart that illustrates a project schedule. This chart lists the tasks to be performed on the vertical axis, and time intervals on the horizontal axis. The width of the horizontal bars in the graph shows the duration of each activity.

Table 8. Gant chart.

Phase	**Performers**	T_k	**Feb**	**Mar**	**Apr**	**May**	**June**
The arrangement of technical task	Abdullah Bin Firoz Eremin A.V. Burkov M.	2					
Prepration of specimen	Abdullah bin firoz Burkov M	30					
Cutting and marking	Burkov M.V Abdullah bin firoz	8					
Mode II interlaminar fracture toughness test.	Abdullah Bin Firoz Eremin A.V. Burkov M.	6					
Cutting of blocks	Burkov M.V.	7					
Gluing blocks to specimen	Burkov M.V.	3					
Mode I interlaminar fracture toughness test	Abdullah Bin Firoz Eremin A.V. Burkov M.	3					
Analysis of results	Abdullah Bin Firoz . Burkov M.	4					
Evaluation of the effectiveness	Abdullah Bin Firoz Eremin A.V. Burkov M.	5					
Delivery of report	Abdullah Bin Firoz	5					

5.4 Scientific and technical research budget

The amount of costs associated with the implementation of this work is the basis for the formation of the project budget. This budget will be presented as the lower limit of project costs when forming a contract with the customer.

To form the final cost value, all calculated costs for individual items related to the manager and the student are summed.

In the process of budgeting, the following grouping of costs by items is used:

- Material costs of scientific and technical research;
- costs of special equipment for scientific work (Depreciation of equipment used for design);
- basic salary;
- additional salary;
- labor tax;
- overhead.

5.4.1 Calculation of material costs

The calculation of material costs is carried out according to the formula 2:

$$\text{C}_m = (1 + K_T).\sum_{i=1}^{m} P_i.N_{cons} \qquad (2)$$

where m – the number of types of material resources consumed in the performance of scientific research;

N_{consi} – the amount of material resources of the i-th species planned to be used when performing scientific research (units, kg, m, m^2, etc.);

P_i – the acquisition price of a unit of the i-th type of material resources consumed (rub./units, rub./kg, rub./m, rub./m^2, etc.);

k_T– coefficient taking into account transportation costs.

Prices for material resources can be set according to data posted on relevant websites on the Internet by manufacturers (or supplier organizations).

Table 9. Material costs

Name	Unit	Amount	Price per unit, rub.	Material costs, rub.
Carbon fabrics	1	5 m2	1962/m2	9810
Epoxy	1	0.6 kg	1800/kg	1080
Carbon nanotubes	1	4.4 g	386/g	1698.4
Total				12588.4

5.4.2 Costs of special equipment

This point includes the costs associated with the acquirement of special equipment (instruments, stands, devices and mechanisms) necessary to carry out work on a specific topic.

Table 10. Rental costs of special equipment

№	Equipment identification	Rental period	Rental price per unit, rub.	Total rental cost of equipment, rub.
1.	Instron 5582	50 hours	2000 rub/h	100,000
2.	Digital camera Canon 700D	15 hours	200 rub/h	3000
3	Computer	120 hours	100 rub/h	12000

5.4.3 Basic salary

This point includes the basic salary of participants directly involved in the implementation of work on this research. The value of salary costs is determined based on the labor intensity of the work performed and the current salary system

The basic salary (S_b) is calculated according to the formula 3:

$$S_b = S_a . T_W \quad (3)$$

where S_b – basic salary per participant; T_w – the duration of the work performed by the scientific and technical worker, working days; S_d - the average daily salary of an participant, rub.

The average daily salary is calculated by the formula 4:

$$S_b = \frac{S_m . M}{F_v} \quad (4)$$

S_m is monthly salary of an participant, rubels ; M is the number of months of work without leave during the year: at holiday in 48 days, M = 11.2 months, 6 day per week; F_v valid annual fund of working time of scientific and technical personnel (251 days).

Table 11. The valid annual fund of working time

Working time indicators	
Calendar number of days	365
The number of non-working days -weekend -holidays	 52 14
Loss of working time -vacation - isolation period -sick absence	48
The valid annual fund of working time	251

Monthly salary is calculated by formula 6:

$$S_{month} = S_{base} . (k_{premium} + k_{bonus.}) . k_{reg} \quad (5)$$

where S_{base} – base salary, rubles; $k_{premium}$ – premium rate; k_{bonus} – bonus rate; k_{reg} – regional rate.

Table 12. Calculation of the base salaries

Performers	S_{base}, **rubles**	$k_{premium}$	k_{bonus}	k_{reg}	S_{month}, **rub.**	W_d, **rub.**	T_p, **work days (from table 7)**	W_{base}, **rub.**
Burkov	36174	1.0	1.0	1.3	94052.4	22	56	239406.10
Eremin	36174				94052.4	22	30	128253.27
Abdullah	18426				47907.6	22	37	80571.8

5.4.4 Additional salary

This point includes the amount of payments stipulated by the legislation on labor, for example, payment of regular and additional holidays; payment of time associated with state and public duties; payment for work experience, etc.

Additional salaries are calculated on the basis of 10-15% of the base salary of workers:

$$W_{add} = W_{extra} . W_{base} \quad (6)$$

where W_{add} – additional salary, rubles; k_{extra} – additional salary coefficient (10%); W_{base} – base salary, rubles.

W_{add}= 0.1*36174=3617.4- Burkov

W_{add}= 0.1*36174=3617.4- Eremin

W_{add}= 0.1*18426=1842.6- Abdullah

5.4.5 Labor tax

Tax to extra-budgetary funds are compulsory according to the norms established by the legislation of the Russian Federation to the state social insurance (SIF), pension fund (PF) and medical insurance (FCMIF) from the costs of workers.

Payment to extra-budgetary funds is determined of the formula:

$$P_{social} = k_b . (W_{base} + W_{add.}) . W_{add} \quad (7)$$

where k_b – coefficient of deductions for labor tax.

In accordance with the Federal law of July 24, 2009 No. 212-FL, the amount of insurance contributions is set at 30%. Institutions conducting educational and scientific activities have rate - 27.1%.

Table 13. Labor tax

	Project leader Burkov	**Researcher Eremin**	**Engineer Abdullah**
Coefficient of deductions	1		
Salary (basic and additional), rubles	36174	36174	18426
Labor tax, rubles	10783.46	10783.46	5492.79

5.4.6 Overhead costs

Overhead costs include other management and maintenance costs that can be allocated directly to the project. In addition, this includes expenses for the maintenance, operation and repair of equipment, production tools and equipment, buildings, structures, etc.

Overhead costs account from 30% to 90% of the amount of base and additional salary of employees.

Overhead is calculated according to the formula:

$$C_{ov} = k_{ov}.(W_{base} + W_{add.}) \quad (8)$$

Where k_{ov} – overhead rate.

Table 14. Overhead

	Project leader Burkov	**Researcher Eremin**	**Engineer Abdullah**
Overhead rate	70%		
Salary, rubles	36174	36174	18426
Overhead, rubles	27853.98	27853.98	14188.02

5.4.7 Other direct costs

Energy costs for equipment are calculated by the formula:

$$C = P_{el}.P.F_{eq.}) \quad (9)$$

where P_{el} is power rates (5.8 rubles per 1 kWh); P is power of equipment, kW; F_{eq} is equipment usage time, hours.

Equipment		Power of equipment (kW)	equipment usage time, (hours)	Energy costs
Instron 5582		1	50 hours	290
Digital camera Canon 700D	Power rates (5.8 rubles per 1 kWh)	0.015	15 hours	1.5
Computer		0.25	120 hours	174
Total				465.5

5.4.8 Formation of budget costs

The calculated cost of research is the basis for budgeting project costs. Determining the budget for the scientific research is given in the table 16.

Table 16. Items expenses grouping

Name	Cost, rubles
Material costs CFRP GFRP AFRP	12588.4 10000 8000
Equipment costs	115000
Basic salary	36174
Additional salary	3617.4
Labor tax	10783.46
Overhead	73150
Other direct costs	465.5
Total planned costs	Cost with CFRP-251778 GFRP- 249190 AFRP- 247190

5.5 Evaluation of the comparative effectiveness of the project

Determination of efficiency is based on the calculation of the integral indicator of the effectiveness of scientific research. Its finding is associated with the definition of two weighted average values: financial efficiency and resource efficiency.

The integral indicator of the financial efficiency of a scientific study is obtained in the course of estimating the budget for the costs of three (or more) variants of the execution of a scientific study. For this, the largest integral indicator of the implementation of the technical problem is taken as the calculation base (as the denominator), with which the financial values for all the options are correlated. The integral financial measure of development is defined as:

$$I_f^d = \frac{C_i}{C_{max}} \quad (10)$$

where I_f^d is integral financial measure of development; C_i is the cost of the i-th version; $C_{\max}$ is the maximum cost of execution of a research project (including analogues).

The obtained value of the integral financial measure of development reflects the corresponding numerical increase in the budget of development costs in times (the value is greater than one), or the corresponding numerical reduction in the cost of development in times (the value is less than one, but greater than zero).

Since the development has one performance, then $I_f^d = 1$.

The integral indicator of the resource efficiency of the variants of the research object can be determined as follows:

$$I_m^a = \sum_{i=1}^{n} a_i b_i^a \quad (11)$$

$$I_m^a = \sum_{i=1}^{n} a_i b_i^p \quad (12)$$

where I^a_m– integral indicator of resource efficiency for the i-th version of the development; a_i the weighting factor of the i-th version of the development; b_i^a, b_i^p score rating of the i-th version of the development, is established by an expert on the selected rating scale; n is the number of comparison parameters.

The calculation of the integral indicator of resource efficiency is presented in the form of table 17.

Table 17. Evaluation of the performance of the project

Evaluation criteria	Criterion weight	Points			Competitiveness Taking into account weight coefficients		
		P_f	P_{i1}	P_{i2}	C_f	C_{i1}	C_{i2}
1	2	3	4	5	6	7	8
Technical criteria for evaluating resource efficiency							
1. Density	0.15	5	4	3	0.75	0.60	0.45
2 .Tensile Strength	0.10	4	3	5	0.40	0.30	0.50
3. Elongation	0.10	3	4	5	0.30	0.40	0.50
4. Stiffness	0.15	5	4	3	0.75	0.60	0.45
Economic criteria for performance evaluation							
1. Development cost	0.15	3	4	4	0.45	0.60	0.60
2. Market penetration rate	0.15	3	5	3	0.45	0.75	0.45
3. Expected lifecycle	0.10	5	4	4	0.50	0.40	0.40
4. Recyclability	0.10	5	4	3	0.50	0.40	0.30
Total	1	33	32	30	4.1	4.05	3.65

The integral indicator of the development efficiency (I_e^p) is determined on the basis of the integral indicator of resource efficiency and the integral financial indicator using the formula:

$$I_e^p = \frac{I_m^p}{I_f^d} \quad (13)$$

Comparison of the integral indicator of the current project efficiency and analogues will determine the comparative efficiency. Comparative effectiveness of the project:

$$E_c = \frac{I_e^p}{I_{fe}^a} \quad (14)$$

Thus, the effectiveness of the development is presented in table 18.

Table 18. Efficiency of development

№	Indicators	Project	analog
1	Integral financial measure of development	0.99	0.98
2	Integral indicator of resource efficiency of development	4.1	3.65
3	Integral indicator of the development efficiency	0.24	0.26
	Effectiveness of Development	0.923	

Comparison of the values of integral performance indicators allows us to understand and choose a more effective solution to the technical problem from the standpoint of financial and resource efficiency.

5.6 Conclusion

Thus, in this section was developed stages for design and create competitive development that meet the requirements in the field of resource efficiency and resource saving.

These stages include:

- development of a common economic project idea, formation of a project concept;
- organization of work on a research project;
- identification of possible research alternatives;
- research planning;
- assessing the commercial potential and prospects of scientific research from the standpoint of resource efficiency and resource saving;
- determination of resource (resource saving), financial, budget, social and economic efficiency of the project.

List of publications

1. Improving the fracture toughness of CFRP by single-wall carbon nanotubes. Abdullah bin Firoz, Burkov Mikhail, Eremin Alexander // Proceedings of International Congress for Young Scientists "Modern Materials and Advanced Technologies (MMAT 2022)", 2022, Tomsk, Russia (accepted to publication).

2. Mode II fracture toughness evaluation of the hybrid single-wall carbon nanotubes modified CFRP, Burkov Mikhail, Eremin Alexander, Abdullah bin Firoz // AIP conference proceedings (submitted to publisher).