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Mechanics

Research on High-Strength Ropes for Protective Mesh against Bird Strikes on Aircraft Engines under Normal and Extreme Temperature Conditions

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The use of lightweight and high-strength protective nets in mitigating bird strikes on aircraft is crucial for enhancing flight safety. Traditional metal nets, commonly used for this purpose, generate metal fragments upon impact, posing a significant threat to engine performance. This study investigates the application of high-strength polymer fibers, including UHMWPE (Dyneema, Spectra, Izanas), Zylon, Vectran, and Kevlar, as alternative materials for protective nets. These fibers are 7-8 times lighter than their metal counterparts while offering superior strength, durability, and thermal stability within a temperature range from -60°C to +60°C. Laboratory experiments conducted using a universal testing machine (UTM-M) and a thermo-cryogenic chamber confirmed the stable mechanical properties of these materials under both standard and extreme conditions. Among the tested high-strength polymers, UHMWPE fibers exhibited the highest tensile strength, moisture resistance, and UV stability, making them particularly well-suited for aviation applications. Beyond static testing, additional dynamic evaluations demonstrated that ropes made from Dyneema fibers fully comply with the technical requirements for protective nets. These findings establish Dyneema as the optimal choice for developing lightweight, resilient, and effective protective barriers for aircraft engines.

bird strikes, protective mesh, high strength polymer fiber

According to the International Civil Aviation Organization (ICAO), over 13,000 bird strikes with airplanes occur annually in the United States alone. In reality, the number of bird strikes is higher than recorded, and nearly half of these incidents involve engine strikes. Addressing this issue is a critical and highly responsible task for aviation. The use of protective meshes to prevent the consequences of bird strikes on aircraft engines is a highly demanding challenge. It requires careful selection and testing of these meshes under both normal and extreme operational conditions of aircraft.

The selected ropes are as follows: UHMWPE: Ultra-High Molecular Weight Polyethylene; Dyneema (DSM, Netherlands) Spectra (Honeywell, USA); Zylon (Toyobo MC Corporation, Japan); VECTAN (Kuraray, Japan); Kevlar (DuPont, USA).

Selection and Characterization of High-Strength Polymer Fiber (HSPF) Ropes

Based on a specialized scientific and technical information database, multi-strand braided ropes made from globally recognized ultra-high-strength polymer fibers were selected. These ropes significantly surpass traditional high-strength polymer ropes, metal wires, and cables in their mechanical properties.

The selected ropes are as follows: UHMWPE: Ultra-High Molecular Weight Polyethylene; Dyneema (DSM, Netherlands) Spectra (Honeywell, USA); Zylon (Toyobo MC Corporation, Japan); VECTRAN (Kuraray, Japan); Kevlar (DuPont, USA). All of these are high-strength, lightweight synthetic materials that stand out due to their exceptional mechanical properties. Their strength, lightness, and resistance to various environmental conditions make these fibers unique materials, ideally suited for demanding applications such as protective meshes in aviation [1-3].

Dyneema: Ultra-High Molecular Weight Polyethylene (UHMWPE) fibers, such as Dyneema (DSM, Netherlands) [4], Spectra (Honeywell, USA) [5], Izanas (Toyobo, Japan) [6], and other similar plastics, belong to the thermoplastic polyethylene family. These fibers are composed of extremely long molecular chains with polymeric intermolecular bonds. Dyneema was first developed in the 1970s by the Dutch company DSM.

Dyneema is unparalleled in its exceptional strength and lightness. It has high tensile strength, low density, high abrasion resistance, and low elongation. This fiber has one of the highest strength-to-weight ratios among all man-made fibers. Its high strength-to-weight ratio makes it 10 times stronger than steel, more durable than polyester, and gives it specific strength that exceeds aramid fibers by 40%. Dyneema can also withstand rapid deformations under high loads, which is a critical factor in dynamic load scenarios.

For testing purposes, another UHMWPE fiber brand was selected: the natural white Spectra fiber rope, produced by Honeywell, a major American manufacturer and international corporation specializing in ultra-high molecular weight polyethylene.

Zylon: The fiber produced by the Japanese company Toyobo MC Corporation, is currently the strongest fiber in the world [7,8].

Zylon is distinguished by its resistance to high temperatures and chemicals. Zylon has a high modulus, meaning it stretches very little under load, allowing it to withstand greater forces before breaking.

Vectran: The fiber is highly resistant to high temperatures (does not burn). The Vectran is also extremely strong and lightweight [9]. It is one of the strongest synthetic fibers, with its molecules tightly bonded, giving it exceptional strength. Vectran was developed in the 1980s by the Japanese company Kuraray [10]. It is used to manufacture equipment that operates under high-temperature conditions, such as fire hoses, protective clothing, and more. Vectran is also widely utilized in aerospace Technologies.

Kevlar [11]: The chemical composition is polyaramid. It is characterized by exceptional strength, lightweight. It was developed in 1965 by the American company DuPont. It is resistant to heat and chemicals. Its applications include bulletproof vests, sports equipment, industrial gloves, automotive parts, and more.

The data presented below is approximate and may vary depending on different sources. The specific properties of a material depend on the manufacturer, the technological production process and many other factors. These details can always be clarified based on the specific brand and manufacturer.

Determining the diameter of high-strength polymer ropes for testing. It was decided that the diameter of the selected ropes would range between Φ=1-3 mm, as this falls within the optimal and desirable size range determined by previous research conducted on various fibers at the Georgian

Table 1. Displaying the mechanical properties of high-strength polymer fibers selected from various sources

N	High-Strength polymer fiber	Specific gravity (g/cm³)	Tensile strength (Gpa)	Elastic modulus (Gpa)	Degrad. temper. (°C)	Moisture absorption (%)
11	Dyneema, Spectra, Izanas	0.97-1	3.6-4,2	120-180	147	0.01-0.05
22	Zylon	1.55 - 1.65	3-5.8	140-280	500-750	0.2-3.5
33	Kevlar	1.44 - 1.46	2.6-3.6	70 - 150	250-350	0.5-1
44	Vectran	1.38 - 1.45	2.8 - 3.5	110 - 180	300-400	0.3-08

Aviation University [12,13]. Specifically, in past years, the University developed a theoretical physical model of the dynamic process of bird collisions with protective meshes. Preliminary calculations and some practical experiments showed that such collisions are likely to result in partial cutting or fragmentation of the bird's body by the high-strength mesh. Consequently, some parts remain on the mesh, while others pass through it.

For our testing, the selected Dyneema rope has a diameter of 1.4 mm, which represents its factory marking rather than the precise diameter of the multi-fiber braided rope.

It is important to note that the strength of the rope almost never equals the sum of the strengths of its individual fibers and is always significantly lower. This discrepancy arises because it is impossible to achieve uniform tension across all fibers during the braiding process. Moreover, the modulus also decreases during braiding. The significant changes in the mechanical properties of HSP ropes depend on several factors:

- Material quality and manufacturing process: The type of material used, its purity, and the manufacturing technology adopted by the producer.
- Denier and number of fibers in the rope: (Denier is a specific term used to describe the linear density of fibers).
- Braiding type: The mechanical properties of the rope heavily depend on the type of braiding used during production, as this directly affects its characteristics.
- Composite design: The rope may include additional types of fibers braided for specific purposes, such as enhancing certain properties or addressing technological requirements.
- Protective sheaths: The rope may feature an outer layer or woven protective sheath made of different materials, such as anti-friction coatings or UV-resistant layers.
- Coatings and treatments: Ropes may be coated or impregnated with special protective substances to enhance properties such as resistance to UV radiation, moisture, abrasion, or harsh environmental conditions.

Determination of the Strength Characteristics of Polymer Rope Samples Using UTM-M

To determine the tensile properties of high-strength fiber ropes under normal and extreme temperature conditions, we used a modernized Universal Tensile Machine (UTM-M). This device serves as a versatile testing stand capable of analyzing a wide range of material types.

The UTM-M was upgraded to meet the specific requirements of testing polymer ropes under diverse environmental conditions. The principal schematic diagram of the machine is shown in Fig. 1.

Testing under these conditions ensures accurate data collection on the mechanical behavior of ropes, including their tensile strength, elasticity, and deformation limits. This approach allows us to evaluate the performance and reliability of ropes in both standard and extreme operational environments.

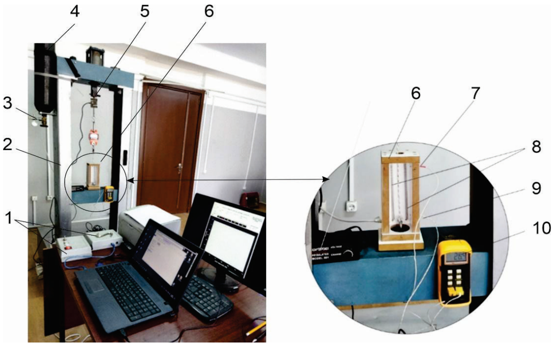

Fig. 1. Universal tensile machine (UTM-M) with measuring equipment used for testing features advanced measurement equipment, including: A: computerized parameter measurement system. B: thermo-cryogenic chamber for heating and cooling.

The system components are as follows: Notebook with tensile speed control and USB-based strain gauge controller; Universal Tensile Machine (UTM-M); Gearbox with a tap for precise adjustments; Liquid carbon dioxide cylinder for temperature control; 500 kgf load cell for tensile force measurement; Thermo-cryogenic chamber for controlled environmental testing; Thermocouples for accurate temperature monitoring; Heating elements (electric spirals) for controlled heating; Dual-channel temperature controller for precise thermal management.

To ensure high accuracy during experiments, a computerized data acquisition (DAQ) system was developed for measuring and collecting data. At the start of the experiment, fields corresponding to the initial parameters are filled in the system. Once the start button is pressed, all parameters are automatically measured in real time, and results are displayed in both numerical and graphical formats.

Before closing the software, the graphical data can be scaled as needed, and all parameters are automatically logged into a designated computer folder, allowing for repeated viewing and detailed analysis of the experimental data (Fig. 2).

The software interface of the data acquisition system for tensile testing includes the following elements: Program start fields: used to initiate the testing process. Data input fields: for entering the initial parameters of the test. Measured parameter windows: displays real-time and recorded values, including: instantaneous force; variable force; maximum force; displacement [mm]; displacement speed [mm/s]; relative deformation [%]. Tensile force [N]: graphical representation of the applied force during the test.

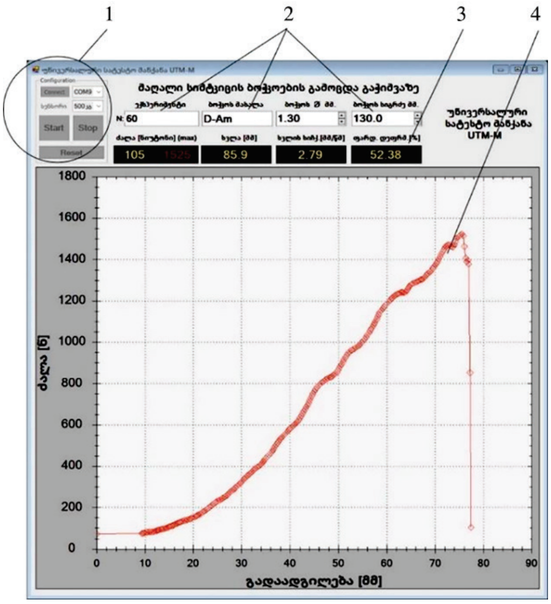

Fig. 2. Software Interface of the Computerized System for Measuring and Collecting HSP Tensile Parameters. The software interface of the data acquisition system for tensile testing includes the following elements: 1 – **Program Start Fields,** used to initiate the testing process; 2 – **Data Input Fields** – for entering the initial parameters of the test; 3 – **Measured Parameter Windows** – displays real-time and recorded values, including: instantaneous force, variable force, maximum force, displacement [mm], displacement speed [mm/s], relative deformation [%]; 4 – **Tensile Force [N]** – a graphical representation of the applied force during the test.

Universal Thermo-Cryogenic Chamber for Tensile Testing

It is well known that the extreme temperatures encountered during aircraft operations range from -60°C to +60°C. To facilitate the testing of selected high-strength polymer (HSP) ropes under such extreme temperature conditions, a specialized thermo-cryogenic chamber was designed, manufactured, and tested for the UTM-M tensile testing machine. This chamber allows the creation of environmental conditions within the temperature range -60°C to +60°C, enabling comprehensive experimental research. The chamber was successfully used to conduct tensile tests on the primary working elements of protective meshes designed for aircraft engines, specifically ropes made from high-strength fibers. To achieve an extreme minimum temperature of -60°C in the testing chamber, compressed and liquefied carbon dioxide stored in a high-pressure cylinder was introduced into the thermo-cryogenic chamber. The evaporation process of the CO_2 within the chamber allowed testing conditions to reach a minimum temperature of -70°C. For increasing the chamber's temperature to +60°C, electric heating spirals were used. The temperature was regulated by adjusting the 0-12 V direct current voltage supplied to the spirals.

From the results of tensile testing under normal conditions, it was observed that the ropes made from Spectra, Dyneema, and Zylon fibers demonstrated the highest tensile strength. However, when examining the tensile strength per square millimeter, these ropes showed almost equivalent breaking force values. For detailed data, refer to Table 2.

Table 2. Test results for the stretching of various materials

N	HSP rope	Factory marking Φ (mm)	Measured cross-sectional area (mm²)	Tensile force (F_e) (kg)	Tensile strength (GPa)
1	Zylon	1.3	1.1	110	1.0
2	Spectra	1.3	1.69	153	1.1
3	Dyneema	1.4	0.96	91	1.0
4	Kevlar	1.6	1.26	96	0.8
5	Vectran	1.6	1.27	97	0.8

Below is a unified Table 3 and graph of tests conducted on ropes made from HSP fibers under normal and extreme temperature conditions.

Table 3. Breaking forces of HSP ropes under extreme temperature conditions

N	HSP rope brand	Ambient temperature (°C)		
		60°C	20°C	60°C
1	Dyneema (d=1.4 mm)	92	91	97
2	Spectra (d=1.3 mm)	130	153	142
3	Zylon (d=1.3 mm)	117	110	116
4	Kevlar (d=1.6 mm)	103	96	103
5	Vectran (d=1.6 mm)	100	97	96

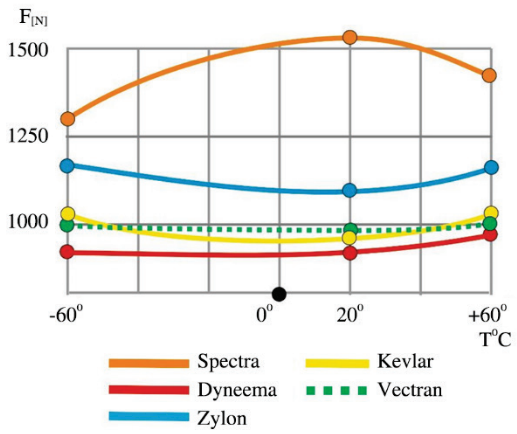

Fig. 3. Tensile strength characteristics of sample ropes made from Dyneema, Spectra, Kevlar, Zylon, and Vectran.

Experimental Study Results of HSP Ropes and Analysis of the Impact of Additional Factors

Ropes made from the world's strongest HSP materials (Dyneema, Spectra, Kevlar, Vectran, and Zylon) were tested on a specialized universal tensile machine under normal and extreme operating conditions of aircraft, ranging from -60°C to +60°C.

Tensile testing results: Laboratory tests conducted on a specialized tensile testing stand with a thermo-cryogenic chamber show that all types of HSP ropes perform exceptionally well and remain stable across the tested temperature range.

Among these, Spectra, Zylon, and Dyneema ropes demonstrated the highest tensile strength. However, Spectra exhibited minor changes in mechanical properties due to temperature variations.

Moisture absorption in extreme conditions: The technical specifications provided by manufacturers include resistance to UV radiation and moisture absorption. These factors are critical for ropes used in aviation, where they may be exposed to rain and extreme temperatures. Moisture absorption is particularly problematic for Zylon, which has a moisture absorption rate of 0.6-3.5%. This can lead to repeated freezing and thawing cycles, causing structural damage and reduced strength. In contrast, ropes made from Dyneema, Izanas, and Spectra have a moisture absorption rate of 0.0%, making them immune to the harmful effects of moisture in extreme conditions.

UV radiation impact: UHMWPE materials (e.g., Dyneema, Spectra) are less sensitive to UV radiation due to their dense molecular structure. However, prolonged exposure can slightly reduce their strength. To mitigate UV damage, technical solutions include: Adding UV stabilizers to the material; Applying protective coatings, such as PTFE (Teflon); Increasing the rope diameter to compensate for gradual degradation over time.

Conclusions

Using special equipment at the Georgian Aviation University, including a universal thermocryo camera and a high-precision computer data acquisition system, the actual strength characteristics of the strongest polymer ropes in the world today were determined under normal and extreme (-60° and +60°C) temperature operating conditions. The results of bench tests of polymer ropes were analyzed, as a result of the impact of almost all possible operating factors that can lead to deterioration of the characteristics of these ropes extreme environments.

Based on the obtained information and experimental results, it can be said that ropes made of UHMWPE fibers (Dyneema, Spectra, Izanas) are the leaders among the best selected materials for protective net ropes, since they meet almost all the requirements imposed on them with their technical parameters.

Performance Highlights of UHMWPE Ropes:

1. High mechanical strength: these ropes exhibit excellent tensile properties, allowing them to absorb impact energy and reduce dynamic loads during collisions.
2. Stability across temperature ranges: they maintain consistent performance in operating conditions from -60°C to +60°C.
3. Moisture resistance: due to zero moisture absorption, UHMWPE ropes are unaffected by freezing and thawing cycles, unlike Zylon.
4. UV resistance: their dense molecular structure makes them less vulnerable to UV radiation compared to other materials.
5. Low melting temperature: while their melting point is relatively low (147°C), this reduces the risk of critical damage if a fragment enters the engine during an incident.

Later experimental dynamic tests have proved that Dyneema ropes are optimal material for protective meshes, meeting all technical requirements and performing reliably under operational conditions.

მექანიკა

საფრენი აპარატის ძრავას ფრინველთან შეჯახებისგან დამცავი ბადის თოკების კვლევა ფრენის ნორმალურ და ექსტრემალურ პირობებში

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თვითმფრინავებთან ფრინველების შეჯახების დროს მსუბუქი და მაღალი სიმტკიცის მქონე დამცავი ბადეების გამოყენება უაღრესად მნიშვნელოვანია ფრენის უსაფრთხოების ასამაღლებლად. ამ მიზნით გამოყენებული ტრადიციული ლითონის ბადეებთან ფრინველების შეჯახებით წარმოქმნილი ლითონის ფრაგმენტები სერიოზულ საფრთხეს უქმნის ძრავას მუშაობას. კვლევა განიხილავს მაღალი სიმტკიცის პოლიმერული ბოჭკოების UHMWPE (Dyneema, Spectra, Izanas), Zylon, Vectran და Kevlar – გამოყენებას, როგორც დამცავი ბადეების ალტერნატიულ მასალებს. ეს ბოჭკოები 7-8-ჯერ უფრო მსუბუქია, ვიდრე მათი ლითონის ანალოგიები და გამოირჩევა უფრო მაღალი სიმტკიცით, გამძლეობით და სტაბილურობით -60°C-დან +60°C-მდე ტემპერატურის დიაპაზონში. ლაბორატორიულ ექსპერიმენტებში, რომლებიც ჩატარდა უნივერსალური გაჭიმვის მანქანაზე (UTM-M) და თერმოკრიოგენული კამერით, დადასტურდა ამ მასალების სტაბილური მექანიკური თვისებები როგორც ნორმალურ, ასევე ექსტრემალურ პირობებში. გამოცდილი მაღალი სიმტკიცის პოლიმერული მასალებიდან UHMWPE ბოჭკოებმა საუკეთესო შედეგები აჩვენა, როგორც გაჭიმვის სიმტკიცის, ტენიანობის, ასევე UV სხივებისადმი სტაბილურობის თვალსაზრისით, რაც მათ იდეალურს ხდის ავიაციისთვის. გარდა ზემოთ აღნიშნული სტატიკური გამოცდებისა, დამატებით ჩატარებულმა დინამიკურმა ტესტებმა დაადასტურა, რომ Dyneema-ს ბოჭკოსგან დამზადებული თოკები სრულად აკმაყოფილებს მათდამი წაყენებულ ტექნიკურ მოთხოვნებს, რაც მათ საუკეთესო ვარიანტად აქცევს თვითმფრინავების ძრავებისთვის მსუბუქი, გამძლე და ეფექტური დამცავი ბადეების შესაქმნელად.

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