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An analysis of the possibility of using foamed polypropylene for the construction of aircraft structural elements

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Abstract

This article contains two selected properties of foamed polypropylene. Durability and water absorption were tested. The tested possibilities are available in terms of the use of the tested material in air structures. Resistance to them is possible due to the fact that they are structural elements of air elements, while the lowest water absorption is required due to the requirements that can be operated by airborne vehicles. The property consisting in the ability to absorb water by the tested material excludes it from the test results and its use in the formation of air substances. The test results do not provide grounds to reject the tested material as a potential use of a structural material in air structures.

Keywords: Aircraft, construction, foamed polypropylene (PPE), safety

1. Introduction

For obvious reasons, the construction of aircraft requires the use of materials that are both durable and as light as possible. The requirement for high strength is placed on materials for structural elements due to the high stresses that accompany the operational conditions of aircraft. The requirement for a low unit mass of material is justified from the point of view of the aircraft's weight and, consequently, its payload, range, fuel consumption, exhaust emissions, etc. In addition to high strength and low weight, materials used to build aircraft also require other requirements, such as corrosion resistance and minimal absorbability, stem from the conditions in which aircraft are operated, meaning they may be in atmospheric layers with high humidity or simply used in conditions of atmospheric precipitation (Galiński, 2016; Kharchenko et al., 2020; Megson, 2016; Katunin, 2019; Bruce, 2013; Fielding 2017; Dingle & Tolley, 2013):

- the immediate strength of a structure is its ability to withstand loads without being damaged, including avoiding permanent deformations,
- stiffness of a structure defines its resistance to elastic deformations that occur under applied loads.
- material plasticity refers to its ability to undergo permanent deformation under load. This is a key property in the production process of structural elements.
- the hardness of a material is its resistance to deformation caused by concentrated forces.

- the heat resistance of a material is its ability to resist corrosion at elevated temperatures.
- the heat strength of a material refers to its relatively small decreases in strength as the temperature increases.
- fatigue strength is the ability of a material to withstand cyclic loads (varying over time) without incurring damage or fractures. This means that the material can endure repeated, fluctuating loads that do not exceed its static strength limit, but may cause micro-damage, which can lead to failure over time resistance to water absorption (moisture),
- water resistance – absorbability is a material's ability to absorb and retain water, typically measured as the ratio of the mass of water the material can absorb to its dry mass. It is usually expressed as a percentage. Absorbability is an important parameter in evaluating building materials such as concrete, bricks, or wood, as it affects durability, frost resistance, and other technical properties.
- a material with high absorbability can more easily absorb water, which may lead to weakening, corrosion, or cracking, especially under fluctuating temperatures.
- many others.

Currently used materials for the construction of structural elements are mostly metallic, non-ferrous materials (Cemal et al., 2013; Siddiqui, 2015; Ashby et al., 2000):

- aluminum and its alloys (avional, pure aluminum),
- titan and its alloys,
- Magnesium alloys (elektron),
- Structural alloy steels for heat treatment – (e.g., 30HGSA, 30HGSNA)
- Structural alloy steels for carburizing – (e.g., 18HNWA, 18H2N4WA)
- Structural alloy steels for nitriding – (e.g., 38HMJA)
- Maraging steels -precipitation-hardened – (e.g., 18N11400, 18N12400)

In addition to the above-mentioned basic groups of metals, polymeric materials are also used in the construction of aircraft (Baker et al., 2016; Titterton, 2015; Pantelakis & Tserpes, 2020):

- polyamides (ERTALON 6 SA, ERTALON 66 SA- GF30),
- composite materials (GFRP – Glass Fiber Reinforced Plastics., CFRP – Carbon Fiber Reinforced Plastics, CMC (ceramic matrix composites),
- glass fibers,
- carbon and graphite fibers,
- boron fibers,
- aramid fibers (Kevlar).

In the construction of aircraft structural elements, structural solutions are used, which involve the use of a thick, multi-layered coating to build the wing, carrying all the loads. The shell structure does not contain structural elements such as girders, ribs or stringers (Kharchenko et al., 2020).

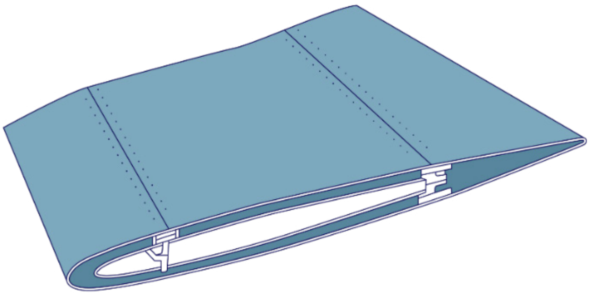

Figure 1. The monocoque structure of an airplane wing, Adopted from: "Budowa Statków Powietrznych I System Żeglugi Powietrznej" by V. Kharchenko et al., 2020. Biblioteka Międzynarodowej Wyższej Szkoły Logistyki i Transportu, Wrocław.

However, in most cases, the structure of the aircraft's load-bearing elements consists of a load-bearing structure made of the above-mentioned materials and a skin made of another material built on it.

An example of a structural solution for a wing based on a girder structure is shown in the drawing below (Kharchenko et al., 2020).

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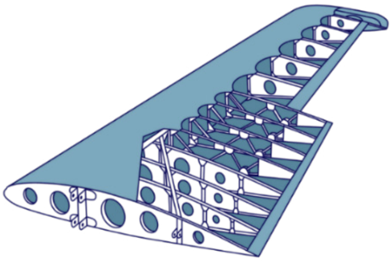

Figure 2. The monocoque structure of an airplane wing, Adopted from: “Budowa Statków Powietrznych I System Żeglugi Powietrznej” by V. Kharchenko et al., 2020. Biblioteka Międzynarodowej Wyższej Szkoły Logistyki i Transportu, Wrocław.

This construction method means that the mass of the aircraft’s supporting element (e.g., wing) results from the sum of the masses of at least two different materials: the material of the supporting structure and the material of the skin.

An example of stress distribution in a flap with a spar structure made of D16AT aluminum alloy (Baraniecki et al., 2008).

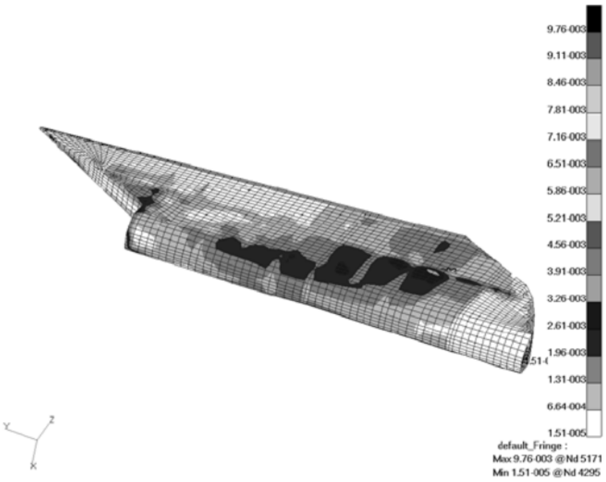

Figure 3. Stress distribution (Huber-Mises) in the flap of a fighter-bomber aircraft – general view. Adopted from: “Analiza Numeryczna Stanu Naprężenia w Klapie Samolotu Odrzutowego” by Baraniecki et al., 2008. Acta mechanica et automatica, 2(1), (2008).

The stress contour presented above in Figure 3 showed that the stresses in the analyzed aircraft flap did not exceed 9.76*10-3Mpa (Sohel, 2016). It should be noted that such values were determined assuming a uniform distribution of unit pressure on the flap surface.

The article undertakes research, the results of which are intended to assess the possibility of making the entire load-bearing element from one type of material. A material commonly used in constructing components of other types of vehicles is foamed polypropylene (PPE). This material is used, among others, in the construction of (Baker et al., 2016):

- car parts – in the automotive industry, EPP is used primarily for the production of seat elements, bumpers, floor molding inserts and trunk construction elements,
- construction models (ship models, air crafts models),
- impact-absorbing inserts,
- many other.

Propylene is most commonly obtained from the thermal cracking process in oil refineries, during which crude oil or natural gas is heated to very high temperatures, causing larger hydrocarbon molecules to break down into smaller ones. As a result, propylen is produced, the primary raw material for polypropylene production. The propylene polymerization process usually takes place in reactors under high pressure and temperature. There are different polymerization methods, but two are most commonly used. Propylene is introduced into the reactor in a gaseous form, where, in the presence of a catalyst (e.g., Ziegler-Natta or metallocene catalyst), it polymerizes into polypropylene molecules. After polymerization is complete, the polypropylene undergoes a cooling process and is then formed into pellets. In this form, it is most often delivered to manufacturers of plastic products. Depending on the application, various substances can be added to polypropylene to modify its properties, such as UV stabilizers, colorants, plasticizers, or other additives that improve its strength, flexibility, or resistance to chemical factors.

The general properties of expanded polypropylene (PPE) largely depend on its degree of expansion (density). The general properties of foamed polypropylene (PPE) depend largely on its degree of foaming (density). The general range of properties for polypropylene foamed to varying degrees is as follows (PRO EPP, 2021; Gurgen & Katalin, 2023; Gokhale et al., 2019):

Table 1. The general properties of foamed polypropylene (PPE). Adopted from: http://eppgroup.pl/o-epp/

Properties	Test	Units	Density (g/l)											
			20	30	40	50	60	80	100	120	140	160	180	200
Energy absorption during dynamic impact	The tower tests vertical Flat stroke 8 km/h 23'C tests vertical Flat stroke 8 km/h 23'C	J/l												
• Deformation 25%			40	70	100	115	160	240	330	460	530	610	710	800
• Deformation 50%			100	160	230	280	370	630	770	1	1.3	1.5	1.7	1.9
• Deformation 75%			200	290	410	500	670	1.2	1.5	2	2.8	3.2	3.55	4
Resistance to squeezing	ISO 844	kPa												
• Deformation 25%			80	150	210	275	340	500	700	900	1.15	1.4	1.7	2
• Deformation 50%			150	20	300	370	475	700	960	1.3	1.6	2	2.5	3
• Deformation 75%			370	460	600	800	1	1.6	2.3	3.2	4.5	6	7.8	9.6
Resistance to stretching	ISO 1798	kPa	340	490	640	785	930	1,21	1,48	1,745	2	2,245	2,48	2,705
Lengthening at stretching	ISO 1798	%	32	30	28	26	25	22	19	17	15	13	11	10
Burning rate	ISO 3795 12.5 mm	mm/min	115	80	60	50	40	30	25	20	18	16	14	13

Shapes made of foamed polypropylene are formed using the SCM (Steam Chest Molding) method, which enables the production of products with complex shapes and various densities. In the production process, the foamed granules are combined using steam applied under appropriate pressure. One of the greatest advantages of foamed polypropylene (EPP) is its environmentally friendly nature. This material is fully recyclable and does not contain environmentally harmful chemicals. EPP plays an important role in promoting a circular economy because it can be recycled many times without losing its key properties. Recycling this material reduces the amount of waste and the need for primary raw materials, which is important for sustainable production and consumption. There are several methods for recycling EPP, each with its own specific applications and requirements. The most commonly used are:

- mechanical recycling, which involves grinding waste into granules that can be processed into new products,
- chemical recycling, in which EPP polymers are broken down into monomers or other chemical substances, reused to produce polypropylene,
- energy recycling, which involves using EPP as an energy source.

The most environmentally friendly method of processing elements made of EPP is the first of the previously mentioned techniques. It is worth emphasizing that this process is both simple and inexpensive to implement, consisting of the following stages:

- preparing material for recycling – selection and cleaning,
- grinding and compacting the material into an agglomerate,
- raw material extrusion,
- granulation – cooled granulate threads are cut in a cutter into granules of the appropriate size,
- packing.

The use of foamed polypropylene in industry helps reduce the carbon footprint. Processed versions of this material are becoming increasingly popular and enable the creation of a wide range of components for various industry sectors.

2. Research

In order to determine the suitability of foamed polypropylene for the construction of aircraft components, we began by examining a very important property – tensile strength.

Tensile strength test samples perpendicular to the end faces were made by cutting three laboratory samples with dimensions of 150 x 150 x 150 mm from an EPP board with dimensions of 1000 x 1000 x 80 mm. Foamed polypropylene with a density of 40 g/l was used to make the samples. These samples were glued to rigid boards using adhesive and attached to a testing machine (self-aligning attachment). Before testing, the samples were air-conditioned for two days at room temperature (23 ± 2) °C and relative humidity (RH) (50 ± 5)%.

The Matest 20kN testing machine from Matest Service was used to measure the tensile strength perpendicular to the end faces (EN 1607, 2013).

The samples, prepared as described above, were placed in the jaws of the testing machine, and then the distance between the sample clamping heads was increased at a constant speed (10 ± 1) mm/min until the sample was damaged.

The test was carried out at a temperature of (23 ± 5) °C. The results obtained during the research were as follows:

The breaking forces of individual samples recorded during the test are presented in Table 2.

Table 2. The breaking forces of individual samples recorded during the test

Sample No	Force, kN
1	611
2	614
3	615

Tensile strength perpendicular to the end faces, marked as σ mt (MPa), was calculated according to the formula:

$$\sigma_{mt} = \frac{F_m}{A_0} \cdot 10^3 \tag{1}$$

where:
F_m – maximum tensile force, kN;
A_0 – sample area (100 x 100) mm, mm2.

The values obtained using the above formula are presented in Table 3.

Table 3. Tensile strength of the tested samples

Sample No	Force, kN	Tensile strength, σ m, MPa
1	611	61,1
2	614	61,4
3	615	61,5

Due to the fact that the tested material is a foamed material and there is a theoretical possibility of water absorption, the water absorption of the tested material was also analyzed during the tests. This circumstance is important because aircraft often come into contact with atmospheric precipitation or high concentrations of moisture during operation. The tendency to soak the tested material with water would exclude its use in constructing aircraft structural elements.

Samples for testing water absorption by partial immersion were prepared by cutting four laboratory samples with dimensions of 200 x 200 mm from an EPP board with dimensions of 1000 x 1000 x 80 mm. Foamed polypropylene with a density of 40 g/l was used to make the samples.

Before testing, the samples were conditioned at room temperature (23 ± 2) °C and relative humidity (RH) (50 ± 5)% for at least 14 days until constant weight was reached.

To determine water absorption during long-term, partial immersion (EN 12087:2013), containers (water tanks) with a device enabling constant maintenance of the water level in the range (±2 mm) were used. The prepared samples with the measured weight were placed in containers on special supports that allowed water to contact the entire bottom surface of the samples. They were loaded to keep the samples in one position and counteract the buoyant force. The containers were filled with water so that the bottom surface of the samples was immersed to a depth of (10 ± 0.5) mm. The water level was kept constant throughout the study period, which lasted 28 days. The ambient temperature was (23 ± 2) °C. The immersed surface of the samples was the UV-exposed surface.

After 28 days, the samples were allowed to drain for (10 ± 0.5) minutes and placed on a steel grid/mesh at an angle of 45°. Then, the mass of the samples was determined.

Water absorption during long-term partial immersion, marked as W_lp, was calculated according to the formula:

$$W_{lp} = \frac{m_{28} - m_0}{A_p} \tag{2}$$

where:
m_0 – sample weight before testing, kg;
m_{28} – mass of the sample after 28 days of partial immersion in water, kg;
A_p – bottom surface of the sample immersed in water, m2.

The results of this study are presented in Table 4.

Table 4. Water absorption of the tested samples

Sample No	1	2	3	4
Sample weight before testing, $\boldsymbol{m_0}$, g	33.1	33.0	33.1	33.1
Sample weight after testing, $\boldsymbol{m_{28}}$, g	33.4	33.1	33.3	33.2
Sample surface, $\boldsymbol{A_p}$, m^2	0.04	0.04	0.04	0.04
Water absorption, $\boldsymbol{W_{lp}}$, kg/m^2	0.01	0.00	0.00	0.00
Average	0.00			

The results obtained in this study indicate that water absorption is close to zero, which is an undoubted advantage in the context of the material's use in the construction of aircraft components.

3. Conclusions

1. The tensile strength tests carried out gave rise to the conclusion that the value of this property (average of the obtained results 61.3 MPa) was not lower than the registered operational stresses in aircraft components. This circumstance indicated the potential usefulness of the tested material in the construction of aircraft.
2. The water absorption results of the tested material obtained during the tests indicated that the water absorption was close to zero, which was considered an advantage in the context of the material's use in aircraft construction.
3. The results of subsequent tests will determine the suitability of foamed polypropylene (PPE) for the construction of aircraft structural elements.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

References

1. Ashby, M., Shercliff, H., & Cebon, D. (2000). *Materials: Engineering, Science, Processing and Desing*. Elsevier.
2. Baker, A., & Murray, L. (2016). *Composite Materials for Aircraft Structures*. American Institute of Aeronautics & Astronautics.
3. Baraniecki, R., Kurdelski, M., & Leski, A. (2008). Analiza Numeryczna Stanu Naprężenia w Klapie Samolotu Odrzutowego. *Acta Mechanica et Automatica, 2*(1), 5–8.

4. Bruce, K. (2013). *Analysis of Aircraft Structure*. Cambridge University Press.
5. Dingle, L., & Tolley, M. (2013). *Aircraft Engineering Principles*. Routledge.
6. EN 1607. (2013). *Thermal insulating products for building applications. Determination of tensile strength perpendicular to faces*. https://standards.iteh.ai/catalog/standards/cen/6bc3a815-c07a-4a20-b1c1-85885fcee1ce/en-12087-2013?srsltid=AfmBOorj2b5w7eHken2vgy8PlultOmdW4fBCqaM1hlo_2nVaeZb9F9Zq
7. EN 12087. (2013). *Thermal insulating products for building applications – Determination of long term water absorption by immersion*. https://standards.iteh.ai/catalog/standards/cen/6bc3a815-c07a-4a20-b1c1-85885fcee1ce/en120872013?srsltid=AfmBOorj2b5w7eHken2vgy8PlultOmdW4fBCqaM1hlo_2nVaeZb9F9Zq
8. Fielding, J. (2017). *Introduction to Aircraft Design*. Cambridge University Press.
9. Galiński, C. (2016). *Wybrane zagadnienia projektowania samolotów*. Instytut Lotnictwa.
10. Gokhale, A., Eswara, N., & Basu, B. (2019). *Light Weight for Defense Aerospace and Transportation*. Springer.
11. Gurgen, S., & Katalin, I.. (2023). *Modern manufacturing Processes for Aircraft Materials*. Elsevier.
12. Katunin, A. (2019). *Aircraft structures: Mechanics, Design and Maintenance*. Politechnika Śląska.
13. Kharchenko, V., Bugayko, D., & Ostroumov, I. (2020). *Budowa Statków Powietrznych I System Żeglugi Powietrznej*. Biblioteka Międzynarodowej Wyższej Szkoły Logistyki i Transportu.
14. Kumar, D., Raj, G., Shivaani, G., & Sreehari, V. (2018). Structural Analysis of Aircraft Wings Made of Natural Fiber Reinforced Composites. *International Journal of Mechanical Engineering and Technology, 9*(11), 1262–1268. https://iaeme.com/MasterAdmin/Journal_uploads/IJMET/VOLUME_9_ISSUE_11/IJMET_09_11_130.pdf
15. Kuşhan, M., Gürgen, S., & Sofuoğlu, M. (2013). *Materials, Structure and Manufacturing for Aircrafts*. Springer Link.
16. Megson, T. (2016). *Aircraft Structures for Engineering Students*. Elsevier.
17. Pantelakis, P., & Tserpes, K. (2020). *Revolutionizing Aircraft Materials and Processes*. Springer.
18. PRO EPP. (2021). *Czym jest Poliprylen spieniony? (EPP)*. http://eppgroup.pl/o-epp/
19. Siddiqui, T. (2015). *Aircraft Materials and Analysis*. McGraw-Hill.
20. Sohel, R. (2016). *Advanced Composite Materials for Aerospace Engineering*. Elsevier.
21. Titterton, F. (2015). *Aircraft Materials and Processes*. Himalayan Book.