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IDENTIFYING THE INFLUENCE OF WINDING ANGLES ON THE STRENGTH PROPERTIES OF CARBON FIBER-REINFORCED PLASTIC TUBES

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In this paper, a study of carbon fiber reinforced plastic tubes, which are widely used in overwhelming of technical industries, including aerospace industry, with single and combined winding angles (30°, 45°, 60° and 80°) fabricated by wet winding method on X-Winder machine has been carried out. The core problem addressed in this research is identifying optimal winding angles of carbon fiber reinforced plastic tubes at which the strength parameters remain in a relative equilibrium. Compressive strength, tensile strength and impact strength tests were carried out.

The results of specimens with single winding angle showed that a maximum tensile strength of 630 MPa was achieved at a winding angle of ±30° and a maximum compressive strength of 380 MPa was achieved at an angle of ±80°. The maximum value of impact strength was achieved at a winding angle of ±60°. In order to obtain a balance in the strength characteristics of the tubular rods, combined reinforced winding with ±30°/45°, ±30°/60°, ±30°/80°, ±80°/45° and ±80°/60° angles were investigated. High values of compressive strength of 434 MPa, tensile strength of 675 MPa and impact strength of 165 kJ/m^2 were achieved with ±30°/80° combined winding angle. The fibers of the material, which were oriented closer to the compression direction, resulted in reduced efficiency of transferring compressive forces between the fibers and decreased compressive strength. This uniform stress distribution permitted the load to be equally divided between the fibers, which effectively utilized their strength properties. Thus, results confirmed the importance of selecting the optimal winding angles to create carbon fiber reinforced plastic tubes with the required strength properties

Keywords: carbon fiber reinforced plastic tubes, epoxy resin, fiber strength, impact strength, stress distribution, winding angles, fiber, matrix

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1. Introduction

Carbon fiber reinforced plastic (hereinafter as CFRP) is a modern aerospace material with a number of undeniable advantages over classical materials. It is characterized by outstanding values of specific strength and modulus of elasticity, near-zero thermal expansion coefficient, high resistance to environmental influences, and manufacturability of products. Because of these qualities, the use of CFRP is a trend in aircraft and spacecraft, they are increasingly exploited in the automotive industry and household appliances.

Composite tubular rods and connecting elements such as couplings, fittings and joints are widely used in the construction of space objects such as satellites, telescopes and spacecraft. These structural elements have high strength, rigidity and unique properties that allow them to operate in the extreme conditions of space. They play an important role in the creation of load-bearing frames and ensure the reliability and durability of space structures [1].

CFRP rods can be manufactured by means of multiple methods. Particularly the winding process belongs to the branch of composites in which plastics are utilized as the matrix material and the dispersed phase, responsible for reinforcement, is in the form of fibers, such as glass, aramid, or carbon fibers. Winding method has a key advantage over other techniques, in varying mechanical parameters by changing the fibers' orientation. In the case of tubular rods, designed to be exploited under high mechanical loads, fibers' winding orientation is crucial to gain optimal strength characteristics [2].

A better understanding of the influence of winding angles on strength parameter of carbon fiber reinforced plastic tubes will ultimately allow to optimize optimal winding angle selection in manufacture of carbon fiber reinforced plastic tubes. Therefore, research devoted to the development of significance of the selection of winding angles is essential and relevant in the manufacture of CFRP tubes.

2. Literature review and problem statement

In space engineering, aluminum alloys have traditionally been used for truss structures. However, to achieve higher performance and improved characteristics, materials used on spacecraft now include a new class of materials, composite plastics, which consist of a matrix, usually epoxy resin, and reinforcing fillers such as glass fiber, carbon fiber or aramid fiber.

The paper [3], presents the impact of winding angles on the filament wound Type 4 composite pressure vessels' stress distribution and burst pressure predictions were investigated using the Ansys ACP Prep/Post and static modules. An analysis has been performed on the effects of both individual and combined winding angles. Finding the angles that have the most significant impact on weight and burst pressure is the aim of this work. By modifying the fiber winding angles, arrangement, and number of layers, composite pressure vessels can be made to fit specific service circumstances while guaranteeing reliable performance. The study is based on numerical methods (FEA) using Ansys. There is a lack of experimental data to validate computational models, such as physical tests for fracture pressure and durability. This data could confirm the accuracy of the simulations.

The data in research work [4] specifies that organoplastic and carbon fiber reinforced plastic, having densities of 1.35 g/cm^3 and 1.45 g/cm^3 respectively, are preferred to meet the minimum structural weight requirements. At the same time, carbon fiber composites have a significantly higher modulus of elasticity both in relation to organoplastics and even more so in relation to AMg-6. Thus, for the fabrication of a dimensionally stable truss from composite materials it is most appropriate to use a carbon fiber composite.

Over the course of the research [5], various methods for obtaining CFRP were studied. To create CFRP samples, manual molding methods with mechanical pressing and vacuum infusion were used. The impact strength of CFRP increased by 34 % (258 kJ/m^2), and the compressive strength increased by 30 % (552 MPa) compared to the unmodified sample. The best performance was achieved using the carbon fiber/Kevlar scheme with polyurethane rubber modified epoxy resin in vacuum infusion. This method resulted in a significant 42 % increase in impact toughness and 35 % increase in compressive strength. However, the strength performance of CFRP was achieved via various material combinations, and this suggests that it is worthwhile to conduct a study to obtain the similar or better results while maintaining the same material by identifying the optimal winding angle. The angles of fiber laying in composite materials play a key role in the redistribution of loads and the formation of strength characteristics. However, this aspect is not directly investigated in the article.

In this research [6], composite tubes with various resins base material, Swancor901, Epiran-1012, and Epiran-06FL reinforced by different fibers glass, carbon, and kevlar fibers, according to the compatible role, with the angle of 45° and unidirectional and same size, thickness, and diameter, were produced by the winding method. The results showed that the highest ultimate tensile strength was obtained for carbon fibers reinforced tube (CFR) equal to 139 MPa, which was 136 % and 26 % higher than kevlar fibers reinforced tube (KFR) and glass fibers reinforced tube (GFR), respectively. Despite the worth noting results, the winding angle of composite tubes was chosen to be 45°.

The article uses a fixed fiber winding angle (45°), but has not been investigated:

– how to change the winding angle (for example, 0°, ±30°, 90°) it affects the tensile, compressive and bending strength;

– how a combination of angles (e.g., alternating 0°/±45°) can optimize performance for different types of loads.

[7] research work investigated the behavior of a cylindrical shell subjected to internal pressure load and axial thrust and to compare the performance of a cylindrical shell made of a standard steel for aeronautics purposes with a carbon-fiber-reinforced composite with a symmetric and balanced layup (90°, 0°, ±45°). The results demonstrated that the carbon-fiber-reinforced cylindrical shell has considerable strength and buckling characteristics compared to traditional steel shells.

The study is based on numerical modeling (CFD and FEM), but there is no experimental verification. There are no real prototype tests that could confirm the reliability of the numerical data.

In [8], the structural behavior and thermal characteristics of composite carbon-epoxy tubes with dimensions 1,040×140×70 mm, and the fiber configuration ±45°/0°/±45°/0°, with 0.05 mm for each layer were studied. A maximum stress of around 42 MPa is found for the connections between two tubes. The stress is approximately uniform along the middle area. This stress distribution also can be improved via combined winding angles. The article is limited to the use of fixed angles of fiber laying, without investigating: the effect of changing angles (for example, ±30°, ±60°); combinations of laying angles to optimize strength characteristics.

To date, there are a range of ways to manufacture CFRP tubes. The wound carbon material (reinforcement) can be in a "dry" state, in the form of prepregs (carbon material impregnated with binder and partially cured) or "wet" – when the reinforcement is soaked with binder just before winding. Carbon reinforcement can be in the form of fabrics, tapes or roving. It has been established that the strongest CFRP tubes are obtained in the "wet" mode of roving winding [9, 10]. Fixed winding angles are used, but their variations and optimal combinations for increasing strength characteristics have not been studied.

The crushing behavior of different winding angles of glass fiber reinforced epoxy resin (GRE) pipes at elevated temperatures is discussed in [11]. Two different winding angles of the composite tubes, ±55° and ±63°, were selected for the study. GRE tubes with ±55° and ±63° angles were compressed using a universal testing machine at room temperature and elevated temperatures of 45 °C, 65 °C and 95 °C. The temperatures were selected based on the glass transition temperature (*Tg*). The results show that the compressive strength decreases significantly with increasing temperature. This is due to the change in the properties of the GRE pipe from a stiff state to a rubberier state as the composite pipe reaches the *Tg* temperature. GRE pipes with a winding angle of ±55° exhibit higher compressive strength compared to ± 63°. The article considers only glass fiber reinforced with epoxy resin, but other materials such as carbon fiber have not been studied. Only two winding angles (±55° and ±63°) are considered, but it is not investigated how the angles ±30°, ±45°, ±60°, ±80° or their combinations affect the mechanical properties.

In this study [12], the effect of winding angle on the impact properties of thin-walled tubes was investigated. Composite specimens with varying fiber winding angle (±0, ±10°, ±20°, ±29°, ±45°, ±60°, ±70°, ±80° and ±90°) made of carbon fiber (Torayca T700S) and PR 102 epoxy resin were investigated. Impact strength tests were performed. Impact energy data were obtained for the unsprung specimens at different winding angles, which showed that the maximum impact energy (234.5 kJ/m^2) was achieved at a winding angle of ±45°. In addition, it was found that at winding angles of ±70° or more, extensive delaminated zone formation occurred. Fixed winding angles are considered (±0°, ±10°, ±20°, ±29°, ±45°, ±60°, ±70°, ±80°, ±90°), but the angles in the intermediate ranges or their combinations have not been studied. There is no analysis of the effect of alternating angles on the properties of the composite.

[13] work aimed to study the effect of winding angle for ±45°, ±60° and ±75° CFRP tubes. The maximum compressive modulus of 3.5 GPa was observed at a winding angle of ±45°, and the compressive strength was 60 MPa. And the maximum compressive strength of 65 MPa was achieved at ±60°. Only three fixed winding angles are considered (+45°, +60°, +75°). It has not been investigated how intermediate angles or their combinations (for example, alternating ±45° and ±60°) can improve mechanical properties.

The study [14] investigates the mechanical properties of composite high-pressure vessels at various winding angles and layer schemes. The optimal scheme was recognized with angles of ±55° and the inclusion of layers at an angle of 90°, which showed a minimum circumferential voltage of 120 MPa, which is 16 % lower than the traditional scheme of +55°/–55° (143 MPa). Increasing the number of layers from 10 to 18 made it possible to further reduce the voltage by 44.3 %.

In [15], experimental results are presented in which stress-strain characteristics were obtained for different winding angles and compared with the results obtained using conventional laminar theory. It was found that the point at which the elastic limit is reached varies with the winding angle, especially when deviating from the ideal value of ±55°. The research is focused only on glass fiber with epoxy resin. Composites with other fibers (e.g., carbon, basalt, or Kevlar) have not been studied.

The study [16] focused on investigating the effect of fiber orientation on the energy absorption capacity of composite tubes under axial compression. Combined reinforced fiber angles (0/90, 15/75, 30/60, 45/45, 60/30 and 75/15) were used in the experiment. The results showed the advantages of fiber orientation at 15/75 and 75/15 angles in terms of pre-compression preload capacity and absorbed energy. Fixed fiber laying angles were considered (±15°, ±30°, ±45°, ±60°, ±75° and 0°/90°). The possibilities of combining the laying angles have not been investigated.

Winding angles of composite tubes allow balancing the strength characteristics by selecting the optimal angle or combination of angles to obtain better strength parameters while maintaining the same dimensions, weight and material of tubular rods. Despite the existence of studies on the effect of winding angles on CFRP tubing, there are still limited reports on combined reinforcement with different winding angles at which the strength characteristics remain balanced under compressive, tensile and impact loads. All this allows to assert that it is expedient to conduct a study on identify the effect of single and combined winding angles on the strength performance of CFRP tubes and provide optimal winding pattern for tubular rods.

3. The aim and objectives of the study

The aim of the study is to identifying the effect of winding angles on the strength performance of CFRP tubes. The optimum winding angles will provide a better compressive, tensile and impact strength of CFRP tubes with better mass efficiency respectively.

To achieve this aim, the following objectives are accomplished:

– determining strength characteristics of carbon fiber reinforced plastic tubes with single winding angle;

– determining strength characteristics of carbon fiber reinforced plastic with combined winding angles.

4. Materials and methods

The object of the research is CFRP tubes with single and combined winding angles obtained by wet winding method. The scientific hypothesis assumes the possibility of improving the strength characteristics of carbon fiber composite tubes by applying combined winding angles, which contributes to a balanced distribution of loads in tension compression and in impact, preserving the geometric dimensions of tubular samples.

Heat-resistant epoxy compound Ethal-Inject-T (Epital) was used for the study, curing mode – 4 hours at 150 °C+1 hour at 180 °C. Carbon roving DowAksa/24k (Aksaca, Turkey) was used as carbon fiber. This material is applied in the creation of structural elements requiring increased rigidity and strength. An X-Winder 2.0 4-Axis Model 4X-23 winding machine (X-Winder LLC, USA) was used to produce carbon fiber tubing, which allows carbon rovings to be wound via the wet winding method (Fig. 1).

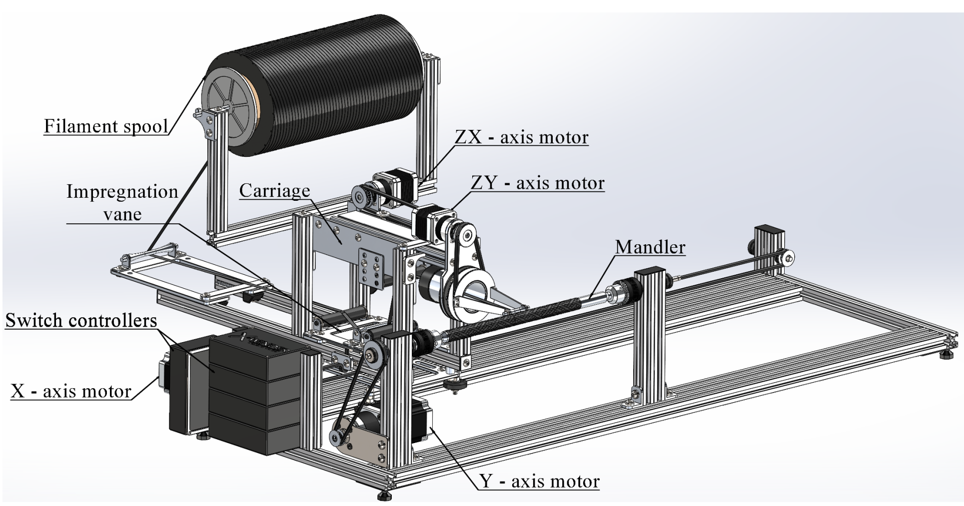

Fig. 1. X-Winder filament winder

The main working elements of the machine are switch controllers, stepper motors on each axis' (*X*, *Y* and *ZX*, *XY*), carriage, mandrel, system of guides for carbon fiber roving, tension control and impregnation vane. The winding process is largely automated, where impregnated continuous filament tow is wound over rotating mandrel. The fiber tension control and resin impregnation control are manual. The synchronized motion of *X*, *Y* and *ZX*, *XY* axis' stepper motors controls fibers path, executing desired winding pattern. Furthermore, each stepper motor can be operated manually. This feature was applied for the final drying process.

To simplify the winding process, these operations were automatized by the X-Winder Designer software. This software allows real-time control of sample length, diameter, thickness, winding angles and material consumption.

Preliminary, it was accepted that specimens of CFRP tubes' dimensions are unified to following parameters: length 300 mm; inner diameter 16 mm; wall thickness 4 mm. The strength characteristics of the obtained tubes were evaluated according to GOST 11262-80 (ISO R527) for tensile-compression, GOST 4647-2015 for impact toughness.

Fig. 2 shows CFRP tubes with different winding angles. At manufacturing of samples of CFRP tubes the samples wound with winding angles ±30°, ±45°, ±60°, ±80°.

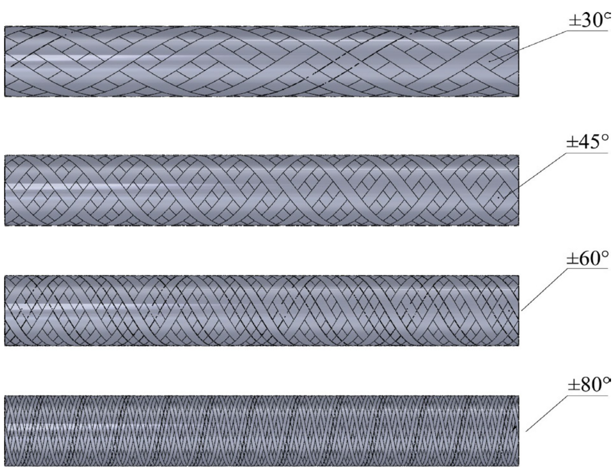

Fig. 2. Samples of carbon fiber reinforced plastic tubes with different winding angles

5. Results of studying strength parameters of carbon fiber reinforced plastic tubes

5. 1. Determining strength characteristics of carbon fiber reinforced plastic tubes with single winding angle

As mentioned earlier, 3 specimens for each strength test were made from a single tube, which were wound at angles of ±30°, ±45°, ±60° and ±80°. In order to fabricate CFRP tube specimens, all the parameters of the resulting product are set in the X-Winder Designer software. In our case, 20 layers were specified to achieve a thickness of up to 4 mm. A total of 12 samples with winding angles of ±30°, ±45°, ±60° and ±80° with a length of 300 mm were fabricated. Then 3 specimens were prepared for each test. Fig. 3, 4 show the strength data of the obtained specimens.

Fig. 3 shows that the maximum compressive strength of 380 MPa is achieved at ±80° winding angle. This is explained by the fact that at this winding angle the fibers of the material are located along the compression direction, which contributes to a more effective transfer of compressive forces between the fibers, enhancing the compressive strength. But has a minimum tensile strength value of 284 MPa, that at this winding angle the material fibers are arranged perpendicular to the tensile direction, which reduces the efficiency of transferring tensile forces between the fibers and leads to a reduction in tensile strength.

The maximum tensile strength of 630 MPa is achieved at ±30° winding angle. At this angle, the fibers of the material are oriented closer to the tensile direction, which ensures a more efficient transfer of tensile forces between the fibers and increases the tensile strength. A minimum compressive strength value of 230 MPa is obtained at ±30° winding angle. Under this angle, the fibers of the material are oriented closer to the compression direction, which reduces the efficiency of transferring compressive forces between the fibers and leads to a decrease in compressive strength.

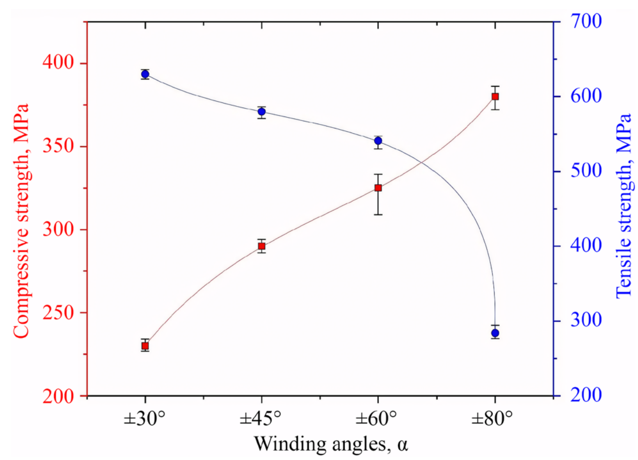

Fig. 3. Strength characteristics of carbon fiber reinforced plastic tubes with different winding angles

5. 2. Determining strength of CFRP tubes with combined winding angles

The attached graph in the Fig. 4 shows that the maximum value of impact strength is achieved at a winding angle of ±60°. At this winding angle, the material is capable of having a denser and more compact structure, which contributes to greater impact strength. The denser structure might prevent the material from breaking on impact and increase its ability to absorb and transfer impact energy.

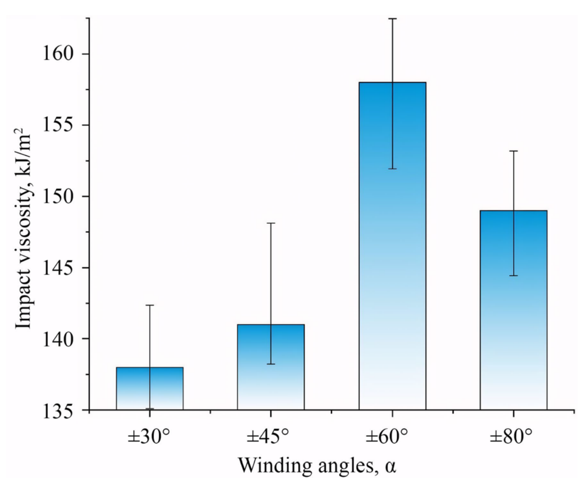

Fig. 4. Impact toughness of carbon fiber reinforced plastic tubes with different winding angles

Hence, the winding angle affects the orientation of the material fibers and in turn the strength characteristics of the material. Different winding angles may result in different strength values depending on the direction of the applied loads. To achieve more balanced strength characteristics, reinforcement with different winding angles can be combined. The winding angles can be selected to achieve the optimum combination of tensile and compressive strengths. Combined reinforcement allows the advantages of different load directions to be utilized more effectively and materials with more balanced strength characteristics to be designed.

Based on the data provided, it was proposed to investigate the effect of different combinations of winding angles (±30°/45°, ±30°/60°, ±30°/80°, ±80°/45° and ±80°/60°) on the strength properties of CFRP tubes.

The strength properties of the CFRP tubes using different combined winding angles are shown in the following figures (Fig. 5, 6).

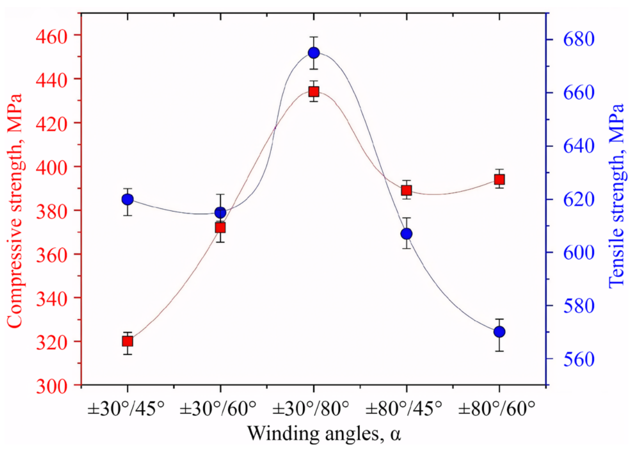

Fig. 5. Strength characteristics of carbon fiber reinforced plastic tubes with combined winding angles

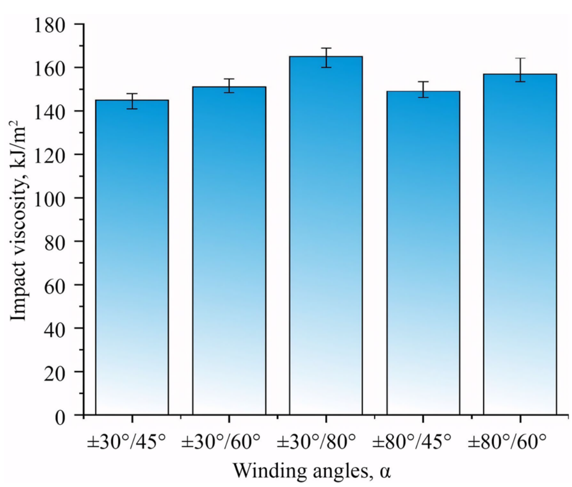

Fig. 6. Impact toughness of carbon fiber reinforced plastic tubes with combined winding angles

These combined winding angles were specified in X-Winder Designer software, which allows the winding process to be modelled and optimized. The data shows that the combination of winding angles ±30°/80° has a substantial effect on the strength properties of CFRP tubes. This combination of winding angles resulted in a high compressive strength of 434 MPa, tensile strength of 675 MPa and impact strength of 165 kJ/m^2, compared to ±30°/45°, ±30°/60°, ±80°/45° and ±80°/60° winding angles.

6. Discussions of results of investigating winding angles influence on strength characteristics of carbon fiber reinforced plastic tubes

Fibers placed at an angle of ±30° are able to better cope with tensile loads, whilst fibers at an angle of ±80° can perform better under compressive loads (Fig. 3). Combined reinforcement with different winding angles also contributes to a more even distribution of stresses in the material (Fig. 5). High compressive strength of 434 MPa, tensile strength of 675 MPa were achieved in the combined reinforcement ±30°/80°. Despite the excellent impact strength of ±45° winding angle [12], the combined reinforcement of ±30°/80° kept this parameter at 165 kJ/m^2 (Fig. 6), whilst similar results were achieved only under 60° (Fig. 4) with not as high tensile load distribution.

According to the results, when combined reinforcement with different winding angles is applied, the fibers are oriented in different directions, which contributes to a greater load distribution. This means that the load is distributed evenly between the fibers, which helps to make more efficient use of their strength properties. As a result, the material becomes more resistant to tension and compression, resulting in superior strength. Alternatively, the interaction between the fibers can also contribute to the strength and stiffness of the material, resulting in improved tensile and compressive strength properties or reduce them, similar to the increasing trend from ±45° to ±60° and decreasing trend from ±60° to ±75° winding angle [13].

The way this phenomenon is explained is as follows: when combined reinforcement with different winding angles is applied, the fibers are oriented in different directions, which contributes to a higher load distribution. Fibers placed at an angle of ±30° are effective in handling tensile loads, whilst fibers at an angle of ±80° are superior in handling compressive loads. In addition, the combined reinforcement with different winding angles promotes a more uniform stress distribution in the material and have advantages in terms of pre-compression preload capacity and absorbed energy [16].

This uniform stress distribution allows the load to be equally distributed between the fibers, which effectively utilizes their strength properties. As result, the material becomes more resistant to tension and compression, thereby increasing its strength. Furthermore, the interaction between the carbon fibers in the combined reinforcement helps to improve the strength and stiffness of the material. This causes an improvement in the tensile and compressive strength properties of the material. Thus, the combined reinforcement allows the material to have higher strength in both tension and compression. It should also be noted that the combined winding allows to achieve the similar strength characteristics of the tubes as the combination of materials [5], while maintaining the mass and dimensional parameters of the tubes.

Notwithstanding, the process of revealing the strength characteristics of CFRP tubes excluded the variability of the environment (temperature, humidity and vacuum condition). These limitations should be considered in future studies to obtain more detailed results. Special attention should be paid to the vacuum conditions, due to the specificities of the bonding compounds.

7. Conclusions

1. It was found that a winding angle of ±30° results in a maximum tensile strength reaching a value of 630 MPa, while an angle of ±80° provides a maximum compressive strength of 380 MPa. This is attributed to the different directions of fiber orientation at different winding angles. Thus, results demonstrate similar strength characteristics to existing studies in which altering the winding angle of CFRP leads to an incline or reduction in strength parameters in single direction.

2. In order to achieve a balance in the strength characteristics of the materials, a study with combined reinforced winding angles was carried out. The results demonstrated that the optimum combination of ±30°/80° achieved high values of compressive strength of 434 MPa, tensile strength of 675 MPa and impact strength of 165 kJ/m^2. This indicates that the combined reinforcement allows the stress distribution to be optimized and the strength properties of the fibers to be exploited far more effectively. Winding angles contribute to a uniform stress distribution in the material. This uniform stress distribution permits an even division of the load between the fibers, which effectively utilizes their strength performance. The material becomes more resistant to tension and compression as a result, which increases its durability. In addition, the interaction between the fibers in the combined reinforcement enhances the strength and stiffness of the material. This results in improving the tensile and compressive strength properties of the material that has not been identified in previously available scientific researches. Combined reinforcement by utilizing winding angles of ±30°/45°, ±30°/60°, ±30°/80°, ±80°/45° or ±80°/60° may be recommended to create materials with high compressive and tensile strength and impact strength.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research, and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of this work.

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