Viability Study for a Carbon-Cork Sandwich Composite

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Abstract

The present work aims at analyzing the current reality of the composite industry in the aeronautics field while studying the development of a new composite material made cork agglomerate (core) and CFRP sheets. The continuous search in the aerospace field for new lightweight materials with up to standards performance, makes cork and carbon fiber a logical choice for the development of a new composite material. This document covers the design and manufacturing phase, the testing and quality control and its economical and environmental impact. The combination of both materials looks very promising in addressing the product requirements for achieving a competitive production cost mainly due to the reasonable price of cork agglomerates. This new composite would also effectively reduce the carbon footprint of the aerospace industry given the reduced environmental impact of cork and the new possibilities for carbon fiber recycling.

Keywords: cork, carbon fiber, sandwich composite, composite design, inner fuselage

1. Introduction

Composite materials are becoming one of the most sought after solutions in a number of fields from aerospace to automotive, from construction to architecture. A composite material is made from two or more different materials with different properties that are combined in order to create a new material. Even though the physical and chemical properties of the different materials remain distinct in the new composite, these constituent materials work symbiotically to get improved properties in the final component, when compared to the original properties of each individual material.

Research in the aeronautics industry regarding composite materials has been extensive and continuous, in order to find new products that comply with specific application requirements. Each application has a specific function, but normally all aim at the production of lighter structures that allow lower fuel consumption and at increasing safety and comfort for both crew and passengers. Furthermore, in an era where environmental consciousness is becoming ever more important, the development of greener and more sustainable materials with smaller carbon footprints is catching the attention of the industry. Within the multiple applications in aeronautics industry using sandwich composite materials, aircraft inner fuselage is currently part of the products that have proof the usefulness of such components. In this particular application, the actual challenges for the industry are: weight reduction, increase crew and passengers comfort (thermal and noise insulation) and environmental sustainability.

This work studies the development and implementation of such new composite materials constituted by a cork agglomerate core and carbon fiber reinforced epoxy resin sheets, discussing the main advantages and disadvantages for its industrial implementation. Moreover, this dissertation will present a global overview of the cost breakdown and environmental impact of this specific class of composites.

2. Composite Proposal

This study aims at analyzing a sandwich composite with a cork agglomerate core and a carbon fiber reinforced epoxy resin skin like the one in Figure 1. This composite has the special purpose of application in the inner skin of the aircraft fuselage. These panels should have special properties like high strength to weight ratios, high resistance under static and dynamic loads, good damping of vibrations, low thermal conductivity and good thermal and acoustic isolation. Sandwich components are also of special interest due to their higher stiffness and better performance under bending which is quite important given the inherent curvature of the fuselage that the panels will be subjected to. The core materials for this sandwich component should have low density, high shear modulus, high shear strength and good thermal and acoustic insulation characteristics [1].

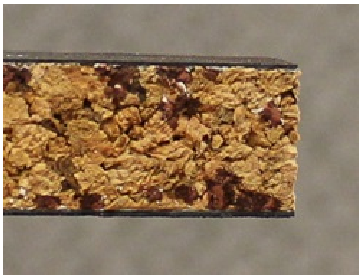

Figure 1: Proposed sandwich composite with agglomerated cork core and carbon fiber-epoxy skins [2]

TThe skins in sandwich structures resist more the bending stresses while the core resists mainly shear stresses. Rigid synthetic foams are often used as core materials and for fuselage insulation however cork agglomerates present themselves as suitable replacements due to its compressive strength, thermal insulation and vibration damping properties. Cork also presents good resistance to fatigue however studies suggest that common cork agglomerates present low static strength which can turn into a problem when dealing with impact loads that would be more critical in structural applications. Comparing cork agglomerate cores with other configurations, it was determined that a cork epoxy agglomerate presented a core shear stress between 1% and 12% lower that honeycomb cores and 38% to 56% higher than PMI rigid foam cores. Regarding the impact tests, PMI foam cores presented maximum load peak around 2 kN while cork agglomerate cores presented 3 kN [1].

The use of this composite in the aeronautical industry can be analyzed through the SWOT analysis in Figure 2.

For the application in the inner fuselage, given that it is not a structural component and the focus is cost reduction, mainly through weight reduction, NL10 should be the type of cork chosen for the core given its lower density and therefore, better contribution to weight reduction. The CFRP sheets should be produced with epoxy resin and the carbon fibers used should have lower electrical and thermal conductivity and higher Young's modulus to assure more stability of the fuselage inner skin.

The proposed sandwich composite will contribute both to the overall comfort of passengers and crew by being a source of thermal and acoustic insulation, and to the fuel and cost efficiency of the aircraft for its low density and high specific strength.

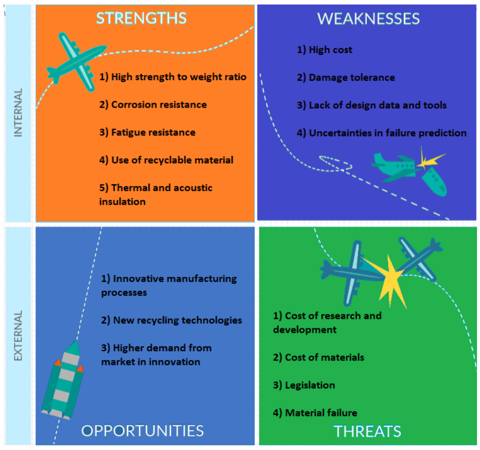

Figure 2: SWOT analysis for the proposed composite material

3. Composite Production

The proposed composite material must meet the requirements for its specific application and the manufacturing method for it is essential to achieve it since final properties greatly differ based on the method used. This composite material should be designed with the task of meeting the user's need by analyzing the four main elements of materials science: processing, structure, properties and performance. These elements connect between each other in a chain according to Figure 3.

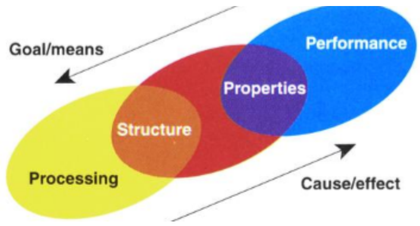

Figure 3: Chain between the four main elements of materials science [3]

To assure maximum safety, safety factors are applied to these design allowables so that failure does not happen due to certain uncertainties like stress concentrations, calculation errors, fabrication processes and material aging. For aeronautical structures, the typical safety factor is 1.5 which means that any structure that has to withstand a certain limit load, should be designed to withstand a load equal to 1.5 times that limit. However, for composite materials, the safety factors applied are often of 2 or more given the lack of extensive experimentation and design knowledge with this kind of materials [4].

3.1. Manufacturing

Regarding the cork for the sandwich core, the cork granules size is one of the most important factors.

When only granules with the same size are used, there are more voids left out that are usually filled in with a resin, resulting in a more reduced density. It has been proven that mixing different granule sizes leads to better mechanical properties due to better bonding between the particles [5].

For the production of the sandwich composite, there are three main candidates: compression molding, vacuum bagging and autoclave. In a previous stage where mass production is still not needed, and in order to explore the possibilities for this new composite, vacuum bagging, following the standard ASTM D5687, is a good option considering its low cost and medium part strength [5].

Regarding the mass production of this composite, closed forming processes seem to be more suitable and produce better results. Out of these, vacuum bagging presents the lower equipment cost while the autoclave presents the highest. Reproductibility is better in compression molding while lower in vacuum bagging. The autoclave process allowed for the obtention of composites with the highest values of impact strength and Young's modulus as well as almost total absence of discontinuities. Methods of compression are cheaper than autoclave and produce similar results when it comes to mechanical properties. Vacuum bagging also achieves quite acceptable results and it is much more low cost [6].

Considering the shape of the panels and considering that both the core and the sheets have already been produced accordingly, compression molding would present as a suitable manufacturing method since it allows for high reproductibility which is needed given the extent of area that has to be covered. Regarding the final mechanical properties, they would not differ much from the ones achieved with the autoclave (process which would lead to the best mechanical properties), with the added value of being much more cost efficient.

3.2. Design Requirements and Behaviour

In order to test the composite and define the property profile of the same, some tests should be performed as well as computational analysis. In reference [7], drop tower impact tests were carried out with a free falling mass, employing different initial heights, for different impact energies. The impact loads were read with the help of a piezoelectric force transducer placed between the impactor and the load carriage. To assess damage tolerance capability, residual strength characterization after impact based on four-point flexural tests was performed using a servo-hydraullic machine with a 100kN load cell. This kind of test aims at assessing the capacity of a specimen to continue delivering on its functions after an impact which can cause the called invisible damage specially if it is a low velocity low energy impact. Using both a drop weight machine and a static test load, damage tolerance can be estimated using both flexure after impact (FAI) and compression after impact (CAI) tests. Studies on composites show both flexural strength and modulus are reduced as the impact energy increases [**?**].

The experiments led in [7] resulted in the graphs presented in Figure 4 and Figure 5.

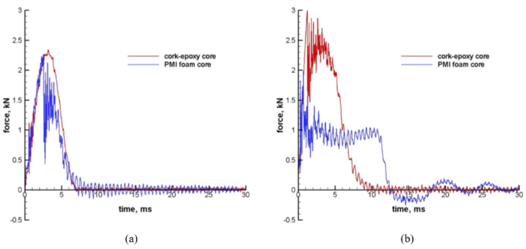

Figure 4: Force-time curves for cork-epoxy or PMI foam 30 mm cores for impact energy of (a) 5 J or (b) 20 J [7]

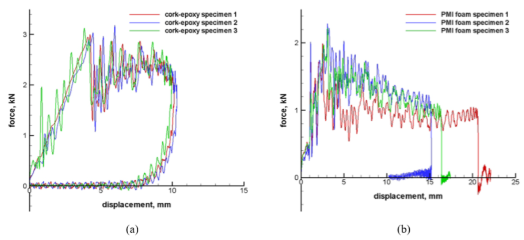

Figure 5: Force-displacement curves for (a) cork-epoxy specimens or (b) PMI foam cores for impact energy of 20 J [7]

From observation of the force-time curves, it can be concluded that cork cores allow for a smoother response to impact from the less evident oscillations after impact which supports the idea that cork composites allow for higher energy absorption. However, the PMI foam cores show a quicker reduction in the curve after maximum peak is reached as well as a much longer plateau. The force-displacement curve shows that the displacement of the impactor is smaller for the cork-epoxy cores and a rebound was observed. The fact that there is no rebound for the PMI foam core proves that the total energy absorbed is higher causing bigger damage. The shorter time of contact for the cork core also indicates that there is a higher percentage of elastic energy involved in the form of vibrations and that deformation is more elastical than in the foam core case. Regarding the flexure after impact tests, the study showed that residual flexural strength for non impacted cork core sandwiches were surprisingly lower than the values for impacted specimens with a variation in load limit of +8.9% after the

5 J impact and a variation of +14.2% after the 20 J impact. These results were much better in comparison with the PMI foam core that showed a reduction in bending load limit of -29.7% after the 5 J impact and a variation of -18.8% after the 20 J impact. It was also noted that the damaged area of the sandwich composite was significantly smaller for the cork agglomerate core in comparison with the PMI foam which further testifies for the important energy absorption capacity of this composite in comparison with traditional foams in the same application.

4. Environmental Analysis

The increased usage of composite materials in the industry, coupled with the environmental policies that aim to reduce pollution and change the ecological behavior of both consumer and producer, turns environmental analysis indispensable when addressing the possibility to introduce a new composite in the market. One of the challenges proposed by the manufacturing of CFRP is the lack of industrial scale composite recycling. Industry is still incapable of addressing the waste management for the increasing waste accumulation, which has a global scale impact. Thus, recycling technologies aim to be technologically capable while environmentally beneficial. CFRP recycling is quite difficult due to the problem related to melting thermoset resins and because it often involves harsh chemicals that can damage the fibers themselves and add to the environmental impact due to the hazardous nature of the caustic chemicals [8].

4.1. Impact

This composite presents 3 main components that will have a seriously diverse impact on the environment among them:cork, carbon fibers and resin. Evidently, cork is one of the most environmentally-friendly materials as it does not affect it negatively. The cork forests act as CO_2 sequestrators and the fact that it is extracted for commercial purposes actually benefits it as the extraction promotes cork growth and further CO_2 sequestration [9]. Regarding the production of CFRP, it is quite an energy intensive process that will have both consequences in terms of energy used in the facilities and in greenhouse gas emissions, being that for PAN-based carbon fibers, it is estimated that these emissions are around 31 kg CO_2/kg of carbon fiber [10].

4.2. Recycling

Given the growing demand for carbon fiber composites, it is of utmost importance to invest in its recycling and end of life technology, from an environmental point of view. Indeed, the impact of smarter end of cycle treatment for carbon fibers is not only good for the environment but also in terms of resource management and economic impact since recycled materials can be used in non critical applications, solving in a way the problem of lack of supply for the existing demand, and the money spent in legal CFRP landfill disposure can be saved. The approach to recycle thermoset composites normally follows one of the following: chemical degradation to turn polymeric chains into single chemical components; thermal degradation to turn it into char and energy and mechanical process in order to turn the composite into filler material. Chemical and thermal processes often fall in the category of fiber reclamation processes where the matrix is broken down and the fibers are recovered without significant degradation. These processes, as well as mechanical degradation, follow the scheme in Figure 6 [11].

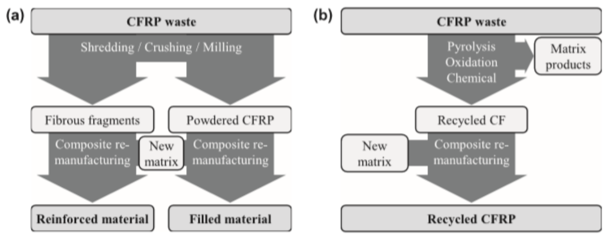

Figure 6: Main technologies for CFRP recycling through a) mechanical degradation or b) fiber reclamation [11]

CFRP recycling processes need to be further developed so that the recovered parts can work in near ideal conditions as the original ones. Fortunately, CFRP recycling is becoming a trend globally and major manufacturers are joining the idea. For instance, Boeing began recycling the CFRP from old F-18A and used scrap from 787 fuselage teste to design new arm rests. Airbus has committed to reach 85% to 95% of recyclability of its components and materials [12].

Regarding the direct application on the proposed sandwich composite, one of the best options would be to first use mechanical industrial cutting in order to separate the core from the sheets and then proceed to the recycling processes independently. The core should be subjected to mechanical grinding which would be the simplest recyclable element since it can be easily used for reuse in new cork products or just for fillers. When it comes to the CFRP sheets, chemical degradation for fiber reclamation is the most promising and the one that would be most efficient since mechanically grinding CFRP for filler material is not a suitable option when there are many other fillers in the market for much lower prices. Fiber reclamation by means of chemical degradation is the best option for this part of the sandwich component despite the complexity of it and inherent problems related to the decomposition of the thermoset resin or to the difficulty to completely remove any traces of resin from the reusable carbon fibers.

5. Cost Analysis

5.1. Cork agglomerate core

For the preparation of this core, cork granules and epoxy resin would be used and it will be assumed a plank of 30cm x 30cm x 3cm, which amounts to a total volume of 2700 cm^3. For the purposes of this study, medium density cork granules are preferable with a density that will be considered of 0.04 g/cm^3 with a price of 4 EUR per kg (Corticeira Amorim). Since the cork agglomerate blocks are the most suitable in terms of shape to the application and since they have a high cork content of 90%, for the plank considered, a total of 97.2g of cork granules would be required.

Additionally, to produce this core and to fill the remaining 10% of the plank volume, epoxy resin would be needed, for a price of 18 EUR per liter (West System) [5].

Considering the normal prices for cork granules and epoxy resin the cost of materials for the production of the cork agglomerate core is shown on Table 1:

Table 1: Overview of costs for the cork agglomerate core

	Price per m^3 [EUR]
Cork granules	144
Epoxy resin	1800
Total	**1944**

5.2. CFRP sheets

Overall, the cost breakdown for each phase of the carbon fiber production alone can be found in Table 2:

Table 2: Overview of costs for phases of carbon fiber production

Process steps	EUR per kg
Precursor and Spinning	10
Stabilization or Oxidation	3
Carbonizing	4.6
Surface Treatment	0.7
Sizing	1.2
Total	**19.5**

For each of the considered planks, the core will have to be covered on both sides by a 30cm x 30cm x 0.2cm sheet which will amount to a total of 360 cm^3 of CFRP sheets for each plank.

For the purposes of this study, a carbon fiber content of 65% in volume is assumed in the CFRP sheets which is a normal value in the industry. Given the normal density of carbon fibers of 2 g/cm^3, there is a need for $360 * 2 * 0.65 = 468g$ of carbon fiber, amounting to a price of 9.13 EUR. To complete the CFRP sheets, the remaining 35% in volume will be filled with epoxy resin, which means that 126 ml or 252 g of this resin will be used, amounting to a price of 2.27 EUR.

5.3. Energy

Cork has quite a low cost when it comes to utilities and, in the case of this composite, most of the cost will be associated with the production of the CFRP. According to [13], currently and with the mainstream technologies available, the production of carbon fiber has a cost of 1134 MJ/kg which is significantly higher than the utilities usage for the CFRP production itself which is 39.5 MJ/kg. The production of epoxy resin also uses 89.8 MJ/kg.

Given that the assumed densities for both the carbon fibers and the epoxy resin are the same, the percentage in weight will be equivalent to the percentage in volume. In this way, and given the 65% of carbon fiber in the CFRP sheets, the energy cost for its production will be of 49.29 EUR/kg of CFRP or 35.49 EUR/kg of sandwich panel.

Summing up all the contributions the total cost breakdown is estimated as follows, with the values expressed in EUR/kg of sandwich composite:

- Cork agglomerate core materials: 3.87
- CFRP sheets materials: 8.4
- Energy usage for CFRP production: 26.15
- Energy usage for core and sandwich production: 2.62
- TOTAL: 41.03

According to Qingdao Regal New Material Co., the price for PMI foam is estimated around 15 EUR/m^2 for sheets with a thickness of 3 mm. This would mean that, for a PMI foam sandwich core, as it is usual the case, with the same dimensions as the proposed one, the price would be of 45 EUR. This price is much higher than the price estimated for the cork agglomerate core of 5.25 EUR, which further testifies for the interesting economical opportunity in this new sandwich composite. The comparison is made between the cork agglomerate and PMI foam as cores alone because they would always have to be covered by sheets of a more resistant material such as CFRP.

6. Conclusions

After this comprehensive overview of a sandwich composite material development constituted by a cork agglomerate core with CFRP sheets for application in the inner skin of the fuselage, it can be concluded that this material is suitable for further research with the aim of being used as a consistent alternative to common materials such as PMI foams. The unique properties of cork combined with carbon fiber result in an extremely light material with very good mechanical properties that could be put to good use in the aeronautical sector. Since one of the biggest challenges in the sector is to find lighter solutions with up to standards and compliant behavior, this is without a doubt one of the options to explore further.

This sandwich composite would be specially suitable for application in non structural inner fuselage panels with function of thermal and acoustic insulation, contributing to the overall comfort of the passengers and crew. Moreover, testing shows that this new sandwich composite could mechanically outperform PMI foams normally used in these applications.

To take into account the environmental sustainability in new product developments for aircrafts, the implementation of recycling processes and sustainable materials is essential. The sole use of cork in this new composite would significantly reduce the environmental impact as it is a much greener material than most of the ones used in the aeronautical industry nowadays such as aluminum, steel or titanium. Regarding the CFRP sheets that are more environmentally harmful, there is a need for further developments in the area of chemical degradation in order to obtain reusable fibers without significant damage.

Cost-wise, the new sandwich composite core presents a lower cost than PMI foam, a material normally used as core is similar panels for this application in the fuselage inner skin.

Summing up, the proposed sandwich composite seems to be an innovative option to consider for application in the inner fuselage, presenting better mechanical properties than industrial foams sandwich composites and assuring as well the functions of thermal and acoustical insulation. Furthermore, besides presenting low density for effects of aircraft weight reduction, it assures a very good environmental sustainability due to its use of cork in the core.

References

[1] J.M. Silva T. Devezas A. Silva L. Gil C. Nunes N. Franco. Exploring the use of cork based composites for aerospace applications. *Materials Science Forum*, 636-637:260–265, January 2010. doi:10.4028/www.scientific.net/MSF.636-637.260.

[2] Jonghwan Suhr James Sargianis, Hyungick Kim. Natural cork agglomerate employed as an environmentally friendly solution for quiet sandwich composites. *Nature Scientific Reports*, 2(403), may 2012.

[3] Gregory B. Olson. Designing a new material world. *Science*, 288(5468):993–998, May 2000. doi: 10.1126/science.288.5468.993.

[4] Katarina Uusitalo. Designing in carbon fibre composites. Master's thesis, Chalmers University of Technology, 2013.

[5] Sungmin Kim. A study on cork-based plastic composite material. Master's thesis, Massachusetts Institute of Technology, 2011.

[6] Aneta Krzyżak Michał Mazur Mateusz Gajewski Kazimierz Drozd Andrzej Komorek and Paweł Przybyłek. Sandwich structured composites for aeronautics: Methods of manufacturing affecting some mechanical properties. *International Journal of Aerospace Engineering*, 2016(7816912):1–10, May 2016. doi:10.1155/2016/7816912.

[7] José M. Silva Pedro V. Gamboa C. Nunes L. Paulo N. Franco. Cork: Is it a good material for aerospace structures? In *52nd AIAA ASME ASCE AHS ASC Structures, Structural Dynamics and Materials Conference*, April 2011. doi: 10.2514/6.2011-2159.

[8] Xiaolong Guo Chengyun Liu Tian Liu Junna Xin Jinwen Zhang Tuan Liu, Meng Zhang. Mild chemical recycling of aerospace fiber/epoxy composite wastes and utilization of the decomposed resin. *Polymer Degradation and Stability*, 139(20), 2017. doi:10.1016/j.polymdegradstab.2017.03.017.

[9] Luis Gil Ana Mestre. Cork for sustainable product design. *Ciência e Tecnologia dos Materiais*, 23(3-4):52–63, 2011.

[10] Sujit Das. Life cycle assessment of carbon fiber-reinforced polymer composites. *The International Journal of Life Cycle Assessment*, 16(3):268–282, mar 2011. doi:10.1007/s11367-011-0264-z.

[11] Silvestre T. Pinho Soraia Pimenta. Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. *Waste Management*, 31(2):378–392, 2011. doi:10.1016/j.wasman.2010.09.019.

[12] Vicki P. McConnell. Launching the carbon fibre recycling industry. *Reinforced Plastics*, 54(2):33–37, mar 2010. doi:10.1016/S0034-3617(10)70063-1.

[13] Deborah Sunter, William Morrow III, Joseph Cresko, and Heather Liddell. The manufacturing energy intensity of carbon fiber reinforced polymer composites and its effect on life cycle energy use for vehicle door lightweighting. jul 2015.