Opportunities Offered by Naturally Occurring Materials in Lightweight Aerostructures Design

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Abstract

The raising concerns towards the environmental impact of the air transport sector have led the international regulation authorities to put pressure on the aeronautical industry in order to achieve ambitious goals both in the short and medium-term. The expected growth in the aviation sector for the upcoming years poses a greater challenge to both airplane manufacturers and operators who need to adopt revolutionary solutions to provide an effective response towards a more sustainable energy supply, including steep reductions in pollutant emissions and a significant improvement in recyclability. Natural materials are a viable path to address this challenge as they rely upon sustainable production processes and offer considerable advantages in terms of renewability, recyclability and biodegradability. Furthermore, evidences from recent research suggest that some natural materials offer mechanical properties equivalent or even better than conventional materials used for engineering applications in the aerospace sector. This paper presents a review of the progresses achieved in the use of natural based materials in aeronautical structures. Most of these materials are in the form of polymer based composites with either the inclusion of natural reinforcing fibres and resins or other types of natural materials used as core constituents in sandwich components, such as cork based composites. The presented data were collected from different research works and cover a broad range of loading conditions as experienced by aircraft under normal operational scenarios and taking into consideration relevant airworthiness requirements, such as fire resistance and damage tolerance. Results are very encouraging and support the use of natural based materials in aircraft structural components, opening a window of tangible opportunities for the design of more fuel efficient and environmentally sustainable aircraft in the near future.

Keywords: sustainability, green aircraft, recyclability, bio-composites.

1. Introduction

Over the last years, we have assisted to a raising interest towards the application of natural materials for engineering applications. A natural based material can be defined as a product obtained from natural and renewable resources extracted from agricultural and forestry feedstock, including by-products and residues (Koronis, Silva & Fontul, 2013). These type of materials have followed a pathway parallel to the evolution of mankind as a myriad of examples of natural occurring materials used with distinct functionalities can be found in many everyday applications, such as wood based products used in civil and naval applications for example.

In the particular case of air transport, it is interesting to note that the choice of materials used in the early aircraft at the beginning of the 20th century was a corollary of the existing technology at that time. In fact, from the dawn of the aviation history and during nearly three decades most aircraft were built from the lightest materials available, which were dominated by wood based materials for structural purposes, like bamboo, balsa wood or spruce (Cutler, 1999). One of the best examples of the prevalence of wood in the aeronautical construction until the WWII is probably the de Havilland DH. 98 *Mosquito*, a British high-speed bomber airplane constructed almost entirely of wood, which granted him the *Wooden Wonder* nickname (Guttman, 2001). Due to the shortage of other strategic materials required for the construction of different military gear to be used in the war, designers had to find ingenious solutions from other existing and abundant materials. The fuselage was constructed of balsa wood sandwiched between layers of plywood creating a remarkably clean-looking aerodynamic configuration and providing strength-to-weight ratios close to the aluminium alloys existing at that time. One important advantage of the wooden design was the easiness and affordability of the related production techniques, most of them common to wood construction used in routine applications.

Another emblematic airplane used in the WWII was the Supermarine Spitfire, a British fighter which was the first reported aircraft using a composite material combining both natural and synthetic constituents, namely flax linen roving held in a urea formaldehyde (phenolic) resin (Marsh, 1996). This

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airplane also used a cellulose based composite made of paper mixed with adhesives to fabricate the pilot's seat. In fact, by the 1940's cellulose based composites using natural fibres to reinforce polymers were a well-known candidate material for many aeronautical applications in non-critical components, although a rampant interest was being shown for structural applications (Baillie, 2005).

The role of natural materials dimmed considerably since the WWII as a result of the advent of many forms of synthetic materials offering superior mechanical properties. In the 1950-60s aluminium alloys have been the dominant material for aircraft construction due to their superior strength-to-weight ratio and reasonable cost. Nevertheless, aircraft designers kept striving for better performance and improved reliability which necessarily demands new materials with optimized properties. This triggered a considerable investment on research activities in the 1960s aiming at introducing new synthetic composite materials with enhanced capabilities which were probably the greatest leap forward in the aeronautical construction in the last century. In particular, fibre reinforced polymer based materials (FRPs) started capturing the attention of designers and manufacturers as an alternative material to metallic alloys due to their considerable advantages, namely: higher strength-to-weight and/or stiffness-to-weight ratios; the ability to customise their properties as a result of the proper selection of different lay-up stacking sequences; excellent resistance to fatigue and to corrosion damage; possibility of designing parts with complex geometries like double curvature (Saúde & Silva, 2014; Soutis, 2005).

Typically, the composite parts used in most recent aircraft are made from glass, carbon or aramid fibres as reinforcing elements, whereas thermoset polymers (predominantly epoxy resins) are frequently used as matrix elements to ensure the best mechanical properties. A good example of how the aeronautical industry has embraced the technology of composite materials is the Boeing 787, a commercial long-range airplane which entered into service in 2011. In this aircraft carbon fibre composites are extensively used in primary structures (ascending to 50% of the total weight) allowing for substantial weight savings compared with the conventional aluminium alloys.

Notwithstanding their superior mechanical properties, synthetic composites are made of polymers and fibres derived from petroleum which is a non-renewable commodity. Furthermore, recent concerns about the recyclability of these materials, as a result of their non-biodegradability, made sound the alarm on the authorities and decision makers all over the world as the disposal of some of these materials has become a critical issue. By definition, composites are made using two dissimilar materials, which poses some challenges regarding its recyclability or reuse. In most cases, composites end up in landfills whereas some are incinerated after use (Netravali & Chabba, 2003).

Recently, the European Commission expressed their vision regarding the future of aviation in Europe in the next 3-4 decades through the (*Flightpath 2050: Europe's Vision for Aviation - Report of the High Level Group on Aviation Research*, 2011). This document points out some priority areas to assist in the development of the aviation sector as one of the most strategic areas in the European agenda. Amongst the many challenges listed in this report, there is a clear goal aiming at protecting the environment and the energy supply which will lead to a drastic decrease of materials and fuels depending on crude oil. There is also a strong commitment to design and manufacture air vehicles with improved recyclability capabilities, which will catalyse the research activities on greener materials, or in other words, with a reduced environmental footprint.

In fact, the climate change has been driving many global initiatives which have sparked off a "*green fever*" around new recyclable and/or biodegradable materials with potential applications in engineering products. Over the last 15 years, significant efforts have been put in the development and characterization of "green composites" which are normally in the form of fibre reinforced polymers (FRPs) incorporating either natural fibres and/or bio-derived polymers. So far, the applications of green composites have been limited to non-critical parts, such as secondary and tertiary structures, panels, fairings, cases, etc (La Mantia & Morreale, 2011). For this type of applications, nature offers a broad range of inexpensive and abundant plant-based fibres possessing many advantages compared to synthetic alternatives: they can be incinerated, are CO_2 neutral when burned, are much less abrasive than inorganic-mineral counterparts to processing machinery, less dangerous for the production employees in case of inhalation, and, because of their hollow and cellular morphology, are lightweight and perform well as acoustic and thermal insulators (La Mantia & Morreale, 2011; Netravali & Chabba, 2003). These latter features are very interesting from the standpoint of their utilisation in certain parts of transport vehicles to improve the ridding characteristics (e.g., noise and vibration mitigation) and minimize fuel consumption. Actually, the automotive industry was one pioneering sector in terms of the successful integration of green composites in many auto parts since the 1990's (Koronis, Silva & Fontul, 2013). Still, and despite the natural charm and euphoria around bio-composites, designers and engineers should bear in mind that these have some pitfalls which cannot be neglected when considering them as candidate materials for structural applications in critical parts.

This paper intends to undertake a very concise review on the existing natural materials to assess the viability of their application in aeronautical parts. It should be noted that the authors did not aim to an exhaustive review of all physical and mechanical properties of natural materials as these aspects have been thoroughly addressed in the literature. Instead, the main objective of this work is to contribute to the identification of possible evolutionary paths for the possible utilization of more sustainable materials and related technologies in the aviation sector as stipulated by the key international stakeholders for the near future. In order to outline the general characteristics of naturally occurring materials in terms of mechanical strength and stiffness, it is useful to refer to the two Ashby plots of Figure 1, developed among others by Dicker et al. (2014).

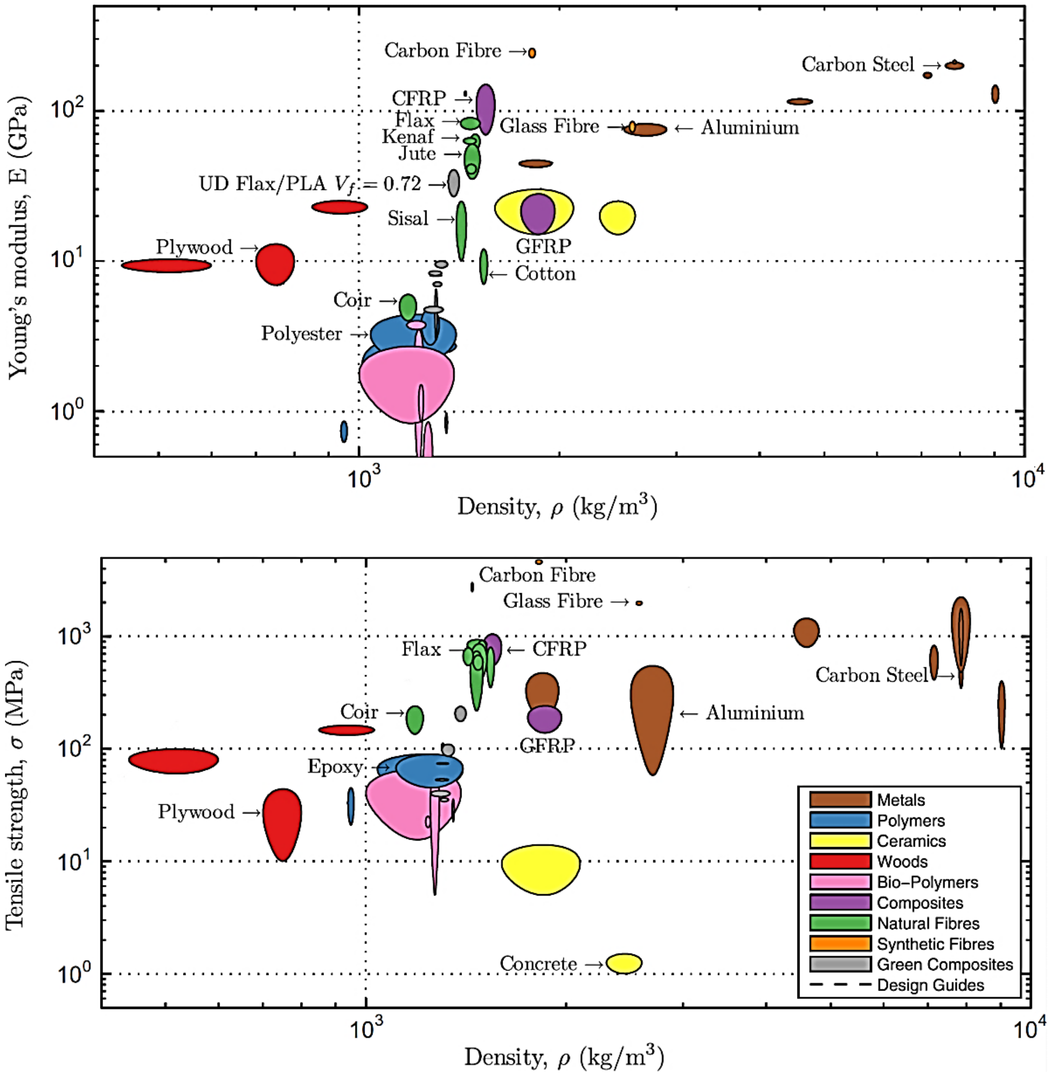


Figure 1. Ashby plots of the mechanical stiffness and strength properties of a wide range of materials. Adapted from Dicker et al. (2014).

2. Composites with natural fibres

Over the past years the development of high-performance composites made from natural resources has been increasing worldwide due to environmental and sustainability concerns. The natural constituents can be used as reinforcing elements (normally in the form of fibres), biopolymers or both. As the reinforcing fibres have a significant impact in the overall mechanical behaviour of composites, and considering the significant number of scientific literature dedicated to natural fibres, the present paper will only analyse this type of materials and therefore will not cover the emerging area of green materials used as matrixes in bio-composites.

Many examples can be found on the use of either plant-based or animal-based fibres as reinforcing elements of FRPs. Figure 2 summarizes the main categories of the different natural fibres grouped according with their extraction sources. Amongst these, vegetable fibres have taken a leading position in the research and production of green-composites over the last decade. The attractiveness of modern agricultural techniques ensuring a high production yield together with very interesting mechanical properties are the key reason for this choice. The cell structure of vegetable fibres is complex with each fibre being a composite of rigid cellulose microfibrils embedded in a soft lignin and hemicellulose matrix (Dicker et al., 2014). The theoretical elastic modulus of a cellulose molecule is predicted to be around 138 GPa which is an higher value when compared with glass fibres and within the same range as aramid fibres (Nishino, Takano & Nakamae, 1995). However, this high rigidity level cannot be maintained when considering long fibres for practical applications due to either naturally occurring structural defects in the fibre, defects incurring during its processing phase or chemical incompatibilities with the polymer matrix (Staiger & Tucker, 2008). Therefore, we need to be moderately optimistic when considering vegetable fibres as competitors against the conventional synthetic fibres used in FRP's. Another important drawback of natural fibres which poses some difficulties to their application on an industrial scale is the considerable variability of their nominal mechanical properties which are largely influenced by the overall environmental conditions during growth and the traditional methods of preparation of the fibres in which some processing variables are difficult to control.

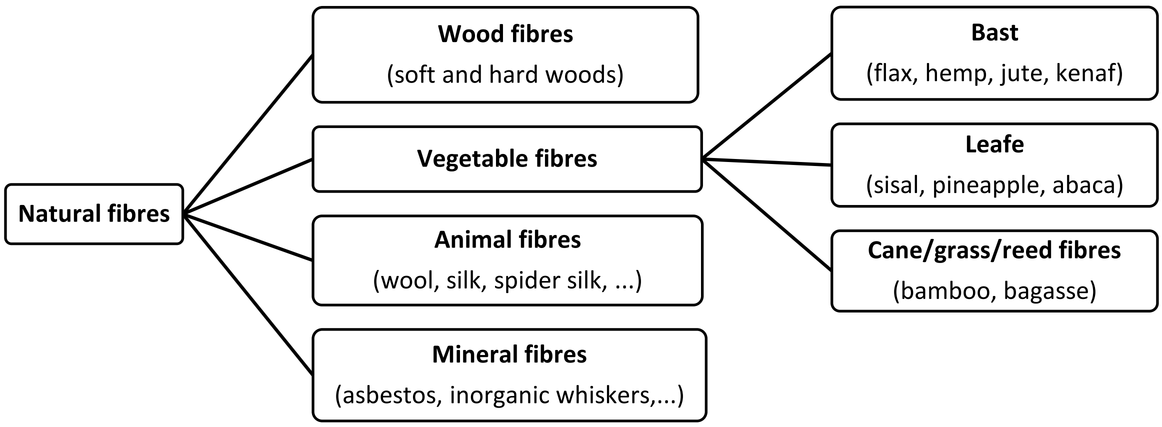


Figure 2. Types of natural fibres depending on their source of extraction.

Nevertheless, and depending on the type of application (and therefore on the design requirements), several works evinced that there might be some cases where the strength (or stiffness) to weight ratios of some natural fibres are in the same range or even higher than some synthetic fibres, namely E-glass fibres. Although glass fibres possess the lowest mechanical properties in the family of engineering composites, they are still extensively used in many applications, particularly in the transport sector (including aeronautics) making it a benchmark material when it comes to measure the performance of green-composites. In the following paragraphs, we will do a short overview on those natural fibres whose properties paint a promising and viable scenario regarding their utilization in structural components for lightweight applications considering their utilisation as reinforcing constituents of FRPs.

Flax is a bast fibre well known from the textile industry. Interestingly, it was also one of the first natural materials to be considered as a composite constituent in the early beginning of the aviation history combined with phenolic resin as a construction material for the Spitfire fighter aircraft. Recently, flax fibres have been considered for sporting equipment applications such as in the reinforcement of snowboards, tennis rackets, racing boats and bicycle frames (Dicker et al., 2014; Lineo-NV, 2014; Stemergy, 2014). In many cases these fibres are combined with other synthetic reinforcements (carbon fibres for example) to ensure improved mechanical properties as it has been reported that this hybrid formulation provides superior vibration dampening. A significant amount of research has been done at the German Aerospace Center (DLR) on biodegradable plastics and composites using flax fibres. Some of these composites had properties comparable to E-glass/epoxy FRPs and were found to be suitable for a variety of structural applications (Netravali & Chabba, 2003). One particular potential application where flax fibres proved to be a serious alternative to glass fibres is in components used in aircraft cabins (Wiedemann, Sinapius & Melcher, 2012). Researchers from the DLR conducted a life cycle assessment to quantify the environmental impacts of flax fibres compared to glass fibres in a cabin panel made from a phenolic resin prepreg. Results showed that flax had clear advantages in terms of the lower energy consumption along its complete life cycle, including the possibility to recover energy through incineration at the disposal phase.

Belonging to the Cannabis family, hemp is another type of bast fibre considered as an alternative to glass reinforcements. Wambua, Ivens and Verpoest (2003) investigated the mechanical behaviour of polypropylene composites reinforced with different natural fibres, including hemp. These authors concluded that hemp based materials led to superior results regarding the tensile strength considering identical volume fractions to the other natural fibres (sisal, kenaf, jute and coir), whereas their flexural strength and tensile modulus were comparable to that of glass matt composites but with the advantage of having a lower density value (1.48 against 2.55 g/cm^3). Another work from Pervaiz and Sain (2003) investigated a polypropylene composite reinforced with hemp and found that an energy saving of 50 MJ/kg (3 kg of CO2/kg) was possible by replacing a glass fibre component with a fibre weight fraction of 0.3, with a hemp fibre component with a 0.65 fibre weight fraction. Other works showed that PP composites reinforced with hemp fibres exhibit interesting recyclability capabilities as the mechanical properties of this type of material remained well preserved despite the number of reprocessing cycles (Faruk et al., 2012).

Kenaf is also another natural fibre normally considered as a reinforcement element in polymer based composites for many applications due to its superior toughness and high aspect ratio in comparison to other fibres. A single fibre of kenaf can have a tensile strength and elastic modulus as high as 11.9 GPa and 60 GPa, respectively (Akil et al., 2011). Further to its interesting mechanical properties, the growth rate of kenaf plants is very attractive (up to 10 cm/day under optimum ambient conditions) which makes it a very affordable and abundant material (Baillie, 2005). From the viewpoint of energy consumption, the production of 1 kg of kenaf requires 15 MJ of energy, whereas this value raises up to 54 MJ to produce 1 kg of glass fibre (Akil et al., 2011). For these reasons, kenaf has been used in many different applications with a special relevance in the automobile industry. Toyota, jointly with Araco Corporation, developed a kenaf based composite which is used in some interior components (such as door trims) providing weight savings and better soundproofing characteristics (Toyota-Motor-Corporation, 2014).

A comparative study of the mechanical properties of kenaf fibre reinforced composites and other natural fibres is presented by Akil et al. (2011). These composites were fabricated using polypropylene films, with natural fibre layers randomly spread between them. In general terms, the tensile and flexural strengths are lower than that obtained for the same weight fraction regarding the hemp and flax fibres (around 10% and 20%, respectively) but still providing superior specific properties than E-glass fibres.

Silk is an animal type of fibre that we decided to include in the list of natural materials as it has a clear potential to act as reinforcement for composites due to its remarkable properties. Silks are generally defined as protein polymers that are spun into fibres by some animals such as silkworms, spiders, scorpions, mites and flies (Altman et al., 2003). Although the absolute stiffness/strength (tensile and flexural) of silk based composites is lower than that of glass-fibre composites, some studies have demonstrated a superior performance in terms of fracture strain capacities and elongation at break, which may be particularly attractive in applications where progressive failure or high compliance is required (Shah, Porter & Vollrath, 2014; Ude et al., 2014). For this reason, potential applications of silk fibres may include lightweight, crashworthy and impact critical components used in the automotive and aeronautical sectors. It is also worthy to mention that the mechanical performance of silk fibres surpasses most of the natural vegetable fibres in terms of interlaminar shear strength and specific impact strength (Shah, Porter & Vollrath, 2014). As downsides, some issues have been reported regarding the compatibility of silk fibres with some polymeric matrixes and high moisture sensitivity.

The data available in the aforementioned references allowed to summarize the main mechanical and physical properties of the natural fibres discussed in this paper in the form of Table1. Average specific stiffness and specific strength are also presented as they are important requirements for the structural design of lightweight structures. It must be stressed out though that these values should be considered as an indicative reference only as they are largely dependent on several factors that might contribute to a significant variability, such as the climate and region influence in the harvesting process and/or the distinct manufacturing processes used to extract the fibres from the plant stem.

Table 1 – Properties of some natural fibres against E-glass.

Type of fibre	Density [g/cm^3]	Tensile Strength [MPa]	Young's Modulus [GPa]	Specific Strength	Specific Modulus
Flax	1.5	345 – 1500	27 – 39	230 - 1000	18 - 26
Hemp	1.47	550 – 900	70	374 - 612	48
Kenaf	1.5 – 1.6	350 – 930	40 – 53	226 - 600	25 – 34
Silk (Bombyx mori)	1.25 -1.35	650 - 750	16	500 - 576	12.3
E-Glass	2.55	2000	70 - 73	784	27 - 28

Notwithstanding the interesting mechanical properties of natural fibres, there are some drawbacks that hinder their application under some particular conditions. The most probable issue is moisture absorption as cellulose is a highly hydrophilic molecule and this property is therefore imparted to natural fibres. Water absorption causes fibre swelling which leads to delamination, surface roughening and a subsequent loss of strength of the material (Dicker et al., 2014). Symington et al. (2009) concluded that moisture plays a significant role in influencing the mechanical properties of some natural fibres exposed to water environments, such as flax and hemp. In this latter case, the degradation level was so intense that the material was unable to be tested, raising concerns around its stability when exposed to various environmental conditions. The moist environment can also facilitate the growth of fungus and bacteria which leads to rotting (Stamboulis et al., 2000).

The chemical incompatibility between the hydrophilic natural fibre and hydrophobic polymer matrix is an additional issue responsible for the decrease in the mechanical properties as it leads to poor fibre wetting, producing an inferior interface and encouraging fibre agglomeration. To overcome this limitation, some treatments have been investigated to modify the fibre surface properties to improve their adhesion with different matrices. The fibre alkali treatment, also referred to as mercerisation, has been utilized with appreciable success (Dicker et al., 2014). This process s improves the capacity for chemical interaction between the matrix and fibres, while allowing for better mechanical interlocking through rougher topography and larger numbers of individual fibrils, having as side benefit the reduction in water absorption.

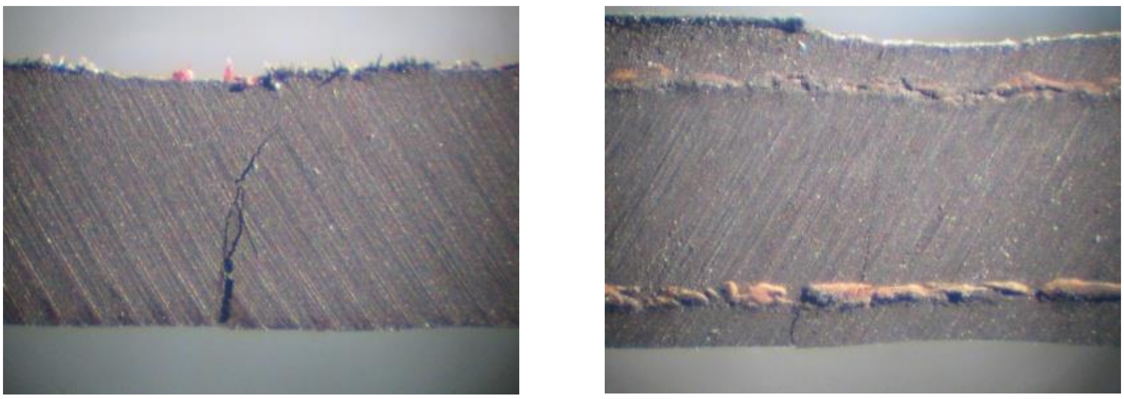
3. Cork: the Nature's foam

As an example of the many benefits of natural materials to the construction of lightweight structures, this section will be focused on the use of composites with cork. Cork is a natural, renewable, sustainable material extracted from the bark of the oak (*Quercus suber L.*) which is periodically harvested from the tree, usually every 9–12 years. The most intensive cork production is located around the Mediterranean basin and China.

Microscopically, cork may be described as a homogeneous tissue of thin-walled cells, regularly arranged without intercellular space laying under an alveolar structure, analogous to that of a honeycomb (Silva, SP et al., 2005), which is at the base of its low density (ranging from 100 - 240 kg/m3). Additionally, the cellular morphology provides greater levels of energy absorption under deformation corresponding to cell edge bending or face stretching for low stress levels or progressive cell collapse by elastic buckling or plastic yielding at higher loads (Gibson, 2005). Although the overall mechanical properties of natural cork are relatively worse than other lightweight materials (such as synthetic foams), its combination with adequate binding agents results in cork based agglomerates with competitive specific properties. Besides, its low thermal conductivity plus reasonable compressive strength make it an excellent material for thermal insulation where compressive loads are present.

Further to its well-known usage in non-structural applications in civil construction (e.g., floor panels, thermal insulator, external cladding) recently cork based agglomerates have been considered for applications in the transport sector owing to their excellent vibration/acoustic suppression capabilities and low thermal conductivity (Gil, 2009). The product range dedicated to the transportation industry comprising panels, flooring systems and anti-vibration barriers can be already found in many components in trains, buses and boats, including parts with structural capabilities (Amorim, 2014). In the aerospace sector, cork compounds have been used for more than 30 years for the fabrication of thermal protection systems applications based in ablative heat shields installed in rockets and space vehicles.

One of the most promising forms of applications of cork based composites is in the form of a core material for sandwich type components due to the cumulative benefit of its lightweight, high loss factor, superior energy absorption properties, thermal insulation and marginal absorption of moisture in the long run. Sargianis, Kim and Suhr (2012) suggested that cork agglomerate cores combined with carbon based FRPs facesheets resulted in a virtually noise-free sandwich structure with excellent damping performance providing increased durability under fatigue loading conditions. Also Silva, JM et al. (2013) proposed the use of a micro-sandwich cork core as an effective and simple solution to enhance the damping behaviour of high strength/stiffness carbon/epoxy laminates for structural applications. Another recent work (Silva, JM et al., 2011) aimed at improving the resilience and damage tolerance of properties of CFRP laminates by using the viscoelastic nature of cork. In this case, two types of materials were considered: a sandwich formed by carbon-epoxy facesheets with a cork-epoxy core and a carbon-epoxy laminate with embedded cork granulates. Results were clear about both the shielding effect provided by the cork core on the minimization of the damage extension induced by low energy impact tests (which are representative of many situations within the real operational context of aircraft) and the extension of the flight envelope without weight penalty by increasing the critical flutter speed (as a consequence of the improved damping characteristics of laminates with embedded cork). A good example of this shielding effect under impact loading is illustrated by the two cross-sections in Figure 3, one referring to a conventional carbon-epoxy laminate (Figure 3a) and the other (Figure3b) pertaining to an identical laminate but considering the inclusion of two very thin cork layers embedded close to the surface of the material. As it can be seen, the damage extension (in the form of a through thickness crack front) in the cork-based laminate resulting from a low energy impact loading has been considerably reduced relatively to the conventional material which is a good indicator of the energy absorption capability provided by natural cork without hindering the low weight requirements of structural composites used in the aerospace sector.



(a) (b)

Figure 3. Damage extension caused by a low energy (10 Joule) impact event on a carbon epoxy laminate: (a): without embedded cork layers; (b): with two cork layers embedded close to the surface positions.

As a general conclusion we can conclude that cork-based composites can be considered as a serious alternative to synthetic foams or metal honeycombs when the need for the maximization of the energy absorption capabilities is a major design requirement. Furthermore, the mechanical properties of polymeric foams are strongly influenced by temperature whereas cork agglomerates can withstand temperatures up to 200°C with minimum mass loss and keeping their nominal properties unchanged.

4. Conclusions

In several industrial applications, naturally occurring materials are of great interest to attain a significant reduction in the use of petroleum-based products and other non-renewable resources, therefore contributing to a more sustainable development. Natural materials are in fact biodegradable, CO_2 neutral and generally less noxious in case of inhalation. In addition to their environmental benefits, some natural materials can be employed as constituents of high performance composite materials due to their competitive mechanical properties. In particular, this paper briefly reviewed the opportunities and challenges arising from the application of selected natural fibres in lightweight composites for the aerospace industry, as well as the potential of using cork based products as an alternative material to synthetic foams in sandwich structures. Based on the existing literature, it was possible to highlight some clear advantages of natural fibres compared to synthetic reinforcements, particularly their low density, reduced cost and tool wear, increased availability, and biodegradability. In certain cases, the specific mechanical properties are comparable or even better than glass fibres, paving the way for possible applications in structural components. The review also addressed cork as an ideally suited core material for sandwich type components due to its lightweight, high loss factor, superior energy absorption properties, acoustic and thermal insulation and marginal absorption of moisture. Nevertheless, there are still some issues that limit the overall performance of natural materials in composites, such as the interfacial adhesion with the matrix, moisture absorption and long-term stability. Significant research is presently underway to overcome these limitations and to create more opportunities for the successful applications of natural materials in lightweight aerostructures as an effective answer to the challenge put forward from both the legislation authorities and general public towards a more sustainable aviation industry.

References

Akil, HM, Omar, MF, Mazuki, AAM, Safiee, S, Ishak, ZAM & Abu Bakar, A 2011, 'Kenaf fiber reinforced composites: A review', *Materials and Design*, vol. 32, no. 8-9, pp. 4107-21. DOI: 10.1016/j.matdes.2011.04.008

Altman, GH, Diaz, F, Jakuba, C, Calabro, T, Horan, RL, Chen, J, Lu, H, Richmond, J & Kaplan, DL 2003, 'Silk-based biomaterials', *Biomaterials*, vol. 24, no. 3, pp. 401-16. DOI: 10.1016/S0142-9612(02)00353-8

Amorim 2014, *Cork Composites*, 24/08/2014, <http://www.corkcomposites.amorim.com/transportation.php>.

Baillie, C (ed.) 2005, *Green Composites: Polymer Composites and the Environment*, CRC Press.

Cutler, J 1999, *Understanding aircraft structures*, 3rd edn, Blackwell Pub, Oxford.

Dicker, MPM, Duckworth, PF, Baker, AB, Francois, G, Hazzard, MK & Weaver, PM 2014, 'Green composites: A review of material attributes and complementary applications', *Composites Part A: Applied Science and Manufacturing*, vol. 56, pp. 280-9. DOI: 10.1016/j.compositesa.2013.10.014

Faruk, O, Bledzki, AK, Fink, HP & Sain, M 2012, 'Biocomposites reinforced with natural fibers: 2000-2010', *Progress in Polymer Science*, vol. 37, no. 11, pp. 1552-96. DOI: 10.1016/j.progpolymsci.2012.04.003

Flightpath 2050: Europe's Vision for Aviation - Report of the High Level Group on Aviation Research, 2011, European Commission - Directorate General for Mobility and Transport, Luxemburg.

Gibson, LJ 2005, 'Biomechanics of cellular solids', *Journal of Biomechanics*, vol. 38, no. 3, pp. 377-99. DOI: 10.1016/j.jbiomech.2004.09.027

Gil, L 2009, 'Cork composites: A review', *Materials*, vol. 2, no. 3, pp. 776-89. DOI: 10.3390/ma2030776

Guttman, R 2001, 'De Havilland Mosquito: Britain's wooden wonder', *Aviation History*, vol. 11, no. 5, pp. 42-8

Koronis, G, Silva, A & Fontul, M 2013, 'Green composites: A review of adequate materials for automotive applications', *Composites Part B: Engineering*, vol. 44, no. 1, pp. 120-7. DOI: 10.1016/j.compositesb.2012.07.004

La Mantia, FP & Morreale, M 2011, 'Green composites: A brief review', *Composites Part A: Applied Science and Manufacturing*, vol. 42, no. 6, pp. 579-88. DOI: 10.1016/j.compositesa.2011.01.017

Lineo-NV 2014, *Applications*, 22/08/14, <http://www.lineo.eu/#!applications>.

Marsh, G 1996, 'Aerospace composites - the story so far', *Reinf. Plast.*, vol. 40, no. 9, pp. 44-8

Netravali, AN & Chabba, S 2003, 'Composites get greener', *Materials Today*, no. April 2003, pp. 22-9

Nishino, T, Takano, K & Nakamae, K 1995, 'Elastic modulus of the crystalline regions of cellulose polymorphs', *Journal of Polymer Science: Part B*, vol. 33, no. 11, pp. 1647-51

Pervaiz, M & Sain, MM 2003, 'Carbon storage potential in natural fiber composites', *Resources, Conservation and Recycling*, vol. 39, no. 4, pp. 325-40. DOI: 10.1016/S0921-3449(02)00173-8

Sargianis, J, Kim, HI & Suhr, J 2012, 'Natural cork agglomerate employed as an environmentally friendly solution for quiet sandwich composites', *Scientific Reports*, vol. 2. DOI: 10.1038/srep00403

Saúde, JML & Silva, JM 2014, 'Aircraft Industrialization Process – A systematic and holistic approach to ensuring integrated management of the engineering process', in PPe al. (ed.), Springer, pp. 81-104.

Shah, DU, Porter, D & Vollrath, F 2014, 'Can silk become an effective reinforcing fibre? A property comparison with flax and glass reinforced composites', *Composites Science and Technology*, vol. 101, pp. 173-83. DOI: 10.1016/j.compscitech.2014.07.015

Silva, JM, Gamboa, PV, Cláudio, R, Nunes, N & Lopes, J 2013, 'Optimization of the damping properties of CFRP laminates with embedded viscoelastic layers', in proceedings of 14th International Conference on Civil, Structural and Environmental Engineering Computing (CC 2013), Cagliari, Italy. DOI: 10.4203/ccp.99.52

Silva, JM, Nunes, CZ, Franco, N & Gamboa, PV 2011, 'Damage tolerant cork based composites for aerospace applications', *Aeronautical Journal*, vol. 115, no. 1171, pp. 567-75

Silva, SP, Sabino, MA, Fernandas, EM, Correlo, VM, Boesel, LF & Reis, RL 2005, 'Cork: Properties, capabilities and applications', *International Materials Reviews*, vol. 50, no. 6, pp. 345-65. DOI: 10.1179/174328005X41168

Soutis, C 2005, 'Carbon fiber reinforced plastics in aircraft construction', *Materials Science and Engineering A*, vol. 412, no. 1-2, pp. 171-6. DOI: 10.1016/j.msea.2005.08.064

Staiger, MP & Tucker, N 2008, 'Natural-fibre composites in structural applications', in *Properties and Performance of Natural-Fibre Composites*, Elsevier Inc., pp. 269-300.

Stamboulis, A, Baillie, CA, Garkhail, SK, Van Melick, HGH & Peijs, T 2000, 'Environmental durability of flax fibres and their composites based on polypropylene matrix', *Applied Composite Materials*, vol. 7, no. 5-6, pp. 273-94. DOI: 10.1023/A:1026581922221

Stemergy 2014, *Plain sailing for flax*, 22/08/14, <http://www.hempline.com/hemp/hemp_articles/191/>.

Symington, MC, Banks, WM, West, OD & Pethrick, RA 2009, 'Tensile testing of cellulose based natural fibers for structural composite applications', *Journal of Composite Materials*, vol. 43, no. 9, pp. 1083-108. DOI: 10.1177/0021998308097740

Toyota-Motor-Corporation 2014, 23/08/2014, <http://www.toyota.co.jp/en/environmental_rep/01/pdf/>.

Ude, AU, Eshkoor, RA, Zulkifili, R, Ariffin, AK, Dzuraidah, AW & Azhari, CH 2014, 'Bombyx mori silk fibre and its composite: A review of contemporary developments', *Materials and Design*, vol. 57, pp. 298-305. DOI: 10.1016/j.matdes.2013.12.052

Wambua, P, Ivens, J & Verpoest, I 2003, 'Natural fibres: Can they replace glass in fibre reinforced plastics?', *Composites Science and Technology*, vol. 63, no. 9, pp. 1259-64. DOI: 10.1016/S0266-3538(03)00096-4

Wiedemann, M, Sinapius, M & Melcher, J 2012, *Innovation Report 2012: Institute of Composite Structures and Adaptive Systems*, DLR, Germany.