Deutscher Luft- und Raumfahrtkongress 2014
DocumentID: 340188

POTENTIAL OF SUSTAINABLE MATERIALS IN WING STRUCTURAL DESIGN

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Abstract

The deliberated selection of structural materials has become a topic aspect of aircraft engineering. The reduction of the structural weight by high performance materials has evolved as an essential technology driver in aviation. Facing the challenge of non-renewable resources when using carbon fiber reinforced plastics; one has to continue this quest for load bearing materials including sustainability aspects.

In this study, the weight reduction potential of natural fiber composites for load bearing structures is highlighted. For this purpose, a model of a civil transport aircraft (airbus A320-200) has been set up. The weight of the respective wingbox is calculated using material properties of preliminary defined natural fiber composites (NFC); the results are compared to a reference wingbox made of an aluminum-alloy of the 7000 series. Being aware of the lower mechanical properties (young's modulus and yield strength) of NFCs compared to aluminum, a weight reduction potential of 12-14% when using Ramie fiber composites can be found caused by a reduced density of these materials without compromising structural integrity. Composites with Hemp and Flax fibers, however, increase the structural weight. In conclusion, results suggest that natural fibers shall not be excluded categorically from applications in load bearing components for aviation.

1. INTRODUCTION

Following the premise of designing lightweight vehicles, the deliberate selection and combination of structural materials has accompanied aircraft engineering from the outset. Beginning with the first structures from wood and sailcloth, light metals like aluminum and magnesium alloys came later into focus. Recently, fiber-composites like glass-fiber reinforced plastics (GFRP) and carbon-fiber reinforced plastics (CFRP) have successfully joined the options of construction materials, containing up to 50% of the structural weight in modern aircraft structures [1].

Simultaneously, aspects of sustainability are coming more and more into discussion, considering emission savings, recyclable structures and looking at the whole lifecycle impact of the aircraft vehicle [2].

Unfortunately, fiber composites are predominantly based on fossil feedstock and are currently barely able to be recycled adequately since retentions of the mechanical properties of the recycled products have to be accepted [3]. The rising demand of CFRP and the price volatility of raw materials exacerbate the situation.

Against the backdrop of this development, the search for sustainable fiber composites has to be initiated.

In a first screening and assessment it was shown that materials from regenerative resources do not meet the boundaries of mechanical properties and reliability aspects set by the structural materials mentioned above. In order to tackle this situation from the material's side we have therefore introduced and defined the loom-in capability as an attribute for new fiber materials in previous work. [4]

At the same time, one can raise the question, if the favorable intrinsic mechanical properties (namely Young's modulus and tensile strength) of aluminum possibly can be matched with other characteristics of bio-based composites that lead to lighter structures. For example, a new material might over compensate the inferior intrinsic mechanical properties by using thicker plates at lower density in the design process.

In terms of a quadrant scheme (see Figure 1), there is a new design field opening. Starting from the reference materials in use, four options are considerable:

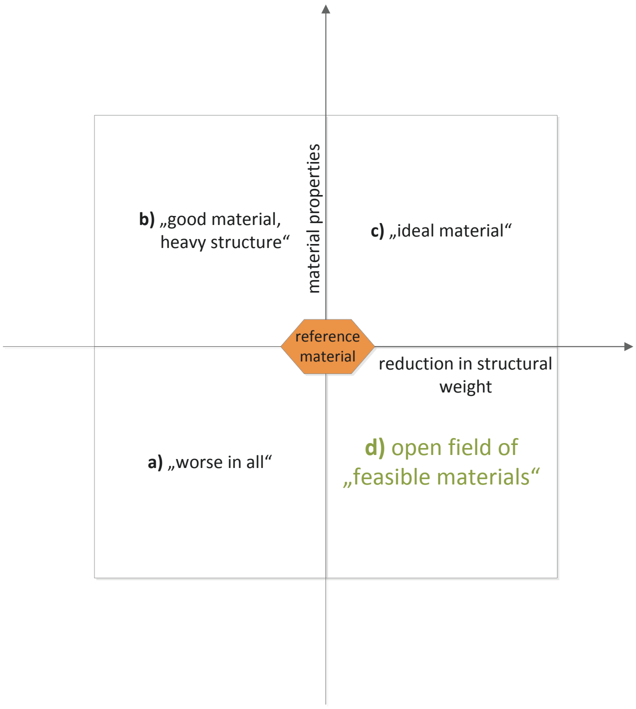

Figure 1: Quadrant scheme of future design options starting from a reference material in use.

a) Designing vehicles with not suitable materials, making the structure less capable for load bearing and enhancing the overall weight at the same time.

b) Materials with acceptable mechanical properties, however, leading to an increased structural weight.

c) The ideal lightweight design case: better mechanical properties in combination with weight reductions.

d) Materials with lower mechanical properties than aluminum but which nevertheless give the potential of structural weight reductions. This open field of feasible materials is discussed in the following.

One approach to answer this question is the calculation of the wing mass by using these new materials.

At Bauhaus Luftfahrt a method for wingbox mass estimation was developed and implemented using the numerical environment MATLAB. This method was employed in previous work to estimate the wing mass of nonstandard wing configurations as for the estimation of the wing mass [5]. As input data for the method serve the dimensions of the wing, airfoil data, location of the spars, flight state information, such as speed and altitude, and of course material properties of the wing.

2. SUSTAINABLE MATERIALS

In 1995 more than 90 wt% of materials consumed in the US were made from nonrenewable resources [6].

Based on this enormous usage, the material utilization of biomass in addition to the production of biofuels, has come more and more into the focus. One considerable class of bio-based materials are natural fiber composites (NFC).

In the present study the potential of NFC in aircraft wings is highlighted. At the beginning, it should be noted that there is no commercial use of natural fiber composites in load bearing structures to date. Therefore, the potential of NFC is to be discussed in this study rather than a recommendation, which composite would be the next structural material for aircraft wings.

2.1. Raw Materials Compendium

This study is focused on potential NFCs, consisting of natural fibers embedded in the corresponding matrix polymers, which were arranged in laminate plies with a dedicated fiber direction.

In a first step the mechanical properties, i.e. Young's Modulus (*E*) and the yield strength (σ_y) as well as the density (ρ), of the NFC raw materials are collected. After screening the data, Hemp, Flax, Sisal and Ramie are selected as fiber materials.

Fibers from Hemp, Flax and Sisal are frequently used in automotive interiors [7], in the building sector, or for further consumer durables [8], and are therefore fibers which can readily be provided in high quantities. From the viewpoint of mechanical properties, fibers made from Ramie are selected additionally due to their commensurately high Young's Modulus and yield strength [9].

The second class of materials that have to be mentioned, are the matrix polymers.

Since epoxy resins are the material of choice for manufacturing semi-finished plies and/or components from CFRP, these matrix resins are considered in the calculation, being aware that nowadays these composites are not made of 100% renewable resources.

In order to make the material entirely from renewable feedstock, polylactic acid (PLA) is brought into discussion as a possible matrix polymer. Based on lactic acid, which can be synthesized from starch, PLA is a frequently used bioplastic with a high potential to substitute conventional polymers [10] and a forecast global production of 800.000 tons/year in 2020 [11].

For better comparability of the material properties, average values are used obtained from one database (M. Ashby et al. “materials and the environment”) [9], see Table 1.

Table 1: Material characteristics of the materials used for further calculations (adapted from [9]).

Material	*E (GPa)*	*σ_y (MPa)*	*ρ (kg/m³)*
Hemp	55-70	200-400	1470-1520
Flax	75-90	150-338	1420-1520
Sisal	10-25	495-711	1400-1450
Ramie	38-44	450-612	1450-1550
Epoxy	2,35-3,08	36-71	1110-1400
PLA	3,45-3,83	48-60	1210-1250

These raw material data are the basis for calculating the mechanical properties of a proposed long fiber NFC.

2.2. Calculating the Mechanical Properties of Natural-Fiber Composites

For the wing mass calculations characterized in Section 3, the model needs four different material characteristics as input, these are *E*, σ_y, ρ and the shear modulus *G*. Furthermore, the assumption is made that materials are isotropic.

Starting from highly anisotropic natural fibers that have much better properties in fiber direction than perpendicular to it, one has to find a possibility to estimate the mechanical properties of a quasi-isotropic fiber composite laminate.

A conservative approach is the “10% rule” investigated by Harth-Smith, assuming that each composite ply, which is not loaded in the fiber direction, contributes 10% to the overall stiffness and strength of the composite. Note that this method is dedicated to have a simple and reliable prediction of the mechanical properties of quasi-isotropic composite laminates. [12]

In the case of a quasi-isotropic laminate (0°, ±45°, 90°), the factor of decimation compared to a uniaxial laminate would be 0,325.

In combination with the rule of mixture,

$$A_{Composite} = A_{Fiber}\varphi + A_{Matrix}(1-\varphi) \quad (1)$$

where *A* can be *E*, σ_y or ρ, the first material characteristics of a NFC can be calculated assuming a fiber's volume content φ of 0,6 according to the volume content of fibers in high performance CFRP [13, 14].

The shear modulus *G* can be derived from *E* in isotropic materials

$$G = \frac{1}{2(1+\nu)}E \quad (2)$$

Within the above mentioned ten percent rule, the Poisson Ratio ν can be assumed to be 0,33.

Since the 10% rule is a conservative approach leading to inferior values compared to mechanical testing [12] we decided to calculate the properties of the proposed composite with the maximum values of the generic data (see Table 1) in order to tackle this disadvantage in an arguable scope.

The summary of the calculated NFC material properties are listed in Table 2.

Table 2: Composite input characteristics for wing mass calculations

Material	*E (GPa)*	*G (GPa)*	*σ_y (MPa)*	*ρ (kg/m³)*
Epoxy/Hemp	14,05	8,92	87,23	1326
Epoxy/Flax	17,95	11,39	75,14	1296
Epoxy/Sisal	5,28	3,35	147,88	1284
Epoxy/Ramie	8,98	5,70	128,57	1314
PLA/Hemp	14,15	8,98	85,80	1366
PLA/Flax	18,05	11,45	73,71	1336
PLA/Sisal	5,37	3,41	146,45	1324
PLA/Ramie	9,08	5,76	127,14	1354

Within this set of material characteristics one can, evaluate the potential wing masses for a comparative discussion.

3. WING MASS CALCULATION

This section is dedicated to the mass estimation method of the wing configurations and the introduction of the wing models.

3.1. Calculation Methods

For the estimation of the wing mass, a MATLAB program has been developed [15, 16], using the vortex lattice method, namely the aerodynamic code of “TORNADO” [17], to calculate the aerodynamic lift forces on a given wing configuration.
The next step is the application of the forces on a beam with finite elements, including non-linear deformation, where the beam represents the primary structure of the wing with spars and skin. Figure 2 displays the generated mesh by TORNADO for the calculation of the aerodynamic forces and the finite element beam.

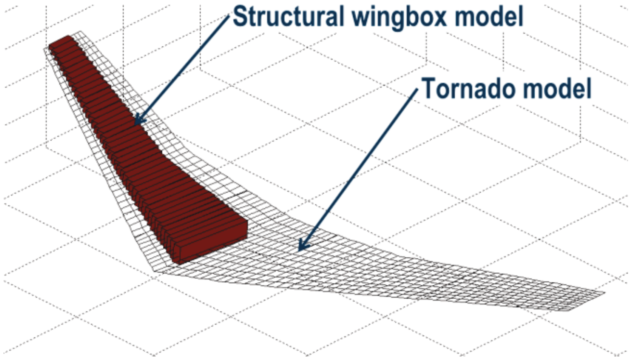

Figure 2: Finite element view on spars and skin of the reference wing

The size of the structure is defined by the spanwise position and the used airfoil. The cross section of the wingbox is simplified as a rectangle and the position of the spars must be defined, as explained in Figure 3.

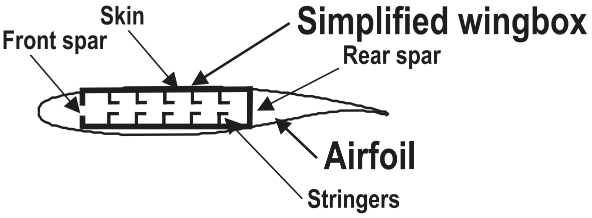

Figure 3: Definition of the wingbox for finite elements calculations

Simplified stringers are inserted, which are considered in the buckling analysis. Due to the occurring aerodynamic loads the thickness of the spars and the skin are dimensioned; the result is a weight estimation of the wing.
According to the deformation of the beam, the aerodynamic lift of the wing changes. Therefore, the aerodynamic forces are re-calculated. This iterating process stops when the deformed wing produces enough lift for the given weight of the considered aircraft and when the deformation of the wing does not change between the last two iterations.
The here considered load cases are maximum maneuver, roll and gust, which represent structural strength requirements for the certification of commercial aircraft, see, for example, the Certification Specifications for Large Aeroplanes (CS25) [18].

3.2. Wing Models Set-up

When calculating the wing masses with the method introduced in section 3.1, one has to set up a reference aircraft in order to precise the aerodynamic forces and with it, the loads applied on the structure. The Airbus A320-200 is chosen, as it is a wide-spread aircraft type.
The required key figures, i.e. maximum take-off weight, number of passengers, cruise speed, cruse altitude, of an Airbus A320 are stated in Table 3.

Table 3: Key figures of an Airbus A320-200

Aircraft Property	*Unit*	*Value*
Maximum Take-Off Weight	kg	77000
Number of Passengers	-	180
Cruise Speed	-	M0,76
Cruise Altitude	ft	35000

The numbers of the Maximum Take-Off Weight (MTOW) and the cruise speed are used for the weight estimation, since the aerodynamic forces depend on the cruise speed and the gravity force on the MTOW.
At last, one has to size the dimensions of the reference. Figure 4 displays a top view of an Airbus A320 [19] with overlaying TORNADO mesh on the wing to show how the aircraft is modeled for the weight estimation simulation.

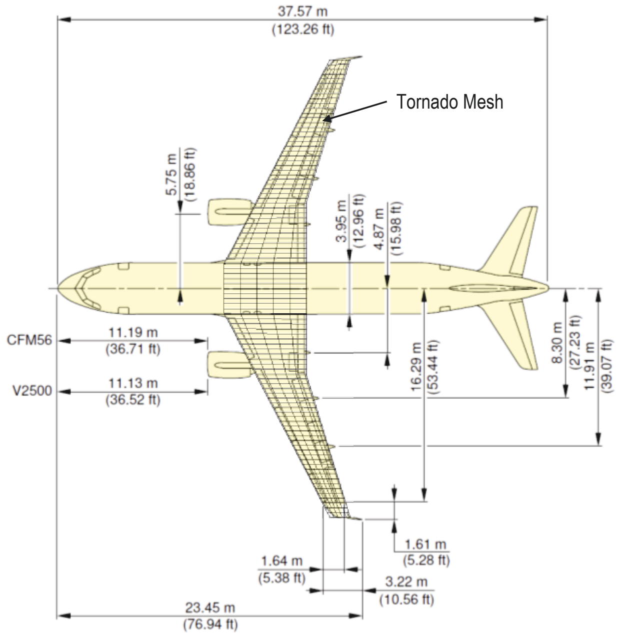

Figure 4: Top view on an airbus A320-200 with TORNADO mesh on the wing.

In order to calculate the wing mass, the dimensions of the Airbus A320-200 wing are used as input. The key parameters are the span, sweep, dihedral, taper ratio and root chord length of the wing.

The mass of the wing is calculated by the computation of the aerodynamic forces acting on the wing for a given load case and applying these forces on the structural model. The cross sections of the finite element beam of the structure are sized according to the occurring loads and assumed material properties. Finally, the wing mass can be estimated with the assumed material density

4. RESULTS AND DISCUSSION

In Table 4, the calculated wing masses *m* are compared to the reference, a wingbox of aluminum alloy of the 7000 series (see the results in [5]). The relative changes in the wing masses Δ*m* (kg) and Δ*m* (%) are shown additionally.

Table 4: Wing masses *m* and relative changes of the wing mass in comparison to the aluminum reference

Composite	*m (kg)*	*Δm (kg)*	*Δm (%)*
Epoxy/Hemp	10503	1674	19
Epoxy/Flax	11355	2526	29
Epoxy/Sisal	n. a.	n. a.	n. a.
Epoxy/Ramie	**7576**	**-1253**	**-14**
PLA/Hemp	10815	1986	23
PLA/Flax	11784	2955	33
PLA/Sisal	n. a.	n. a.	n. a.
PLA/Ramie	**7758**	**-1070**	**-12**
Aluminum 7000	8829	reference	reference

In the case of the sisal composites, the model was not able to finish the finite-elements iterations that can be owed to the lowest values of *E*.

The results are surprisingly divergent since Hemp and Flax fiber composites seem to increase the wing masses while Ramie fiber composites offer a potential of weight reduction.

Another point of discussion is the exiguous difference when using epoxy resins or PLA as matrix polymers. However, at this step one has to be aware of the different nature of the two matrix polymers. Epoxy resins are thermoset polymers, whereas PLA is a thermoplastic material. A substitution of epoxy resin is therefore coupled with fundamental changes in the manufacturing process.

Regarding the sustainability of the natural fiber composites, the price and carbon dioxide emissions are one of the proposed qualities postulated in literature to be discussed [20].

With the raw material price of Ramie (1,5 \$/kg [9]) and the corresponding prices for the matrix resins (epoxy resin: 8,0 \$/kg and PLA: 2,4 \$/kg [9]), the costs of the wing's raw material would be in the range of 14400-31100 \$. In comparison to the raw material prices of aluminum (2,4 \$/kg [9]), the costs of 21200 \$ for an aluminum wing cannot be reduced dramatically.

Considering the CO_2 footprint of the wing's raw materials, the use of natural fibers can reduce the production of greenhouse gases. A NFC wing made of Ramie would have a carbon footprint of 12600-22600 kg, in comparison to the emissions for the production of Al-alloy of 97100 kg (data derived from [9]) this offers a remarkable potential of CO_2-reduction. Regarding CFRP, the emissions when producing aircraft structures can be reduced when working with fiber composites compared to aluminum. [21]

Closing the circle from the postulated design options described in the introduction, one can draft a quadrant scheme (see Figure 5) spanned by the specific modulus E/ρ and Δm with the values from Table 2 and Table 4.

Within the simulations conducted in this study, the existence of the proposed design field can be demonstrated. It seems that the lower *E* and E/ρ of Ramie fiber composites in comparison to conventional structural materials might be compensated, leading to lighter aircraft structures.

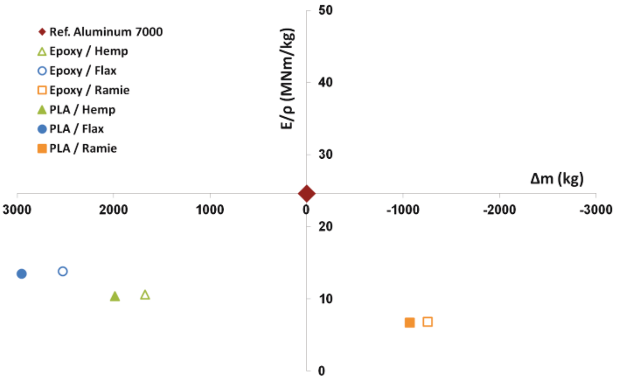

Figure 5: Quadrant scheme of design options applied to the specific Young's Modulus E/ρ and the relative wing mass changes Δ*m*.

It is interesting that, independently from the material, it seems to be possible to design lightweight wings with lower mechanical properties than the aluminum's one.

The next scheme (see Figure 6) shows the benefit of the ramie composite:

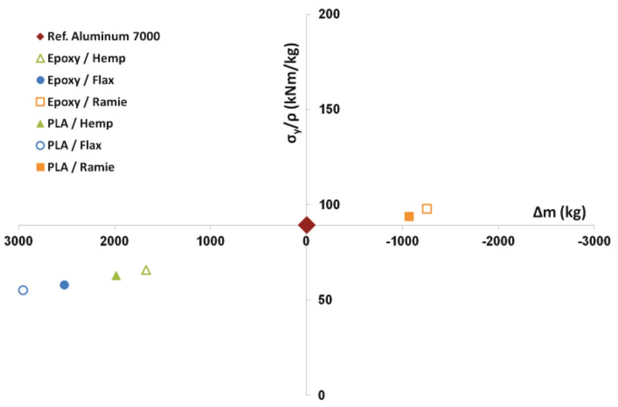

Figure 6: Quadrant scheme of design options applied to the specific Yield Strength σ/ρ and the relative wing mass changes Δm.

Applying the metric “specific yield strength” σ_y/ρ on the material, the Ramie fiber falls into the “ideal design case” field, having better mechanical properties and allowing weight reduction at the same time.
Summarizing both graphics, the yield strength seems to have more impact than *E* on the weight reduction potential since a reduced *E* is balanced by an enhanced σ_y.
This conclusion has, however, to be accurately analyzed in further works. The comparable low values of the Young’s modulus will also lead to an excessive buckling of the wing structure. The following consequences for aircraft design have to be investigated.
At last, it has to be noted that only quasi-isotropic materials were considered in this model. Additionally, the 10% rule is a rather conservative approach. It can be expected that the mechanical properties and with it the weight reduction potential is actually better than in this model.
The potential of a load guided structural layout has to be discussed yet in related studies.

5. CONCLUSION AND OUTLOOK

At the end of this study, the calculation of the weight reduction potential of NFC has exhibited as a fascinating engineering field. On the one hand, it can be shown that there is a potential of weight reduction using Ramie fiber composites without compromising structural integrity. On the other hand, Hemp and Flax fiber would increase dramatically the structural mass.
In summary, a well defined material selection has to be conducted concerning NFC in order to reduce the structural weight of the wing. Revolutionary reduction potentials, as the use of CFRP [5], are not to be expected until now. Analog to the technological implementation of CFRP, the application of NFC in aircraft structure will have to cope different challenges.
Facing the high cost of CFRP and the commensurately high CO_2 emissions of aluminum and CFRP components [21], the application of bio-based materials becomes apparent. Including the potential of NFC calculated in this study, bio-based materials should not be categorically excluded from structural applications.
As addressed in the introduction, a promising approach to produce fibers from renewables followed in further studies is the introduction of their loom-in capability as a premise. This means that we should be able to produce a fiber that is able to be taken as an identical substitute from the implementation side [4].
Furthermore, this study has shown an extraordinary point of view to be pursued: particularly, it is possible to use materials with lower *E* and σ_y than aluminum, nevertheless reducing the structural weight of the wing.
On a higher level, the notion of a material selection based on the mechanical requirements would be inspiration of such an approach. This was not in the scope of the model, which has been set up to generate a simple overview on the wing mass, but further works might be inspired by a determination of the desired mechanical properties combined with a successional material selection.
Integration aspects as the probably reduced tank volume by using thicker plates in the design process will have to be analyzed. Following the estimations with the 10% rule and the wing mass calculation model conducted in this study, a dedicated structural layout of the wing has to be executed in future studies.

AKNOWLEDGEMENTS

The authors would like to thank Andreas Sizmann for inspiring discussions on the design options and Christian Endres for a further exchange of ideas.

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