Hybrid Natural Fiber Composites in a Helicopter Cabin Door – Mechanical Properties and Ecological Efficiency

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ABSTRACT

The overall goal of this work is the application of bio-based materials in an aerospace structure, while maintaining the structural-mechanical performance in accordance with its certification standards. This goal was pursued through the use of hybrid composites made from a combination of conventional (carbon) and bio-based fiber composites (flax). The cockpit door of an ultralight helicopter was chosen to prove the applicability of this hybrid composite. A reference door, built from carbon-fiber-reinforced polymers, was considered a benchmark to the requirements in terms of mass, stiffness, damping, ecological efficiency and costs.

First, the benchmark door was built and characterized. Then the geometry was redesigned for the application of flax fiber composites, leading to an increase of the areal moment of inertia. The new geometry was then analyzed using multiple gravity loads. Highly loaded areas were locally reinforced with carbon prepregs. Tensile tests and sub-component cantilever beam tests were iteratively analyzed for the development and advancement of the finite element analysis (FEA) model. A significant material nonlinearity in form of a reduction of elasticity with increasing strains is inherent in flax-fiber composites, this phenomenon was interpreted as a yield point and included in the failure analysis. The resulting hybrid design showed promising results, as the stiffness matched the reference doors and a mass reduction of 6% with an increase in the bio-based material mass from 0 to 43% was achieved. But, due to manufacturing issues, additional epoxy layers had to be used in the flax weave, which significantly reduced the fiber volume content. As a result, the built hybrid door consisted of a bio-based mass of only 30%.

The ecological efficiency, in terms of material primary production, of the hybrid door is significantly better than the reference doors. By calculation, the hybrid door's materials consumed 221.7 MJ - eq less energy, while emitting 11.0 kg CO_2 - eq less carbon. However, drawbacks in the operational life due to an increased mass are inherent and break even on the ecological efficiency. This weight-drawback needs to be prevented, which could be achieved through a denser flax-fiber weave. In order to point out the potential of natural fibers, the designed hybrid version is also compared to the reference. Furthermore, benefits in terms of costs, vibration behavior, and mechanical damping are itemized in this work.

INTRODUCTION AND MOTIVATION

Natural fibers offer lightweight potential and their use is typically motivated by the improvement of the ecological efficiency (Ref. 1). The main aspect is the significantly lower energy input and the associated decrease of carbon emissions in the production process (Refs. 2–4). Furthermore, flax-fiber reinforced material as used in this application shows excellent damping properties combined with an ultimate strength ($R_{UD} = 275$ MPa) comparable to conventional metallic materials and an initial stiffness of more than $E_{UD} = 30$ GPa, comparable to glass fiber reinforced polymers (Ref. 5).

The aim of this work is to demonstrate the potential and drawbacks of bio-based fiber materials in helicopter structural applications. Thus, a proof of structural-mechanical performance as well as quantification of its ecological efficiency is presented.

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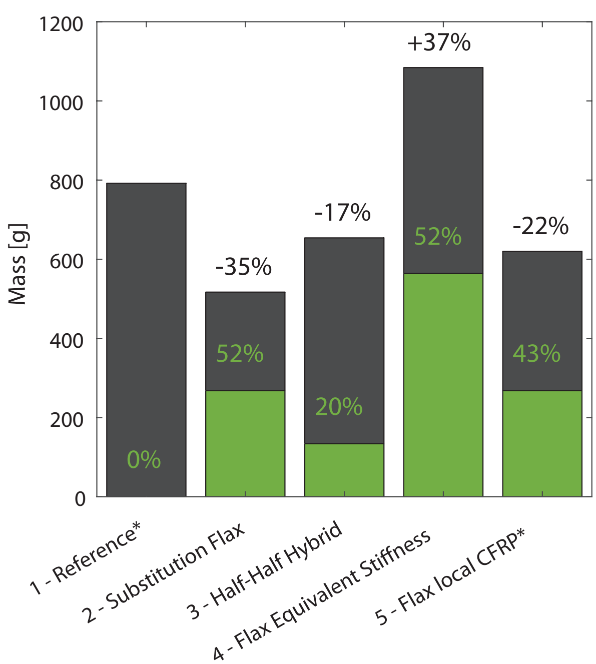
State-of-the-art helicopter cabin structures are likely to be made out of carbon-fiber reinforced materials, with typically no ambition in ecologically efficient material use. Nevertheless, conventional cabin structures are optimized in terms of weight, which results in energy savings in the operational life. In line with those considerations, the present work assesses the ecological efficiency of the primary production of bio-based fiber materials to implications on their operational life. The term ecological efficiency is analyzed in terms of cumulative energy demand (CED) and global warming potential (GWP). Both metrics have already been used in this context by relevant literature (Refs. 4, 6).

Besides the demonstration of ecological efficiency, the application of bio-based materials in helicopter structural appliation is shown to be desirable in terms of costs, vibrations and mechanical damping. Prices for flax fibers are given in (Ref. 4) by 2.1–4.2 USD kg^{-1} while carbon fiber costs 124–166 USD kg^{-1}. Considering processed prepreg materials with epoxy coating, the prices will converge, but a remaining, significant benefit is expected. The real prices paid for the

used materials are also compared in the last section.
Additionally, vibrations are a common but undesired phenomenon in helicopter structures, as well as noise, which is likely to be induced by the cyclic loading and interaction of the rotor and cabin. The high damping ratios of natural fiber reinforced polymers (NFRP) (up to 5–10 times higher than carbon fiber reinforced polymers (CFRP) according to (Refs. 7–9)) are considered technically beneficial.

DESIGN

The platform designated for this endeavor was the cockpit door of an ultralight helicopter, the CoAX 2D by edm aerotec GmbH. A reference door was built as a structural demonstrator. It has a size of approximately 1.30 m times 1.00 m, and is made of two layers of carbon-woven prepreg with a 2/2-twill weave style and a fiber grammage of 200 g m^{-2}; this material is not used by the manufacturer, only in this study. The carbon reference served as a benchmark in stiffness, in dynamic, economic, and environmental performance. The demands for structural integrity arose from emergency landing conditions and are thereby multiples of the door's own weight.
The design approach for the new flax door was as follows: First, the geometric shape of the reference door was adapted on the outside, as the aerodynamic behavior of the helicopter should not be influenced, and the inner geometry was redesigned in order to increase the bending and torsional moment of inertia. Within this step the cross-sectional moments of inertia could be increased in a range of 5 to 20% and in one outstanding position by 100%.



* built and characterized versions

Fig. 1. Bio-Based Mass (Green) and Overall Mass Comparison to the Reference of Pre-Design Door Versions

Next, highly loaded areas were identified as positions for reinforcements, where a FEA model iteratively optimized the needed reinforcements and amounts of layers. In order to pursue the goal of reducing the embodied energy, a new version with a high bio-based mass proportion was envisaged. Therefore, different material contents were analyzed and five resulting configurations were the matter of investigation using the following material combinations: 1 - pure carbon, 2 - pure flax, 3 - half-half carbon-flax, 4 - flax with flax reinforcements and 5 - flax with carbon reinforcements. The FEA model data refer to the technical data sheets and were not experimentally determined at this point, therefore the masses and bio-based contents are hypothetical values. The results of the pre-design study are plotted in Fig. 1. It has to be considered that versions 2 and 3 are a simple layer substitution of the materials, and these versions would not meet the requirements in stiffness and strength.
In the analytical comparison of all versions, the best compromise between stiffness and bio-based material content was identified as version 5 - flax with carbon reinforcements. This design used two layers of 150 g m^{-2} flax in ±45°-fiber-angle orientation as the base material and additional carbon for local reinforcements of the type twill 2/2 with 200 g m^{-2}, with fibers oriented in load-path directions. The areas of reinforcements are shown in black in Fig. 2 and Fig. 3; the base layers of flax are plotted in gray.
The load-case design was performed using the frame structure of the door and a mass simulation of the plexiglass window. The bonding of the inner and outer shell was modeled using beam elements. The hard design constraints from the national ultralight helicopter certifications (LTF-ULH 2016 (Ref. 10)) were: no deformation when accelerated by maneuvering loads of $3.5/-1.0$ g in Y and Z directions and no failure when accelerated by ±3 g in Y-direction, by 9 g in X-direction and by ±4.5 g in Z-direction (axes as shown in Fig. 2 and 3).

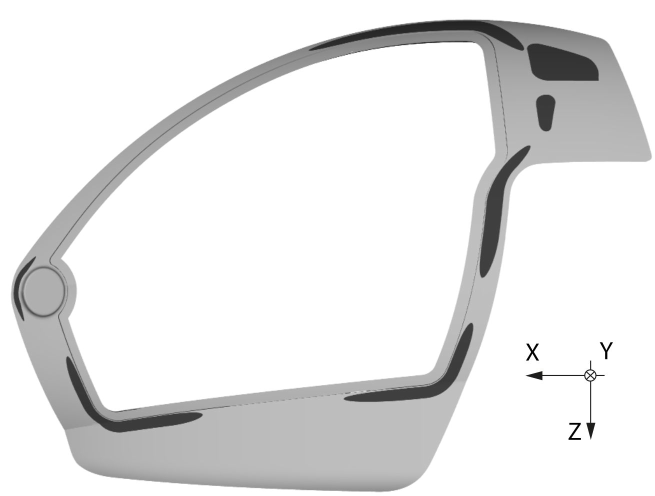


Fig. 2. Outside View of the Cabin Door, Gray: Flax Fiber Material, Black: Carbon-Fiber Reinforcements

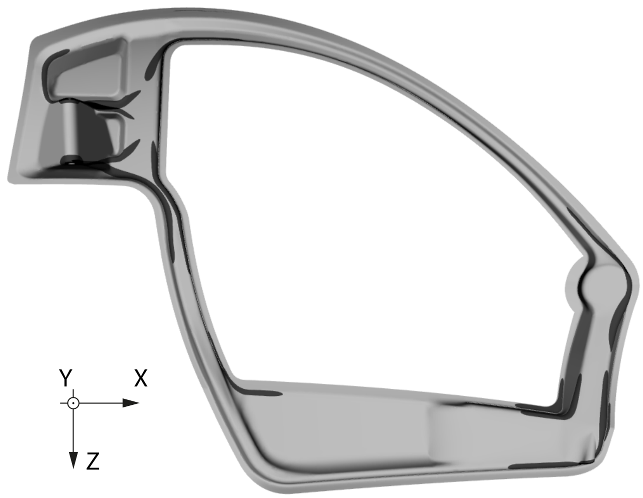


Fig. 3. Inside View of the Cabin Door, Gray: Flax Fiber Material, Black: Carbon Fiber Reinforcements

These constraints were derived in relation to the maneuvering loads and the demand: No passengers should be harmed by an emergency landing. As the doors are right besides the passengers, these should not fail but maintain their protective function in case of an emergency landing. Soft design constraints considered the aerodynamic load in a fast forward flight, the aerodynamic load of a gust when the door is open and a handling load from a person leaning on the door. But as the reference door also showed large deformations under these soft constraints, and aerodynamic loads were not verified, these constraints were substituted by an equal stiffness demand with respect to the reference door.

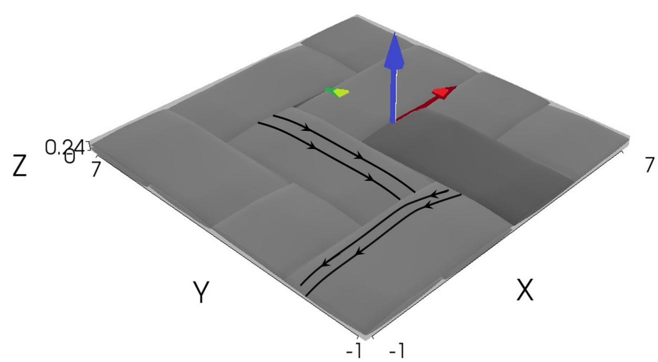
Conclusively, a reference door was built first and characterized in order to set a benchmark design. The results, mainly from experimental data, are used in the next section when comparing both versions. Its final weight was 659 g, 17% lower than the reference in the simulation. Due to the use of foam molds, the laminate was particularly dry on the mold surfaces; in order to increase the surface quality, a higher epoxy content should be aimed for so that the mass would be closer to simulation results.

The evaluation of the new hybrid design still resulted in benefits in weight of 6%, when compared to the built reference door. The results from the stiffness characterization were used to update the hybrid design. It turned out that these were the critical design constraints instead of the multiple g-loads from maneuvering and emergency landing.

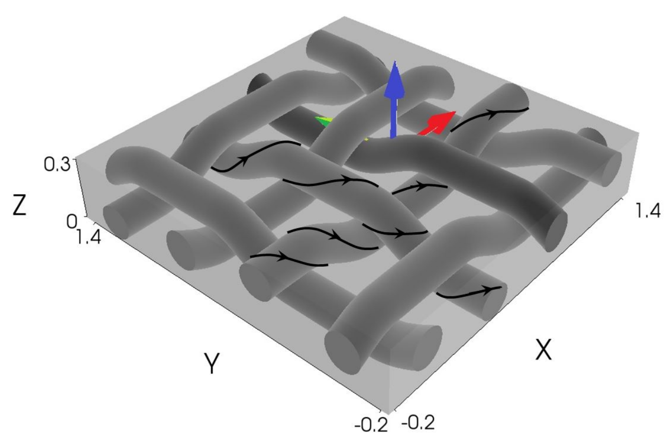
FLAX COMPOSITES

As explained in the Introduction, flax composites offer potential in several areas, however weight-specific stiffness and strength are significantly lower compared to carbon fibers. Additionally, when processing flax to a weave, the performance drops further. As a matter of fact, carbon fibers can be produced endlessly and flax fibers can not, they are grown by nature to certain lengths. This leads to the problem in processing a weave in which fibers need to be spun into a yarn in order to process them economically, which inevitably implies fiber angles and leads to a more circular shaped bundle. As a result, the weave shows large spacings between the bundles, and additional fiber angles are induced by both spinning and weaving; Fig. 4 shows this schematically compared to a carbon weave, the graphics were generated with the software TexGen. The geometric course of particular fibers are drawn in black, where the twist angle of flax should be emphasized. Additionally, the large spaced weave of flax should be shown compared to the neat elliptic bundles in the carbon weave; both angles and sizing result in a low performance of the flax weave.

In the initial attempts to manufacture a two-layered laminate from the weave (Lineo FLAX-Preg BL 150), problems with a proper inter-laminar bonding appeared. Parameter studies on the curing cycle, including a variation of temperature, time and pressure, did not lead to satisfying results. Therefore, an epoxy film (Henkel Loctite EA 7000 Aero) was added in a proportion of 1:1 to the weave, by which a proper inter-laminar bonding could be achieved.



a) Carbon Weave



b) Flax Weave

Fig. 4. Schematic 3D-Alignment of Fibers and Fiber Bundles in a) Carbon 2/2-Twill and b) Flax 2/2-Twill Weave

Using the additional epoxy film layers, the fiber volume content was reduced significantly to only 29%, compared to the initial assumption of 45%, according to the FFRP datasheet. With this material combination, coupon tensile tests were performed at a 0°- and 45°-fiber-orientation-angle and as it is a bidirectional material, the reinforcing fibers are oriented in two directions: 0/90 and ±45, respectively. The resulting material characteristics are listed in Table 1.

One finding was, analogically to the unidirectionally reinforced specimens, the stress-strain relations do not follow a linear correlation, but a nonlinear one (Ref. 5). Therefore, the typically from conventional laminates expected linear behavior is not sufficient to modeling flax composites. As a conclusion, a material yield point was identified and constrained the design to the linear region of the material. (Refs. 11–13) analyzed the influence of fiber and matrix nonlinearities on cyclic loading of the composites in detail, it turned out that strains beyond this yield point result in permanent deformations.

In order to identify a quantitative yield criterion, a bilinear approach, initially developed for unidirectionally reinforced laminates in (Ref. 5), was adapted for this case using a smeared approach and a multi-angle layered laminate. Different angles were derived from the geometrical basics of the weave and added in conformance with the rule of mixtures (ROM) and the classical laminate theory.

It turned out that a plastic deformation can be expected starting from $\sigma_{t,1,K} = \sigma_{t,2,K} = 30.3\,\text{MPa}$ elongation in loading directions x and y of the bidirectional weave, which happens at approximately $\varepsilon = 0.15\%$ tensile strain. While the transversal yield point was defined at $\sigma_{t,3,K} = 5.9\,\text{MPa}$ and the shear yielding at $\tau_{12,K} = 32\,\text{MPa}$.

Table 1. Elasticity, Stress and Strain Characteristics of Carbon and Flax Weave from Experimental Results and FEA Model

Parameter	Unit	Flax W	Carbon W
fiber grammage	[g m^{-2}]	150	200
weave type	-	twill 2/2	twill 2/2
t	[mm]	0.35	0.24
V_F	[%]	32	54
$E_1 = E_2$	[GPa]	8.733	63.010
E_3 *	[GPa]	2.500	6.000
ν_{12}	[-]	0.14	0.14
$\nu_{13} = \nu_{23}$ *	[-]	0.3	0.3
G_{12}	[GPa]	1.371	4.710
$G_{13} = G_{23}$ *	[GPa]	0.500	0.750
$\sigma_{t,1,ult} = \sigma_{t,2,ult}$	[MPa]	96.4	776
$\sigma_{t,1,K} = \sigma_{t,2,K}$ **	[MPa]	30.3	-
$\sigma_{t,3,ult}$ *	[MPa]	31	60
$\sigma_{t,3,K}$ **	[MPa]	5.9	-
$\tau_{12,ult}$	[MPa]	36.3	102
$\tau_{12,K}$ **	[MPa]	32	-
$\tau_{13,ult} = \tau_{23,ult}$ *	[MPa]	25	50
$\tau_{13,K} = \tau_{23,K}$ *	[MPa]	25	-
$\varepsilon_{1,ult} = \varepsilon_{2,ult}$	[%]	1.53	1.17
$\varepsilon_{3,ult}$ *	[%]	1.03	1.00
$\varepsilon_{K,0} = \varepsilon_{K,90}$	[%]	0.15	-
$\varepsilon_{K,45}$	[%]	0.625	-

* estimated values, not determined by experimental results
** determined by ROM from UD-coupon-tests (Ref. 5) and semi-empirical model

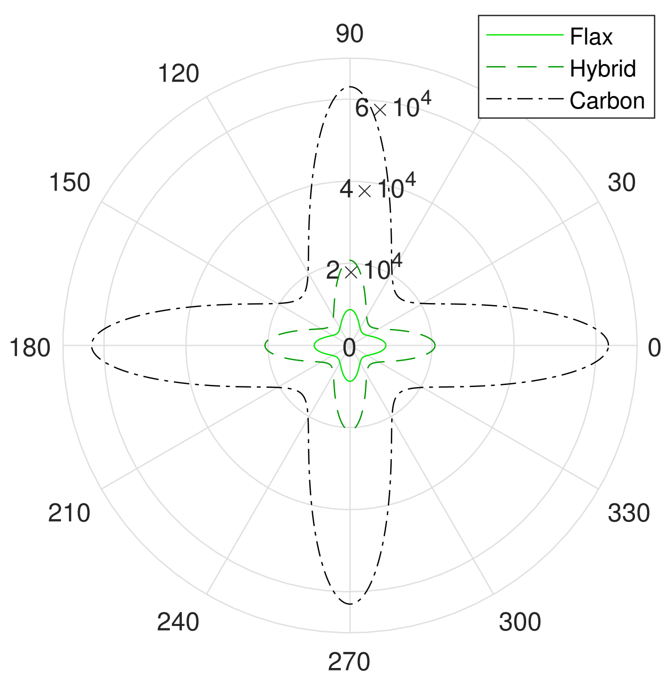


Fig. 5. Polar Plot of Elasticity Properties of Flax Weave, Carbon Weave and Flax-Carbon Hybrid

These values were used within a Hashin failure evaluation in the design phase. The derived yield criterion was applied for loads where no deformation was allowed, whereas the maximum stress criterion was applied for the load cases where deformation was allowed. Table 1 shows the material characteristics for the global modeling of the cabin door with shell elements and a linear material model.

As local reinforcements by carbon-fiber weaves were envisaged, tensile tests with the symmetric lay-up $[C_{45}, F_{45,3}]_S$ were performed and used to verify the composite layer modeling method in the FEA model. Fig. 5 shows the polar plots of the FEA linear material models, which were based on and in good agreement with the experimental results. It can be seen that by the addition of only two carbon layers to the flax material, the stiffness can be enhanced by almost three times from 8.7 GPa to 21.4 GPa.

As expected, the pure carbon weave shows the highest stiffness values. Concluding to a design where areas of low stiffness contribution were made of FFRP, while high-loaded areas were reinforced effectively using carbon prepregs. For the global modeling of the door structure, the derived material models are used in the design and analysis process.

With additionally necessary epoxy layers the mass was finally 885 g, thus 34% higher than the reference. For the performance comparison in the next sections, there will be three versions compared, namely the reference design, which was built and tested using only carbon prepregs, the ideal hybrid design which used the manufacturer's material data with a high fiber volume content of 45%, and the real hybrid design, which was built and tested with additional epoxy film layers and thereby of a low fiber volume content. The tensile coupon and beam tests were performed using the additional epoxy film layers, and all mechanical performance comparisons were done on the real hybrid design.

EXPERIMENTAL ANALYSES

From the existing material model derived by coupon tests, as described in the previous section, the next step was a preliminary model validation using sectional beams, following the test pyramid after Rouchon (Ref. 14) and a V-model approach.
In order to validate the implemented FEA material model on a simple shape, a beam geometry of the most stressed section in the door was extracted and symmetrically balanced. An omega profiled cross-section below the hinge was chosen. Three beams were manufactured and tested, one pure flax beam, one hybrid beam and one pure carbon beam, from left to right in Fig. 6.

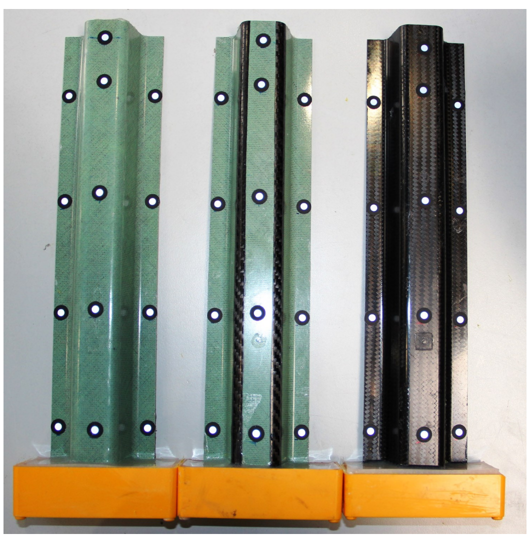


Fig. 6. Photograph of Epoxy Embedded Beams from Left to Right: Flax, Hybrid, Carbon

These sub-component beams were analyzed preliminarily in terms of mass, bio-based content, stiffness, damping, and failure. In the respective following sections, the results of the beams will be explained shortly, but as this paper focuses on the doors and in order to reduce redundancy, some of the respective beams' results will not be listed separately.
After validation of the beams' experimental results, the whole hybrid door was built with the necessary additional epoxy layers. The concluding final mass was 882 g, thus 33.8% higher than the built reference, instead of 6% lower as simulations showed. The built door, of low quality and high mass, was still used for a characterization of damping, stiffness, and failure validation of the design. The results are explained in detail in the following.

Quasi-Static Deformation and Failure Tests

Static load tests are described and analyzed in this section, including multiple bending load steps on the beams and on both door versions in all orthogonal axis directions. The tests on the hybrid door were carried out and analyzed in respect to the FEA model and the reference door performance. Deformations were analyzed on several points using photogrammetric measurements; exemplary measurement points are visible as reflecting marks in Fig. 6 and Fig. 9.
First, the pure woven carbon beam with a fiber orientation of [±45] served as a benchmark, similarly to the reference door. Then, a woven flax beam with the mentioned epoxy film layers, also with the fiber orientation [±45], served as the pure flax reference. Finally, a hybrid beam with flax fibers in [±45] orientation and reinforcements with a [0/90]-orientation were applied in Pos A of Fig. 7. All beams were glued in the area of Pos B using ScotchWeld 9323, see again Fig. 7. In order to imitate a fully stiff clamping, the beams were embedded in epoxy and filled with epoxy at the areas of load initiation.

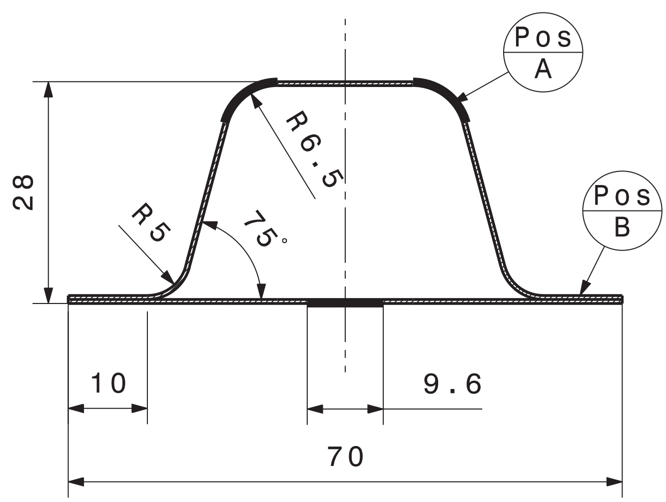


Fig. 7. Section Cut with Lay-up Definitions of the Omega-Beams: Carbon, Flax and Hybrid

Two load steps were applied to the beams, both modeled using geometrically nonlinear analyses, which was necessary in order to properly simulate the appearing buckles. The material was modeled linear and the first load step was defined close to the identified yield point. To a very limited extend, all beams showed a permanent deformation after the load applications in a range of 3-7%. But there was a significantly higher permanent deformation in the pure flax beam post its first load step, see Fig. 8. The load step of

the flax beam was determined right after the beginning of its material yield point, which was reached when loaded by 50 N. For the carbon and hybrid beams the first load was determined to be right before the yield point, by a load of 86 N.
The second load step was only performed with the carbon and the hybrid beam, where the yield point of flax was exceeded. Still, the hybrid beam showed comparable permanent deformations to the pure carbon beam. As a result, the experiment with the pure flax beam could verify the beginning of material yielding to a limited extend, while the hybridization could prevent the hybrid beam from showing high permanent strains.
Compared to the FEA models, the beams showed a higher deformation than the simulations predicted. A significant influence was associated with the epoxy clamping, as modeling a soft clamping showed better agreement with the results. Still, we could see that higher deformations resulted in higher divergence from the linear material model, in the flax beam experiment. Thereby, the importance of modeling the material nonlinearity could be emphasized. The divergence between model and experiment of the carbon and hybrid beam was generally smaller and comparable in quantity. This leads to the conclusion that the hybridization is suppressing the nonlinear material behavior to some extend.
Final conclusions drawn from the beam tests were that a stiffer clamping would be necessary in order to verify deformations reliably and the earlier described material nonlinearities can be reduced by a proper hybridization. However, the failure analysis of FFRP needs to take yield points into account in order to result in a reliable design without permanent deformations. This is considered crucial for designing cyclic or multiple loaded structures made from FFRP, especially.
For the door, a stiff and variable clamping using the hinge axis was designed to test both of the door structures in all 3D-directions. Two load steps were applied in each direction, both below the derived yield criterion was reached. Fig. 9 shows the experimental setup and the built door structure. The load was initiated for all load cases at the very left side of the door.
The deformations in the simulation and from the experiments were compared in their vector orientation and length. The total vector length at the maximum deformation was compared for the carbon reference design and the real hybrid design. All relevant load directions defined in the requirements were compared, see Fig. 11. In most directions, the load-deformation ratio showed comparable results in both versions. Only in the Y+ direction the carbon reference showed considerably higher stiffness than the hybrid reference. This was attributed to the quality issues with the hybrid door and is expected to diminish by increasing the weave and manufacturing quality. Additionally, this direction is supported in usage by the ultralight helicopter's frame structure.

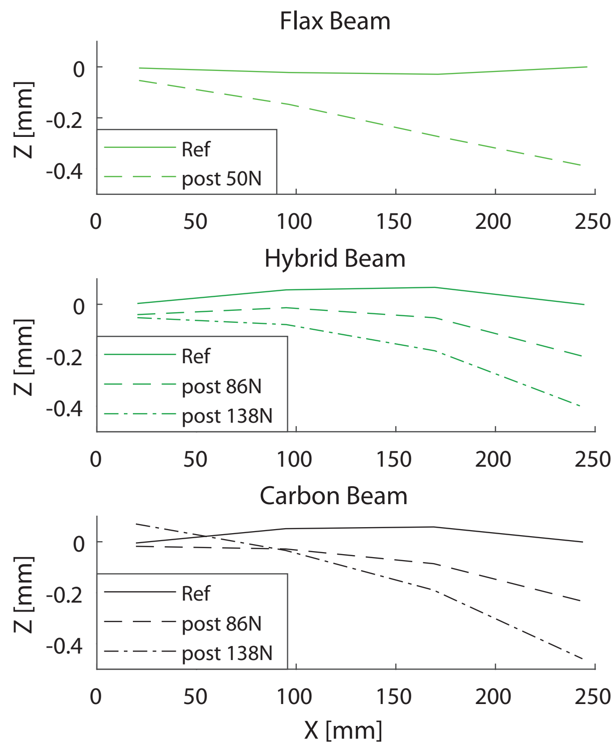


Fig. 8. Comparison of Permanent Deformations of the Tested Beams

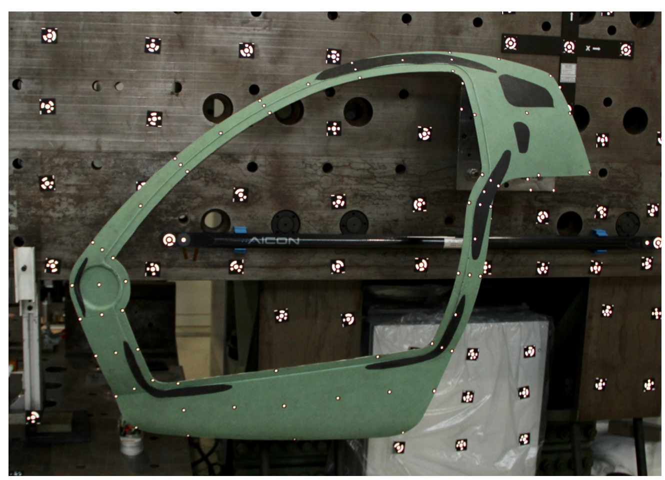


Fig. 9. Experimental Setup for Static Load Tests on Built Hybrid Cabin Door

The two load steps do not show a significant stiffness decrease, which verifies the aimed design in the linear material region. The carbon reference door shows the tendency of a decreasing stiffness in some load directions, this observation was contributed to geometrical nonlinearities, such as buckling.

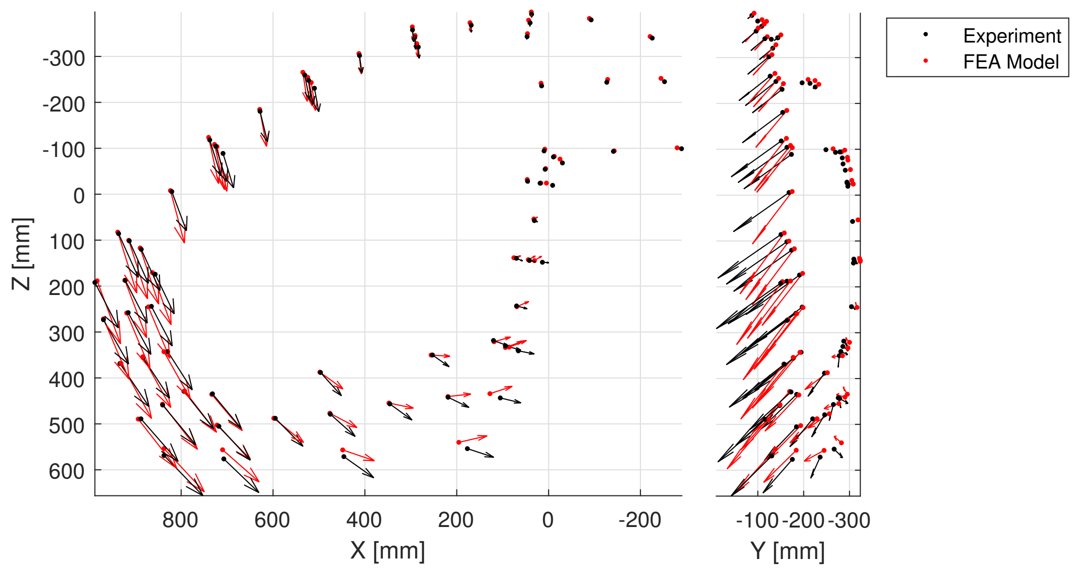


Fig. 10. Deformation Vectors of Simulation and Experiment of the Hybrid Cabin Door under 11.8 N **Load in positive Z-Direction**

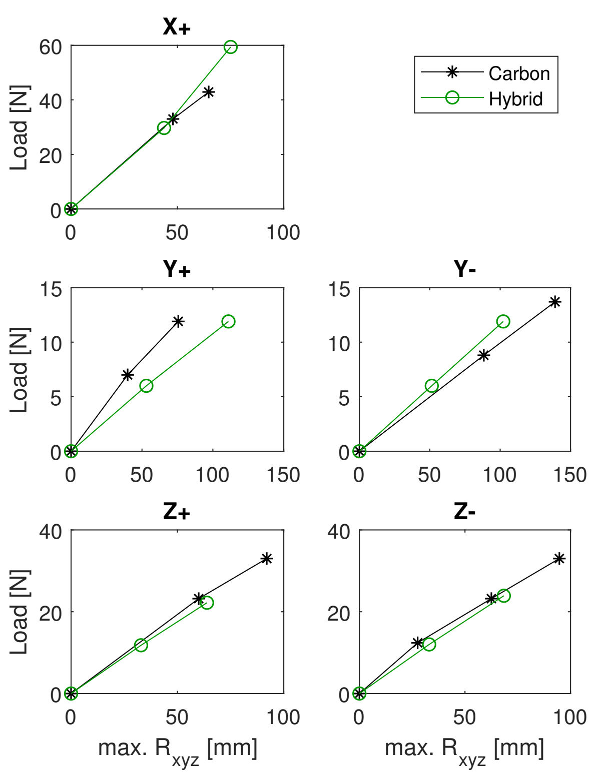


Fig. 11. Experimental Load-Deformation Comparison of Carbon Reference Door and Built Hybrid Door

As the derived yield criterion aimed to suppress permanent deformations in both load steps, the unloaded deformations of the hybrid door were also measured after the load steps. An almost linear relation between the deformations post loading and the applied load could be observed, while the permanent deformation after the load step was in a range of 3-5% for all directions. The range permanent deformations was considered acceptably low and were contributed to some sort of setting effects or viscoelasticity.

In order to verify the design by which the certification requirements were proven, the deformation vectors were compared to the simulation in a more detailed manner. The model and experiment matched in the first load step in X+ and Z-directions almost perfectly by a deviation of 0-3%; in Y-directions, the agreement was between 5 and 11%, comparing the maximum deformation vector length. The second load step showed higher deviations, but these were still in an acceptable range. Geometrical nonlinearities were included in the simulation for all loading directions, but there was only limited verification done, which is considered accountable for the higher deviations.

However, as the simulations of the multiple gravity loads of the certification requirements resulted in lower deformations than the first experimental load, the test set-up was considered suitable for proving the proper performance of the newly designed cabin door. Additionally, in the use-life application, the plexiglass window and the structural frame of the helicopter provide extra stiffness, where clamping is supporting the door at three points.

For a comparison of deformation vectors, Fig. 10 shows all measured points in the experiment and the simulation. It can be seen that some areas match well with the experimental data while others show differences in the vector orientation. The vector lengths match well throughout the whole geometry.

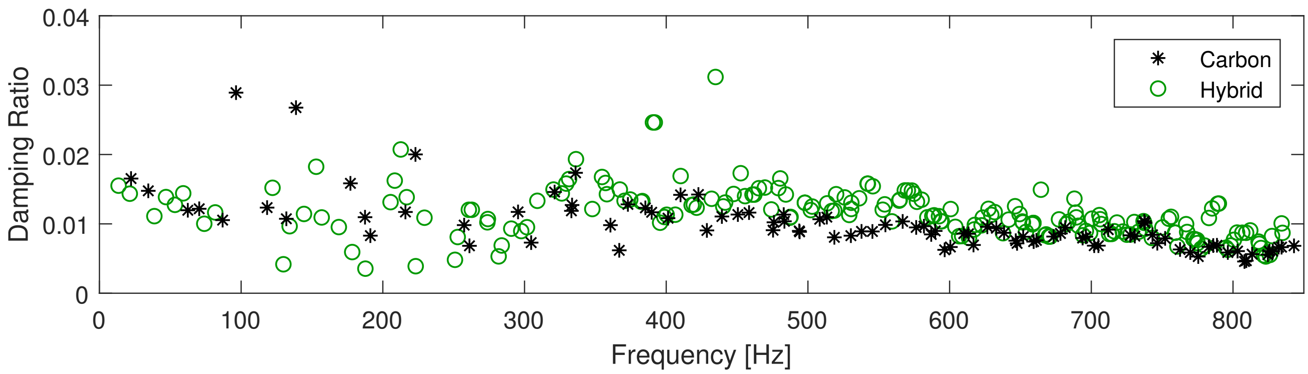


Fig. 12. Damping Comparison of Reference Carbon Door and Hybrid Door

Modal Analyses and Damping

In several references, the damping capabilities of natural fibers are emphasized (Refs. 15–18), as well as a high potential in noise and vibration canceling, according to (Refs. 19–21). Therefore, damping properties of the real hybrid door were determined experimentally. The question was, whether the stiffness-increasing hybridization still provides superior damping capabilities, as stiffness and damping often behave anti-proportional (Ref. 18).

Damping ratios were determined for the beams and both doors using the half-power bandwidth method and the modal frequency response functions (FRFs), as described in ASTM Standard E756 (Ref. 22). The beams were very lightweight and acceleration responses were small, which resulted in prominent white noise in the signals. Therefore, a finite-duration impulse response (FIR) filter was applied to the FRFs before the damping analysis, which resulted in a moving average signal. The damping ratios of the woven carbon beam were 0.84% on average, 3.40% for the woven flax beam and 3.19% for the hybrid beam, where the results of the most prominent resonance frequencies were averaged. It has to be mentioned that despite the noise filter, the signal analysis was still of weak quality and the results should be considered carefully. Nevertheless, the damping ratios of the beams underlined the potential of the hybrid laminate, as its damping values were in the same range as the values of the pure flax beam, while both were approximately four times higher than the damping ratio of the pure carbon beam. For the whole door structures, the experiment was performed with a higher resolution.

Next, the dynamic behavior of the reference door and the built hybrid door was characterized. 12 tri-axial sensors were applied in the experiment in three configurations with 4 sensor positions each, resulting in a 36-degrees-of-freedom acceleration response function. All configurations were excited by an impulse hammer at the same position and direction.

The FEA simulation of the hybrid door could be validated in terms of natural frequencies. The results of the simulation and experiment matched well in the compared range of 0-150 Hz, while most of the values were in a range of ±3 Hz and ±5% accuracy (see Fig. 13).

A validation of the mode shapes could not be achieved. Possibly the highly viscoelastic material behavior is accountable for that.

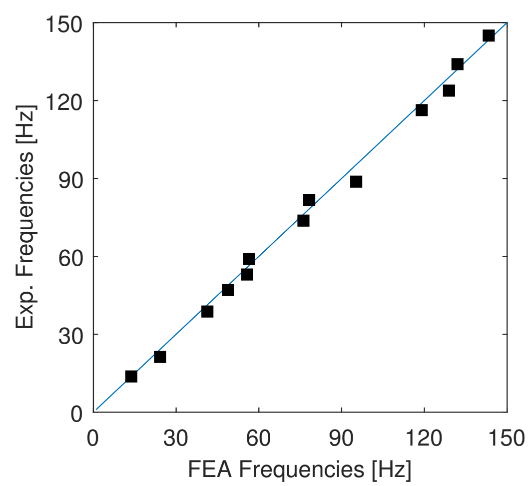


Fig. 13. Natural Frequencies of FEA Simulation over Experimental Modal Analysis Results

The half-power bandwidth method was applied to the FRFs of both doors, using a least-squares complex exponential curve fitting algorithm on all 36 FRFs, one per measured accelerometer degree of freedom and configuration. The median of the identified natural frequencies was in a range of ±3 Hz and their respective damping ratios are plotted in Fig. 12.

In the range of 0-400 Hz, there was no significant difference in damping observable between both door structures. In the range of 400-850 Hz, there was an offset of approximately 30% (0.003 loss factor) with higher values for the hybrid door, this offset was lower than expected. In these experiments, the carbon reference door showed high values for CFRP damping ratios, compared to other references (Refs. 23, 24). This was explained by the rather dry weave quality, and rather thin, soft structure; while the damping ratios of the hybrid flax door match other values from the data sheet and past measurements with unidirectionally reinforced material (Ref. 9). Generally, a decrease in damping with increasing frequencies was observed for both door versions.

ECOLOGIC AND ECONOMIC ASSESSMENT OF NATURAL FIBER COMPONENTS

This section discusses the apparent ecological superiority of flax fiber to carbon fiber in primary production in comparison to its weight implications on the helicopter door. It will further briefly outline the economic advantage of flax fiber. Table 2 presents the cumulative energy demand (CED), global warming potential (GWP) and price of the materials used in the door production. As is evident, values for flax fiber are lower than values for carbon fiber by more than one order of magnitude.

Table 2. Specific Cumulative Energy Demand and Global Warming Potential of Materials used in the Door (Refs. 4, 6, 25–27)

	CED [$\frac{\text{MJ-eq}}{\text{kg}}$]	GWP [$\frac{\text{kg CO2-eq}}{\text{kg}}$]
Carbon Fiber	770.9	38.9
Flax Fiber	45.0	2.6
Epoxy Resin	140.0	7.5
Foam (PET)	72.2	2.0

The door versions within the scope of this comparison are listed by Table 3. As outlined in Figure 1, these are the versions 1 (pure carbon reference) and 5 (flax with carbon reinforcements). The table comprises the built and characterized reference door, the simulated ideal hybrid as well as the real, built, and characterized hybrid door. Besides the total mass of each door version and the material share of carbon fiber, flax fiber, epoxy and other, Table 3 provides the total CED, GWP and the material price per door. Other materials are, in this case, glue and foam core inserts. The assessment is based on literature data on the used materials primary production, which are considered simply on the used material-mass shares. The prepreg processing is not included.
The Δ-values indicate that the built pure carbon door is 223 g lighter than the built hybrid door. However, the hybrid door requires less energy (221.7 MJ-eq) and leads to less carbon emissions (11.0 kg CO_2-eq) in primary material production. An ideal hybrid door would be 39 g lighter than the built carbon reference. Due to this advantage in weight and a higher bio-based mass share, its savings in energy demand and carbon emissions are even higher (258.4 MJ-eq and 12.9 kg CO_2-eq).

An assessment of the eco-efficiency, however, requires us to take into account the materials' implications on the use phase. For helicopters, a change of structural mass leads to a change in induced power and consequently in fuel consumption. Thus, we compare the savings in energy consumption and carbon emissions described above, to changes in those quantities implied by the new mass. Fig. 14 shows the development of the two quantities over the operational lifetime, depicted in flight hours. Solid and dashed lines represent the development of comparisons $\Delta_{built}\,(5-1)$ and $\Delta_{ideal}\,(5^*-1)$. The circle-, triangle- and diamond-shaped symbols indicate whether the underlying flight state of the model is hover, best range, or best endurance.

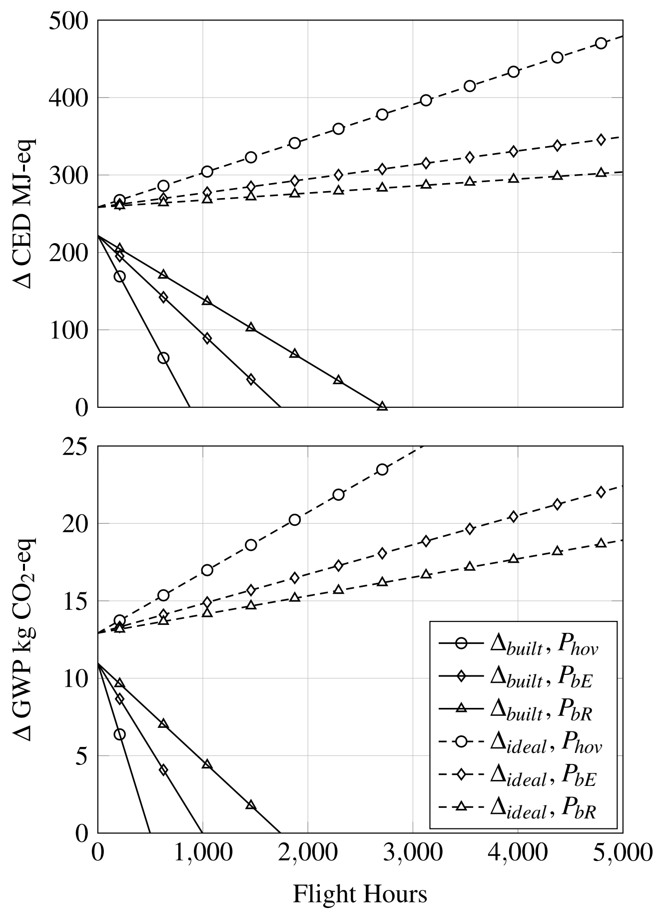


Fig. 14. Temporal Development of Ecological Superiority of Hybrid Door compared to pure Carbon Door

The idea of the graphic is as follows: A potential saving in e.g. energy consumption during primary material production is apparent at the beginning of the operational life. With an increasing amount of flight hours, this saving either cancels out or increases, based on whether the new component is heavier or lighter than its reference. For the built hybrid door, it is evident that initial savings of both, energy consumption and carbon emissions, cancel out quite early in the operational life. The built hybrid door (solid line: Δ_{built}), 223 g heavier than its carbon reference, leads to an additional hover power require-

Table 3. Comparison of Ideal and Built Door Versions in Mass, Share of Bio-Based Material, Cumulative Energy Demand and Global Warming Potential

Units	Mass [g]	Carbon [%]	Flax [%]	Epoxy [%]	Other [%]	Bio [%]	CED [MJ-eq]	GWP [kg CO_2-eq]	Price [€]
1 - $Carbon_{built}$	659	57.6	0.0	31.1	11.2	0.0	330.7	16.8	150.50
5^* - $Hybrid_{Design}$	620	3.1	43.2	41.8	11.9	43.2	72.4	3.9	105.50
5 - $Hybrid_{built}$	882	2.2	30.4	58.8	8.7	30.4	109.1	5.8	225.50
Δ_{ideal} $(5^* - 1)$	-39	-54.5	43.2	10.7	0.7	43.2	-258.4	-12.9	-45.00
Δ_{built} $(5 - 1)$	223	-55.5	30.4	27.7	-2.5	30.4	-221.7	-11.0	75.00

* built version mass proportions with an assumption of 45 vol.-% flax fiber in the cured flax prepreg weave.

ment of approximately 28 W. Including a gear efficiency of $\eta_g = 0.99$ and a gasoline motor efficiency of $\eta_m = 0.4$ the initial energy savings cancel out after 875 hover flight hours. The induced power reduces in forward flight, which is why break-evens at best endurance and best range conditions occur at a later stage, after 1,740 and 2,710 flight hours, respectively.

With an assumed specific fuel consumption for the ultralight helicopter piston engine of $225\,g\,(kWh)^{-1}$ and the sum of carbon emissions for produced and burnt Kerosene of $3.52\,kg\,CO_2\text{-eq}\,kg^{-1}$, the additional carbon emissions in hover flight are approximately $22\,g\,h^{-1}$. Production savings of carbon emissions are $11.0\,kg\,CO_2$-eq, thus for the hover case the additional emissions cancel out the savings after only 500 flight hours.

However, the ideal hybrid door (dashed line: Δ_{ideal}) is much lighter than the one built and tested. It could achieve a reduction in the structural weight of 39 g per door, compared to the built carbon reference. With the potentially reduced weight, the induced power demand and fuel consumption decrease. Thus, initial savings in energy consumption and carbon emissions would grow during operation.

An evaluation of the potentials in recycling has been neglected so far, but is expected to increase the positive effect of the use of natural fiber composite materials in helicopters.

With the data being generated by momentum theory calculations based on information on the ultralight helicopter provided by Feil et al. (Ref. 28), the results have to be interpreted as a rough estimate. Two conclusions can be drawn at this stage: First, possible savings of consumed energy and carbon emissions due to the application of bio-based fiber materials in aerospace structures, are of the same order of magnitude as the material's weight implications. The energy saved with the built door resides for an already substantial share of the operational life. It is expected to reside even longer with potentially lighter hybrid door configurations. Second, and as expected, weight is the major driver of eco-efficiency. Reducing the added mass in new designs will lead to a significant shift of the described break-even to later stages of the operational life. With lighter structures, the shift to potential break-evens beyond the expected operational life can lead to an unequivocal increase in eco-efficiency.

In order to achieve more lightweight structures, a better prepreg quality of the flax weave is required. This would lead to a higher fiber volume content and the omission of extra epoxy-film layers. The ideal hybrid door weighs 30% less compared to the one built within this research and 6% less than the pure carbon reference. Flax fibers have a lower density and in low loaded components, where carbon strength and stiffness is disproportionate, the application could be beneficial in terms of mass reduction.

Additionally, flax laminates are also superior to carbon laminates in terms of costs. Comparing a twill weave prepreg material, the prices are approximately $35\,€\,m^{-2}$ for the flax fiber material and $50\,€\,m^{-2}$ for the carbon material. These prices were paid for a small batch of the used materials of different fiber grammage (flax weave: $150\,g\,m^{-2}$ and carbon weave: $200\,g\,m^{-2}$). Comparing the ideal door version, where no additional epoxy film would be needed, a cost reduction of 45 € (30%) per door would be inherent regarding material costs, where manufacturing and storage is considered equal and therefore not included. The built hybrid door's costs are a lot higher than the carbon reference's, as the additional epoxy film layers were needed. This means that if the prepreg quality of flax increases and no additional epoxy is needed the economic assessment can be expected to be beneficial regarding the material supply.

CONCLUSION AND OUTLOOK

Overall, the goal of building a partly flax fiber reinforced helicopter cabin door was pursued successfully, with a bio-based mass content of 30.4%. The performance of the door was designed to match the certification needs and the stiffness characteristics of a previously built reference door made from CFRP.

In order to create a FEA model of the material, tensile coupon tests and cantilever beam tests on sub-components were performed and used for verification of the material model. It turned out that a nonlinear material behavior significantly influences the stress-strain relation at higher loads and should be taken into account to the design of structures with FFRP. Quasi-static tests on the deformations were in reasonable agreement with the calculations, and the overall stiffness of both door versions matched well. Furthermore, the determined yield point from tensile tests, indicating the beginning of nonlinear tensile behavior, could be verified by the experimental results of the structural parts.

In terms of damping, both doors showed about the same damping ratios between 1-2%. These ratios are considerably high for a carbon weave and are explained by its dry and very thin wall structures of low stiffness. Nevertheless, in the range of 400-850 Hz, approximately 30% higher damping ratio could be determined for the hybrid door version. Still, a higher offset is expected when a higher fiber volume content would be achieved.

The ecological efficiency analysis on the hybrid door shows the potential for energy and carbon emission savings in production through the use of natural fibers. However, the concomitant weight increase of the built hybrid door melts these savings in the operational life. Nevertheless, when assuming the same amount of flax and carbon fiber as in the built door, but a fiber volume content of 45%, an ideal door version with an overall mass reduction of 6% can be designed. Based on this potentially high weight efficiency, bio-based fiber materials promise to outperform conventional fiber materials in term of ecological and economic efficiency in the long run.

Nevertheless, a benefit in ecologic and economic life-cycle assessment could only be determined for the simulated ideal door version with a lower overall mass, as additional epoxy film layers were needed and resulted in a low fiber volume fraction.

The endless carbon fibers can be processed to a significantly neater and denser weave than the grown flax fibers, of which the weave showed large spacings in between the yarns and needed additional epoxy film layers to consolidate in a proper inter-layer strength. As a result, the fiber volume content decreased significantly and the initially more lightweight hybrid design was 34% heavier than the built reference.

As a conclusion, with respect to the low TRL of 2-4 of this project and the recent introduction of flax prepregs to the market, a better flax weave, better fiber matrix adhesion and a larger market is expected in the following years, which would lead to the availability of a superior flax prepreg weave which would testify in the mentioned possible weight reduction.

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