Recyclable bio-based composite Flax/Elium for UAV applications

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ABSTRACT

Bio-based flax fiber reinforced composites (FFRC) are more and more used for land or aerial applications because of their good specific mechanical properties [1, 2, 3]. The use of those composites allows to design strong and light structures with minimum environmental impact. In this study FEA (Finite Element Analysis) simulations are executed on an autonomous long range drone (ELCOD drone; www.elcod.eu). A long range fuel cell powered drone was developed and built to do aerial pollution monitoring. The objective is now to replace the current glass fiber reinforced composite (GFRC) structure by a recyclable flax fiber structure. After exhaustive mechanical experiments at different scales of the composite (microscopic and mesoscopic), mechanical properties of the material obtained are computed into FEA simulations and load factor from 1 to 10 G is applied on the structure with a maximum permissible load of 7.5 G. The failure criterion studied is the Hashin factor. Simulations show that structure made with a fully bio-based composite has lower resistance compare to glass fiber structure and failure can occurs prematurely in compression. However, the use of FFRC offers a substantial gain weight. Hence, the ideal composition is an hybrid glass/flax composite or a carbon/flax fiber composite. The last part of this study presents simulation with a hybrid structure made with carbon fiber reinforced composite (CFRC) mixed with FFRC.

1 INTRODUCTION

Carbon fiber reinforced composites and glass fiber reinforced composites are suitable for UAV structure because they are lightweight and have excellent mechanical properties. The fixed wing drone Stork prototype has been developed and designed during the ELCOD INTERREG project with a conventional CRFC and GFRC structure. This drone features a brushless motor powered by a hybrid fuel cell and LiPo battery source. However, conventional composites if they are made with thermoset matrix (epoxy or polyester), are non recyclable and have a very high environment impact. For instance, the carbon footprint of CFRC is 12 times higher than GFRC (calculated in kg CO_2 eq/t) and the carbon footprint of GFRC is 6 times higher than FFRC [4]. Moreover, FFRC are good alternatives to petro-based composites because flax fibers have comparable mechanical properties with glass fibers for the strongest variety and have lower density. The objective is to investigate if recyclable bio-based FFRC are suitable for UAV applications and if it's possible to avoid the use of carbon fiber in the next generation of the Stork drone MkII. The first part of the study presents experimentation on the flax elementary flax fiber and the FFRC in quasi-static at different scale of the material. The objective is to find homogenization law to find the mechanical properties of FFRC from the mechanical properties of elementary flax fibers. The second part of this study presents simulations to design the drone structure and a comparison between a fully glass fibers structure and a fully flax fibers structure. For simulations the FFRC mechanical properties used are the ones determined with mechanical experiments. Moreover, a simulation with a CFRC wing spar and cap is simulated for comparison (see figure 7 for technical words).

Figure 1: ELCOD Drone Stork Prototype - 5 m wingspan; 16 kg without payload; MTOW: 25 kg

2 MATERIAL TESTING

2.1 *Quasi-static testing - Flax fiber*

Experiments in quasi-static are executed at the scale of the flax fiber and at the scale of the composite. The objective is to find homogenization laws to switch from the micro-

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scopic scale to the mesoscopic scale of the composite laminate. In the table 1, mechanical properties of flax fibers are compared with glass and carbon fibers. It can be noticed that the range of mechanical properties for flax fibers is wide as a consequence of the heterogeneous composition and structure of natural materials [3].

Fiber	Density [g/cm^3]	YM [GPa]	TS [MPa]	Price [$/kg]
Flax	1.4-1.5	30-80	350-2000	0.5-1.5
E-Glass	2.5	70-85	2000-3500	1.5-3
Carbon	1.4	230-240	4500-4800	10-20

Table 1: Mechanical properties of fibers (YM for Young's modulus and TS for Tensile Strength) [1, 5, 6].

In order to model the mechanical behavior of the composite, tensile test are executed on elementary flax fiber. In this study, flax tows are supplied by Eco-Technilin (Normandy, France). Elementary flax fibers are typically considered as a multiscale bio-composite because of their multi-component composition and their multi-scale structure. Elementary fibers have a diameter between 10 and 40 µm and are linked together in the stem of the plant with pectin to form a bundle [7, 8]. Technical fiber is the adjective uttered for a bundle of tens of elementary fibers (between 10 and 40 units). Each elementary fiber is composed of a thin external layer of 0.2 µm, called the primary cell wall, a thick secondary cell wall and a hollow in the center called lumen [9, 10, 7]. Cell walls are naturally bio-composed of cellulose microfibrils laid in spiral with various structures around the fiber axis and embedded in hemicellulose bonds and a non-cellulosic polymer (pectin and lignin) [11]. Those components are called bio-molecules. The spiral structure typically has an angle between 6 and 11° with the longitudinal axis [6, 7]. This angle is called microfibrils angle or MFA (see figure 2). Tensile tests on elementary fiber are based on the standards NF T 25-501-2. Tensile test are performed with an Instron 5944 with a load cell Instron 100 N. Elementary flax fibers are manually extracted from the bundle according to the standards defined and dried for 24 h at 40 °C. The fiber is glued in a frame before mounting: The elementary fiber is glued with cyanoacrylate on two parts of sanding paper (figure 3). This paper reduces the sliding risk of the sample during the tensile test [11]. For quasi-static tensile tests, 105 fibers are prepared and 71 are exploitable and results are plotted in the figure 4 and showed in the table 2.

Tensile stress strain curves of elementary flax fibers are plotted in the figure 4 and shows all the fibers tested and highlight the significant variability of the tensile behavior of elementary flax fiber. This hyper-elastic non-linearity of the tensile behavior of flax fiber can be explained by a reorientation of the cellulose micro-fibrils (micro-fibrils angle or MFA) during the tensile tests [11, 8].

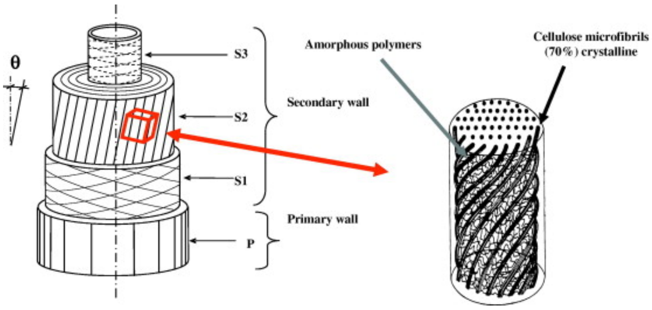

Figure 2: Schematic representation of one elementary flax fiber [11].

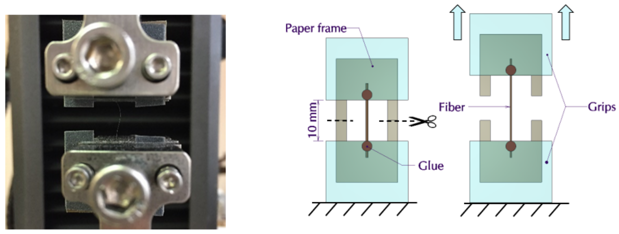

Figure 3: Experimental setup for tensile test on flax fiber.

In conclusion, flax fibers show very good mechanical properties, comparable to glass fibers for the Young's modulus, but with high variability. However neither glass or flax fibers can replace carbon fibers. But, considering the low density of flax fiber, that make them suitable for aerial applications.

2.2 *Quasi-static testing - Flax fiber reinforced composite*

Tensile tests are performed with an Instron 5969 with a load cell Instron 50 kN. Flax fibers are supplied by Eco-Technilin (Normandy, France) in the form of unidirectional plies (FlaxTape 110 g/m^2). The composite plates are then made by the vacuum infusion process at 0.9 bar with Elium resin at Arkema's technical center (Lacq, France). Elium matrix is a thermoplastic polymer with mechanical properties similar to epoxy. Moreover, this thermoplastic matrix can be processed by hand lay-up for composite parts. Laminated plates are made to test the different orientations of the

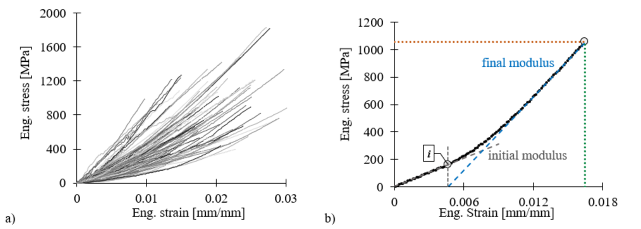

Figure 4: Experimental results - Tensile tests on : a) All fibers; b) One particular fiber - Increasing of stiffness.

Young's modulus [GPa]	Tensile strength [MPa]	Strain at failure [%]
61.5 (24.0)	805.2 (370.9)	1.72 (0.5)

Table 2: Averages mechanical properties for all fibers tested (Standard deviation).

composite in traction and compression: $[0]_{12}$ and $[0,90]_{3s}$ for traction (figure 5) and $[0]_{40}$ and $[0,90]_{10s}$ for compression. Cylindrical specimens are cut so that the fibers are coplanar to the cylinder axis for compression testing (figure 6). The chosen L/D ratio is 0.5 with a diameter of 8 mm and a thickness of 4 mm. This aspect ratio is commonly used in the literature to test under compression bio-based composites [12, 13]. This ratio is chosen according to ASTM E9-89 for compression testing. The fiber volume fraction of the composite is calculated as $V_f = 38 + / - 3\%$. The fiber volume is calculated by making smooth sections and measuring the area occupied by the fibers.

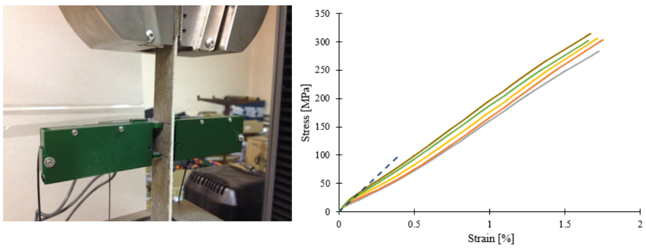

Figure 5: Tensile experiment and results on composite laminate [0]12

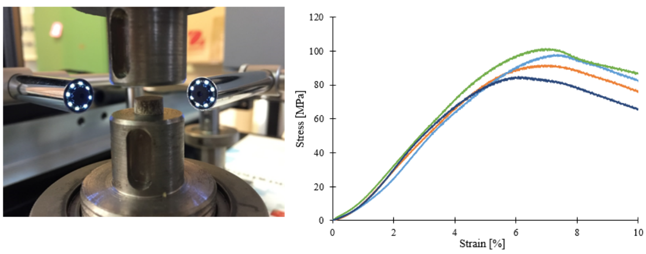

Figure 6: compression experiment an results on composite laminate [0]40

All the tensile tests and compression tests allow to get the mechanical properties of one Flax/Elium ply. Hence, the mechanical properties of the composite obtain with experimental results are sorted in the table 3:

$X_{T/C}$ is for the tensile strength and compressive strength respectively in the longitudinal direction. If the stress reaches this level in the composite, failure occurs. It can be noticed that the tensile properties of FFRC in tension are excellent and comparable to GFRC. However, mechanical properties

	Tension	Compression
E_l	24.8 GPa	2.1 GPa
E_t	3.7 GPa	1.2 GPa
G_{lt}	1.6 GPa	0.6 GPa
ν_{lt}	0.29	0.18
$X_{T/C}$	296.5 MPa	93.3 MPa

Table 3: Mechanical properties of one ply Flax/Elium

are lower in compression. In compression, the properties of the composite come mainly from the matrix. In tension, the properties come from the fiber [13].

2.3 Homogenization from microscopic (elementary flax fiber) to mesoscopic (FFRC scale)

In this part, homogenization laws are used to predict the mechanical behavior of FFRC from the mechanical properties of elementary flax fiber. Tsai with contiguity equations are used for homogenization and they are described by [14] :

$$E_l = E_{fL}.V_f + E_m.V_m \quad (1)$$

$$E_t = A\left[(1-c)\,B + c.C\right] \quad (2)$$

Where the constants A, B and C are :

$$A = 2\left[1 - \nu_f + V_m\left(\nu_f - \nu_m\right)\right], \quad (3)$$

$$B = \frac{K_f\left(2.K_m + G_m\right) - G_m\left(K_f - K_m\right)V_m}{\left(2.K_m + G_m\right) + 2\left(K_f - K_m\right)V_m} \quad (4)$$

$$C = \frac{K_f\left(2.K_m + G_f\right) - G_f\left(K_m - K_f\right)V_m}{\left(2.K_m + G_f\right) - 2\left(K_m - K_f\right)V_m} \quad (5)$$

$$K_f = \frac{E_{fL}}{2\left(1-\nu_f\right)}, K_m = \frac{E_m}{2\left(1-\nu_m\right)} \quad (6)$$

Composite are made of fibers and polymer matrix with different mixing ratios. V_f is the fiber volume fraction in percentage in the composite and V_m is the matrix volume fraction. G_f and G_m are the shear modulus for fiber and matrix respectably. c is the contiguity factor, with $0 \le c \le 1$. In the case of all of the fibers are in contact in the composite and continuity thus, $c = 1$. In the case of all the fibers are separated (or isolated) in the composite, thus $c = 0$. In the case of the study, this coefficient is difficult to determine. However, a value of $c = 0.1$ allow to minimize the error between experimental value and modeling value. In the table 4, it can be noticed that Tsai with contiguity model gives very low error with experimental values. Tsai with contiguity factor model allows to determine the mechanical properties of the composite by knowing the elementary properties of the matrix and the fibers. Thereafter we will use the calculated mechanical properties of these composites to perform our FEA simulations.

	Experimental	Tsai model	Error
E_l	24.8 GPa	25.4 GPa	2%
E_t	3.7 GPa	3.8 GPa	1 %
G_{lt}	1.6 GPa	1.6 GPa	0 %
ν_{lt}	0.29	0.28	2 %

Table 4: Mechanical properties of one ply Flax/Elium

3 DRONE SIMULATIONS

3.1 Geometry and boundaries conditions

Simulations are executed with Abaqus CAE. Half a drone is design to compute simulations. The lift calculated with Star CCM+ is then mapped on the wing surface of the drone, representing 250 N for a cruise speed of 25 m/s. Then the gravity is applied to all of the structure (figure 8 and 9). The lift coefficient is then changed to have a load factor from 1 to 10 G. The maximum limit for the UAV is define to 5 G according to White et al. [15], with a factor of safety equals to 1.5 based on the FAA regulations (FAR 25.303) is chosen. The maximum load factor on the structure is equal to 7.5. Stack sequence is created in Abaqus with the different composites. GFRC values come from literature and FFRC come from previous experiments and model. It has to be noticed that in all simulations the wing joiner of the drone is fully made with CFRC and the elevator is made with FFRC. The fabrics used for simulations are: a 110 g/m^2 for flax fiber, a 100 g/m^2 for glass fiber and a 80 g/m^2 for carbon fiber with theoretical fiber volume fraction of 45 %. The wing structure is described in the figure 7. The upper surface and lower surface are made with glass (GFRC) or flax (FFRC) twill fabrics and AIREX C70 PVC foam with the following layup : [(0,90),AIREX,(0,90),(+45,-45)]. The spar caps are made with glass (GFRC) or flax (FFRC) twill and unidirectional fabrics with the following layup : [0,0,0,(0,90),(+45,-45)]. The layup for the hybrid carbon / flax reinforced composite structure (CFRC / FFRC) is : [0,(0,90),(+45,-45)]. The high strength carbon fibers allow to reduce the number of unidirectional plies at 0° in the longitudinal direction for the spar caps.

3.2 Flax fiber structure vs conventional glass fiber structure

One of the main advantages for FFRC is a low density in comparison to GFRC because flax fibers have a lower density than glass fiber (see table 1). In the following study, FFRC is the name given for the structure 100 % made of FFRC, GFRC is the name given for the structure 100 % made of GFRC. For weight comparison, the conventional GFRC structure is defined as the reference. Simulations are then used to verify the structure integrity under various load factor and to evaluate

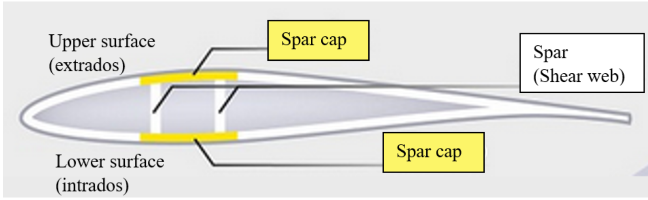

Figure 7: ELCOD drone wing section; structure with double spars.

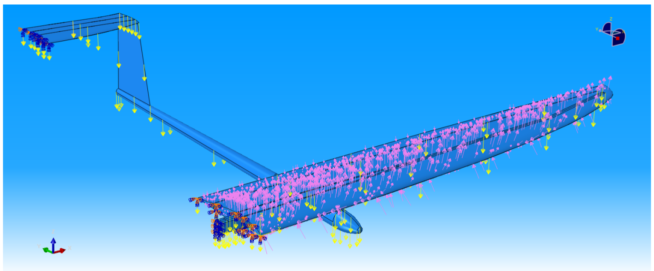

Figure 8: Boundaries conditions on the ELCOD MkII Stork drone - Gravity applied ; lift mapped ; symmetric link.

which structure is the most performing considering the gain weight. The most adequate value to design the drone structure is to use Hashin criterion. Indeed, this criterion distinguishes failure in tension and in compression and compares the structure stress to a maximum value [16]. Failure occurs when this ratio is over 1. If this factor equals to 1 in compression or tension, failure occurs in a composite ply (see equations 7 and 8). However, to design the drone structure, a safety coefficient s is used. The safety factor is usually set at 1.5. Hence, Hashin ratio are compared to 0.67 instead of 1. For every simulation, the maximum value selected is situated on the cap of the upper surface at the root of the wing for the compression and on the cap at the root of the wing of the lower surface for the tension. Because during cruise flight or important load factor (wing gust, stall recovery), bending occurs to the wing structure (see figure 9). Hence, the upper surface is solicited in compression and the lower surface is solicited in tension.

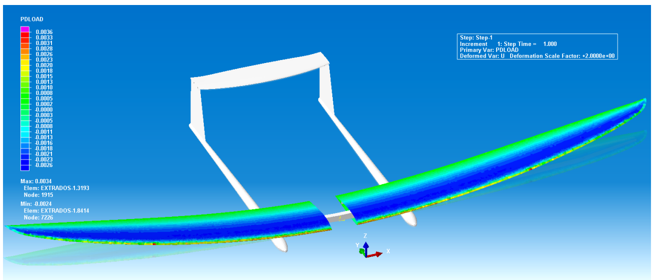

Figure 9: Lift pressure mapping - Overview of the wing bending.

The spar of the wing is solicited in shearing.

$$\left(\frac{\sigma_{11}}{X_T}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq \frac{1}{s} = 0.67 \tag{7}$$

$$\left(\frac{\sigma_{11}}{X_C}\right)^2 \geq \frac{1}{s} = 0.67 \tag{8}$$

X_C is the compressive strength of the composite. X_T is the tensile strength of the composite. S_{12} is the shear strength of the composite. τ_{12} is the shear stress and σ_{11} is the stress in the longitudinal direction of the wing. Due to bending, the preponderant stress is in the longitudinal direction 11 of the wing (see figure 9). Results for FFRC and CFRC are plotted in the figure 10 and 11. In this study, for all composites laminates, fibers volume fraction is equals to 45 %. First of all, the use of a fully flax fiber structure allows to reduce weight to 11 % in comparison to a fully glass fiber structure for the total drone weight. For comparison, a value of 10 % of weight saving is also calculated in the study of Clifford et al. [2] for a wind blade made with FFRC. For both cases, it is clear that composite are stronger in tension, hence Hashin tension factor is lower than Hashin compression factor. Those figures show that until 10 G, the 100 % GFRC structure is under the limit in traction and compression. However, the 100 % FFRC structure is well under the limit in traction but over the limit in compression. The simulations show that failure will probably occur in compression with the 100 % FFRC structure around 5.5 G. The use of FFRC allows to reduce weight, but on the other hand, limits the load factor range on the structure.

3.3 Structure optimization: Hybrid composite

Regarding to the low mechanical properties of FFRC in compression two hybrid structures are tested. The objective is to use the benefit of low density of FFRC and avoid important stress in compression for FFRC. The first hybrid structure is made of FFRC for the spar of the wing and the lower surface (intrados) of the wing and made of GFRC for the upper surface (extrados) of the wing. As see previously, the upper surface is the part solicited in compression during cruise flight or for an important positive load factor. GFRC / FFRC is the name for the hybrid structure with lower wing surface made with FFRC and upper wing surface made with GFRC.

Results for hybrid composite GFRC / FFRC are plotted in the figure 10 and 11. It is clear that the hybrid structure allows both advantages of weight saving and good mechanical properties: The hybrid structure allows to stay under the limit in tension and compression and also allows a weight reduction to 10 %. At 5 G, the bending of the wing tip is at 161 mm for the FFRC structure, 126 mm for the GFRC structure and 155 mm for the GFRC / FFRC structure.

3.4 Hybrid composite with carbon fiber

Carbon fibers are well-know for light weight and high mechanical properties and are massively used for aerial applications [1]. The last simulation is performed with a hybrid

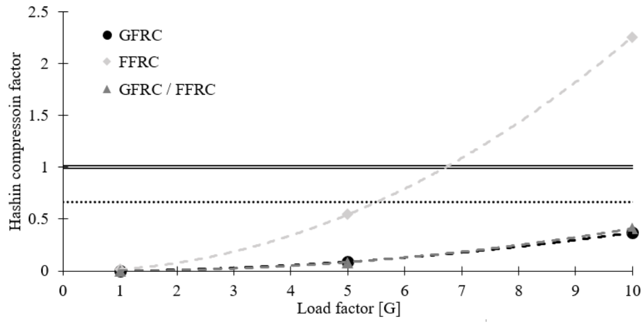

Figure 10: Hashin factor in compression function of the load factor; Limit value to 1 and 0.67 with safety coefficient.

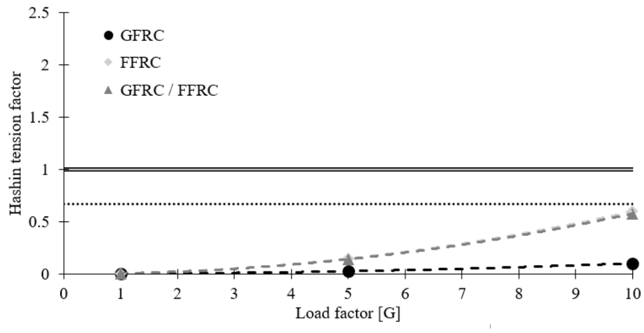

Figure 11: Hashin factor in tension function of the load factor; Limit value to 1 and 0.67 with safety coefficient.

CFRC / FFRC. This hybrid composite simulated for comparison is created with lower and upper surface skin made of FFRC and a wing spar and caps made of CFRC. This last simulation is called CFRC / FFRC. The figure 12 reveals that the use of CFRC for the spar and caps allows a maximum load factor of 17.5 G on the structure. Moreover, it allows a gain weight of 15 % compare to a fully glass fiber structure. However, the footprint of CFRC is 17 times higher than GFRC. In this case, the use of a hybrid CFRC / FFRC structure can be questionable if the objective is to reduce the footprint of material for UAV. However, the hybrid composite CFRC / FFRC has also many advantages: Flax fibers and carbon fibers have a similar density and a similar elongation at failure. A hybrid composite allows the flax to increase vibration absorption in the very stiff and strong carbon structure. Moreover, the carbon fibers are only used for the small surfaces of the caps. Then, the footprint for the use of carbon fiber is reduced.

The table 5 shows that the structure made of GFRC is the heaviest and the hybrid CFRC / FFRC structure is the lightest. The hybrid structure allows an important weight reduction to 15 % in comparison with the 100 % GFRC structure. The drone weight corresponds to the weight of both wing, wing joiner, elevator and twin booms. The weight of the fuselage and equipment (batteries, motor) are not taking into account.

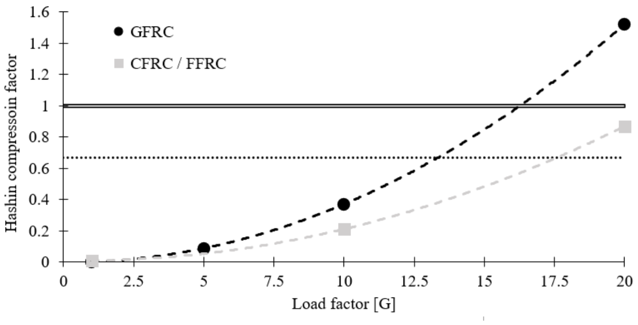

Figure 12: Hashin factor in tension function of the load factor - GFRC vs CFRC / FFRC.

Drone structure	Drone weight
GFRC	8.4 kg
FFRC	7.5 kg
GFRC / FFRC	7.6 kg
CFRC / FFRC	7.1 kg

Table 5: Weight comparison for several composites structures.

4 CONCLUSION

The table 6 summarizes all the results for Hashin ratio for all structures simulated. The results show that even with the safety margin, the used of flax fiber as reinforcement don't causes premature failure on the structure in traction. And structure can be design in with flax or glass fibers. However, in compression, the Hashin factor is above 1 with a fully flax fiber structure at 7.5 G. The Hashin factor is equals to 1 around 6.8 G and equals to 0.67 around 5.4 G. If the FFRC structure is used, then the maximum load factor has to be reduced to 4.5 G. Previous flight tests with the Stork drone prototype show that this level of load factor can be easily reach during special aerial manoeuvres. The table 6 show that the used of carbon fibres for the spar and the caps and flax fibers for the skin allows the lowest Hashin ration in compression and traction for all load factors. Moreover, it allows a lighter composite structure.

It has been proven in this study that the use of FFRC offers a weight gain for UAV structure around 10%. However, FFRC has to be carefully used with compressive stress due to low mechanical properties in compression. For composite structure, the optimum is to design hybrid structures to benefits of the advantages of petro-based composites and bio-based composites. Another limit to the use of FFRC is the variability of the mechanical properties. The single fiber mechanical properties variability is reduced at the scale of the composite thanks to average effect with thousands fibers. However, is some industrial applications where low variability is required, the used of FFRC can be limited. Research has to be done to reduce the variability of natural fibers and allow their used for industrial applications. Concerning the study, the following step is to build a hybrid FFRC / GFRC wing and do experiment on the structure to validate the numerical model. The objective will be to fix strain gauges in the wing laminate and do bending tests on the wing and simulate a 5 and 7.5 G loading on the structure. The strain gauges will allow to compare the strain with the simulation and the strain in the real wing. With simulations, it has been proven that a fully FFRC structure is limited for long range UAV applications. However, a wing made of carbon fiber for the wing spar and flax fiber for the upper and lower surface will have excellent mechanical properties with a minimum weight. The drawback of this structure is the very high carbon footprint due to the use of carbon fibers. A good balance to design UAV, is to use hybrid composites GFRC / FFRC or CFRC / FFRC that will have enough strength for high load factor and will allow a gain weight between 10 and 15 %. However, when designing hybrid structure, the recyclability of the composite has to be investigated. If the thermoplastic matrix is theoretically recyclable, mixing FFRC with GFRC or CFRC could make the composite more complicated to recycle finally. One better solution is to design hybrid structure but without mixing material on same parts an allow easy separation of parts at the end of the cycle of life of the structure.

	1 G	5 G	7.5 G
Drone structure	Hashin factor - Compression		
GFRC	0.002	0.088	0.205
FFRC	0.016	0.545	1.257
GFRC / FFRC	0.003	0.085	0.215
CFRC / FFRC	0.0024	0.071	0.118
Drone structure	Hashin factor - Traction		
GFRC	0.002	0.088	0.053
FFRC	0.004	0.147	0.332
GFRC / FFRC	0.004	0.139	0.399
CFRC / FFRC	0.005	0.016	0.035

Table 6: Hashin criterion values for several composites structures.

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