A CFRP monocoque fairing for a multirotor UAV

Design, FEM-driven layup optimisation and autoclave manufacture of a lightweight airframe shell

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Scope. This report documents an academic team project carried out by the three authors, from geometry definition in CAD through structural verification in ANSYS to in-house autoclave fabrication of the finished part. It contains no confidential or proprietary information belonging to any organisation; all resources used were academic.

1. Application and design targets

The component is the primary structural fairing — a thin-walled composite monocoque outer shell — of a small multirotor UAV. It reacts the loads of the propulsion group (three brushless motors carried on the right, left and rear booms), the battery pack and the two aerodynamic surfaces, and it must survive both a survival-level impact and a broadband vibration environment while remaining as light as possible.

Two objectives and two hard constraints were fixed at the outset. The objectives were to *minimise structural mass* and to *optimise the stacking sequence* so that the laminate is as simple and repeatable as possible to lay up by hand. The constraints were compliance with the applicable **ISO 5309** standard and a finished-part mass **below 480 g**. The design was driven top-down from these figures: the load cases were built first, the worst case was isolated, and only the regions the analysis flagged were reinforced, so that mass was added exactly where the structure needed it and nowhere else.

Quantity	Target / value	Unit
Structural mass (constraint)	< 480	g
Governing standard	ISO 5309	–
Survival impact (quasi-static)	35	g ($\times$ 9.81 m/s^2)
Harmonic excitation band	10–600	Hz
Carried masses	3 motors, battery, 2 wings	–

Table 1. Design targets and load envelope for the fairing.

2. Materials

Two Angeloni woven prepregs were used, both a T300-class carbon in a 2×2 twill with IMP503 epoxy matrix: a fine 200 g/m^2 fabric for the visible outer skin and the general shell, and a heavy 630 g/m^2 fabric reserved for local reinforcement. Because both fabrics are balanced, two cutting orientations (0° and 45°) cover all four canonical fibre directions, which is one of the levers used to keep the layup simple. The measured lamina constants are collected in Table 2; they are the input to both the equivalent-isotropic screening model and the ply-by-ply composite model.

3. Modelling approach and mesh convergence

All structural analyses were run in ANSYS 2024 R2 (Mechanical for the metal-equivalent screening, Composite PrepPost / ACP for the ply-by-ply model). The propulsion units, battery and wings were introduced as remote point masses at their attachment features. A preliminary $1\,g$ static case was solved first to determine the global stiffness K of the shell and to sanity-check the displacement field before the severe cases were applied.

Property	Tw 200	Tw 630	Unit
Areal weight	200	630	g/m^2
Cured ply thickness t	0.24	0.63	mm
Longitudinal modulus E_1	55000	65000	MPa
Transverse modulus E_2	55000	65000	MPa
Poisson ratio ν_{12}	0.045	0.040	–
In-plane shear G_{12}	3500	4000	MPa
Shear strength S_{12}	100	110	MPa
Tensile X_t / Y_t	650	700	MPa
Compressive X_c / Y_c	550	600	MPa
Interlaminar shear (ILSS)	65	60	MPa
Density ρ	1500	1500	kg/m^3

Table 2. Lamina properties. Prepreg codes: Angeloni GG200T-IMP503Z (Tw 200) and GG630T-IMP503Z (Tw 630). Values are per cured ply.

Before any result was trusted it was made independent of the discretisation. A single scalar — the model *maximum stress* — was monitored while three mesh controls were swept parametrically: global element size, element growth rate and curvature normal angle. For each control the monitored quantity was plotted against the parameter and the settings were fixed on the plateau, i.e. at the coarsest mesh that still reproduces the converged value, so that compute cost is minimised without loss of fidelity (Fig. 1). The retained settings are given in Table 3.

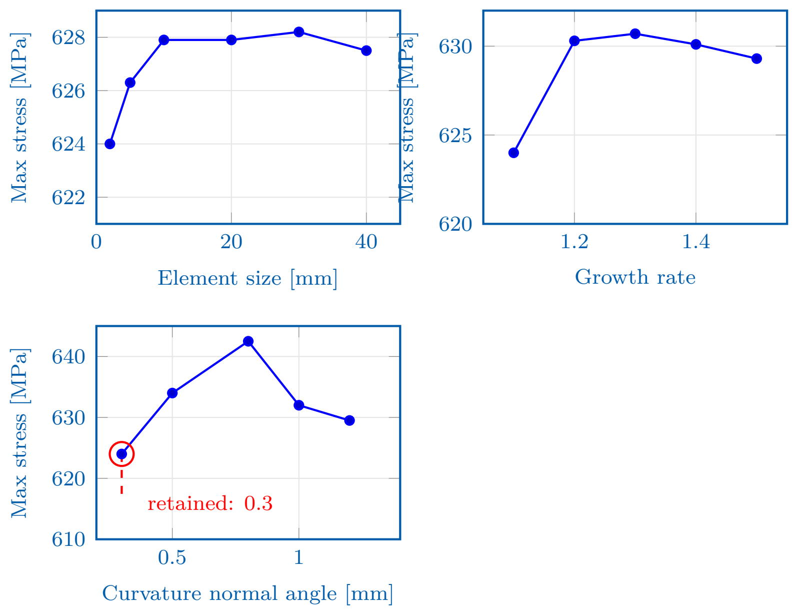

Figure 1. Parametric mesh-convergence study on the monitored maximum stress: element size, growth rate and curvature normal angle. Settings are fixed on the plateau; the curvature normal angle is deliberately taken at the fine end (0.3) to resolve the tight fillets, at a modest cost.

4. Load cases and structural verification

Two independent load cases were assessed on the converged mesh: a survival impact and the operational harmonic (vibration) environment. Both were first screened on a quasi-isotropic *equivalent* model — the woven laminate replaced by an isotropic-equivalent solid — to size wall thickness cheaply, and then confirmed on the full ply-by-ply composite model.

Mesh control	Retained value
Element size	10 mm
Growth rate	1.2
Curvature normal angle	0.3
Converged max stress	$\approx$ 628 MPa

Table 3. Retained mesh settings after the convergence study.

4.1 Impact (shock) load

Equivalent screening. A $35\,g$ quasi-static acceleration (3.5×10^5 mm/s^2) was applied to the whole shell with the landing feet / fins restrained, representing a survival drop. On the quasi-isotropic equivalent model with the trial wall thicknesses the peak von-Mises stress reaches 623.97 MPa (Fig. 2), which set the first-pass reinforcement map.

Composite verification. The same case was then re-run ply-by-ply with the design stack of §5. Failure was evaluated through the Inverse Reserve Factor (IRF), which peaks at $\mathrm{IRF}_{\max} = 1.31$ in a narrow band at a restrained edge and stays well below unity over the bulk of the shell. The peak is a boundary-condition concentration rather than a physical failure — in the real part the load is introduced over a finite bonded area, not a knife edge — and it is precisely one of the regions carried by the local reinforcement scheme.

4.2 Harmonic response

Harmonic response. The operational vibration case was solved as a base-excitation harmonic response over 10–600 Hz with linear frequency spacing, four clusters and the mode-superposition method. A per-axis acceleration profile (Table 4) was imposed equally on the three global directions. The problem size and solve metrics are reported in Table 5. The response peaks at low frequency: the total-deformation envelope reaches 18.8 mm (maximum over frequency), with the largest single-frequency amplitude of $\approx$ 34 mm near 10 Hz, and the equivalent-stress envelope (maximum over frequency) reaches 1813.5 MPa at a local concentration.

Frequency [Hz]	a_X	a_Y	a_Z [mm/s^2]
1	1000	1000	1000
15	15000	15000	15000
89	15000	15000	15000
90	50000	50000	50000
600	50000	50000	50000

Table 4. Base-excitation acceleration profile imposed in the harmonic analysis, per global axis.

Solve metric	Value
Model size	131 507 nodes / 134 089 elements
Degrees of freedom	782 037
Solver type	Direct
Time to solve	41 m 33 s
Max RAM used	6.04 GB

Table 5. Harmonic-response solve metrics (ANSYS 2024 R2).

4.3 Governing load case

Governing case. Comparing the peak equivalent stress of the two cases (Table 6) shows the harmonic response to be markedly more severe than the impact. The laminate architecture and

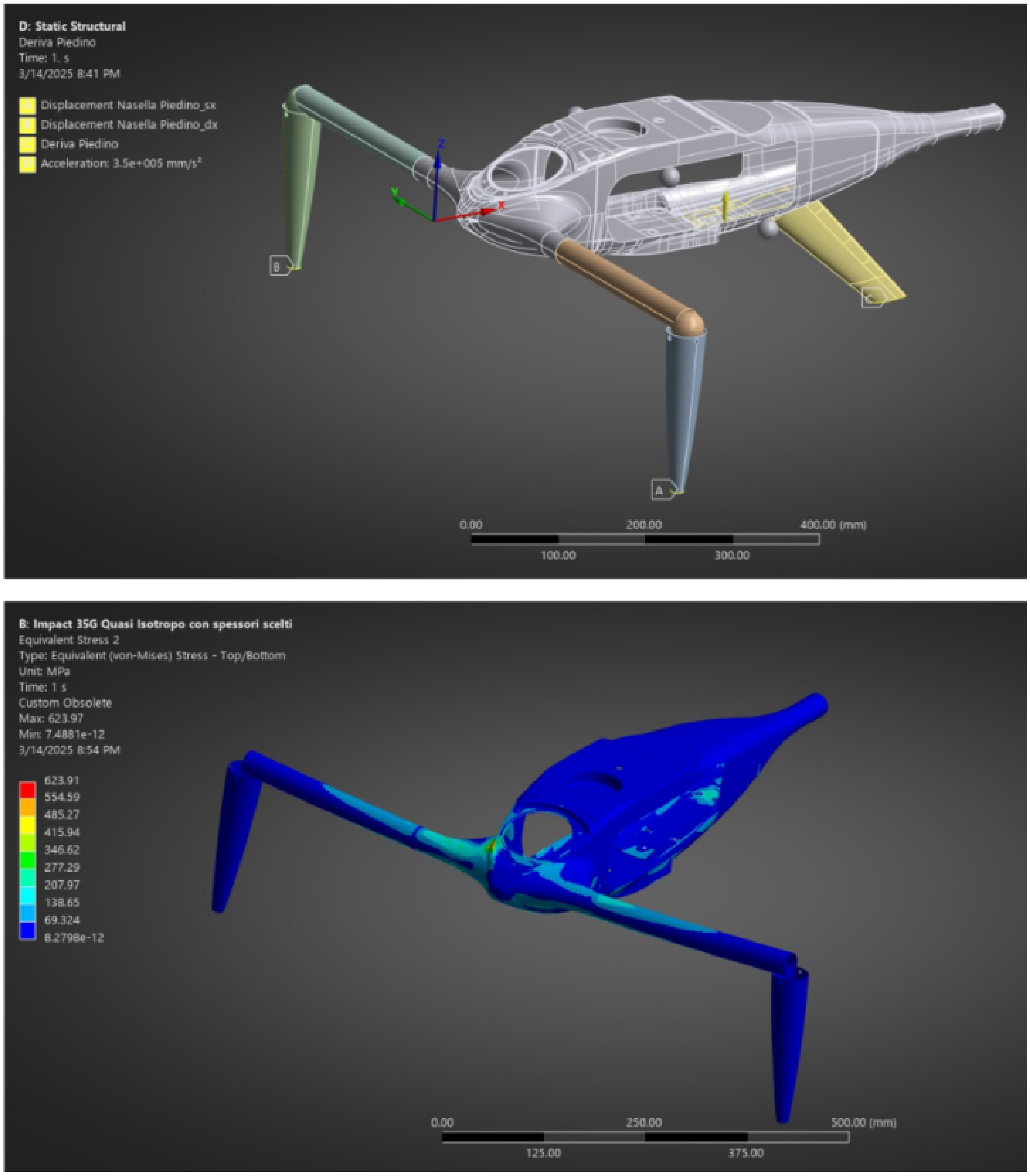

Figure 2. Impact ($35\,g$) analysis. Equivalent-isotropic screening returns a peak stress of 623.97 MPa; the ply-by-ply composite model returns $\mathrm{IRF}_{\max} = 1.31$, confined to a restrained-edge concentration.

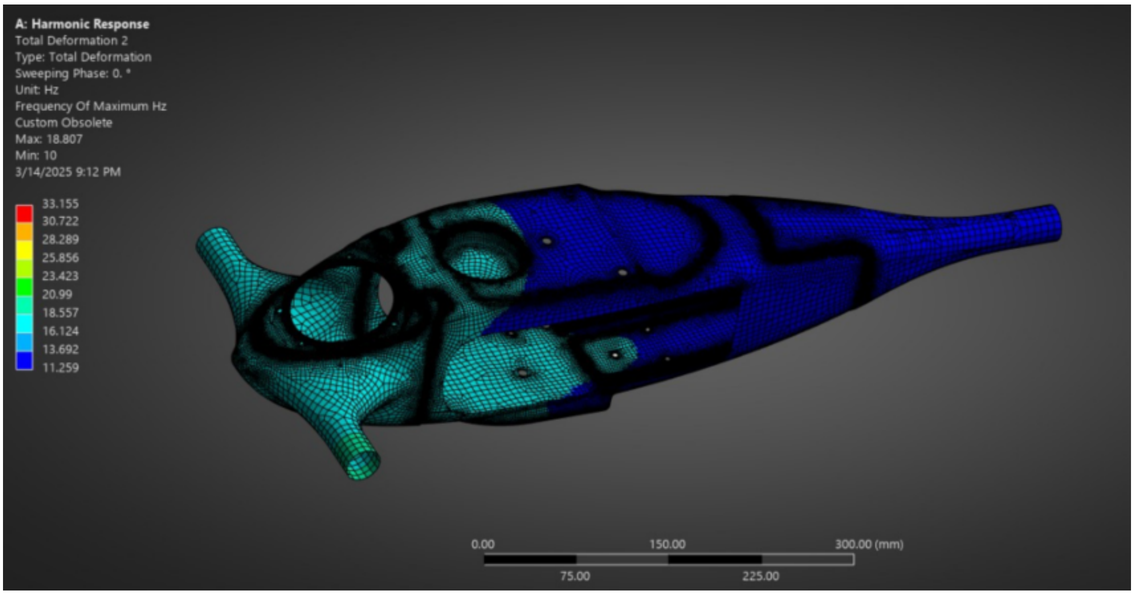

Figure 3. Harmonic response over 10–600 Hz. Peak total deformation 18.8 mm (max over frequency); equivalent-stress envelope up to 1813.5 MPa at a local concentration.

the local reinforcement map were therefore anchored to the harmonic envelope, with the impact case treated as a secondary check.

Load case	**Peak equivalent stress [MPa]**
Harmonic response	1813.5
Impact (shock)	503.24

Table 6. Governing load case. The harmonic response is the case to be watched most closely and drives the layup.

5. Laminate architecture and ply book

The shell is built from a thin quasi-isotropic base skin plus discrete local reinforcements. The base skin is a [0/45/0] stack of Tw 200 (three plies, 0.72 mm), laid outer-face first so the fine twill gives the cosmetic surface; being balanced and near-symmetric it introduces negligible membrane–bending coupling and does not warp off the tool. Reinforcement is then added as Tw 630 plies at 0° only in the regions the FEM flagged — nose, motor-boom roots, fin/foot junctions and the canopy ring — building up to a worst-point (analysis-point) stack of six plies and 2.61 mm (Table 7). Ply drops are staggered to preserve symmetry and to avoid resin-rich pockets at the terminations. The reinforcement footprints are shown in Fig. 4.

Region	**Layup (tool→bag)**	**Plies**	t **[mm]**
Global shell (everywhere)	$[0/45/0]_{\mathrm{Tw200}}$	3	0.72
Intermediate reinforcement	$[0/45/0]_{\mathrm{Tw200}} + [0]_{\mathrm{Tw630}}$	4	1.35
Peak region (boom roots / fin-foot)	$[0/45/0]_{\mathrm{Tw200}} + [0/0/0]_{\mathrm{Tw630}}$	6	2.61

Table 7. Ply book. The base skin is common to the whole part; Tw 630 plies are added locally to reach the analysis-point stack.

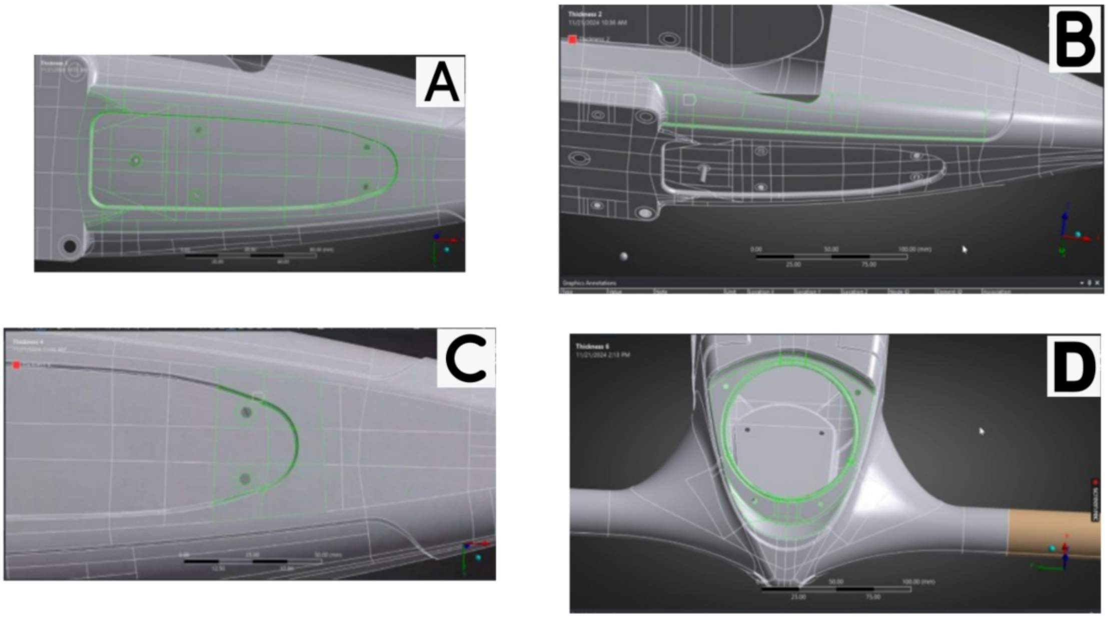

Figure 4. Local reinforcement footprints defined in ANSYS ACP, one per high-utilisation region identified by the analysis.

6. Manufacture

The process route was defined to be executable and then executed in-house. Prepreg plies are cut to nested shapes, oversize to leave stock for post-cure trimming and indexed against a fixed angular reference so the 0/45 sequence in the drawing is actually the sequence in the part. Layup is by hand onto a released tool, outer Tw 200 first for finish and the Tw 630 reinforcements on top; the stack is then vacuum-bagged and cured in autoclave (Fig. 5).

The cure cycle (Fig. 6) ramps at 2 °C/min to a 130 °C dwell under 3 bar, then cools at 3 °C/min, for a total of about 6 hours. Two process refinements proved decisive for quality: fillet “beads” (*cordoli*) added in the convex regions to prevent the bag bridging over the corners, and a short 10–15 min pre-debulk (*pre-tiro*) that consolidates the stack before the final bag is drawn.

After demoulding the part is trimmed and the surface finished; the finished shell weighs $\approx$ 477 g (Fig. 7), inside the 480 g target.

7. Outcome

The fairing meets both constraints. Final mass is $\approx$ 477 g, inside the 480 g budget, and the part is compliant with ISO 5309. Structurally, the harmonic response was identified as the governing case and the layup was anchored to it; the impact case is covered with the same reinforcement scheme. The optimisation objective was met on two fronts: mass was added only where the analysis demanded it, and the layup was kept simple — two fabrics and two cutting orientations, a cosmetic outer skin with local 0° reinforcement.

The engineering loop exercised here — requirements, CAD geometry, equivalent-model screening, mesh-converged FEM, ply-by-ply composite verification, a manufacturing-aware ply book and in-house autoclave fabrication — was carried end-to-end by the three-author team, from the first CAD surface to the finished, weighed part. Open items are stated as such: correlation of the harmonic model against a prototype vibration test, fatigue characterisation, and a further mass trim once the flight loads are measured.

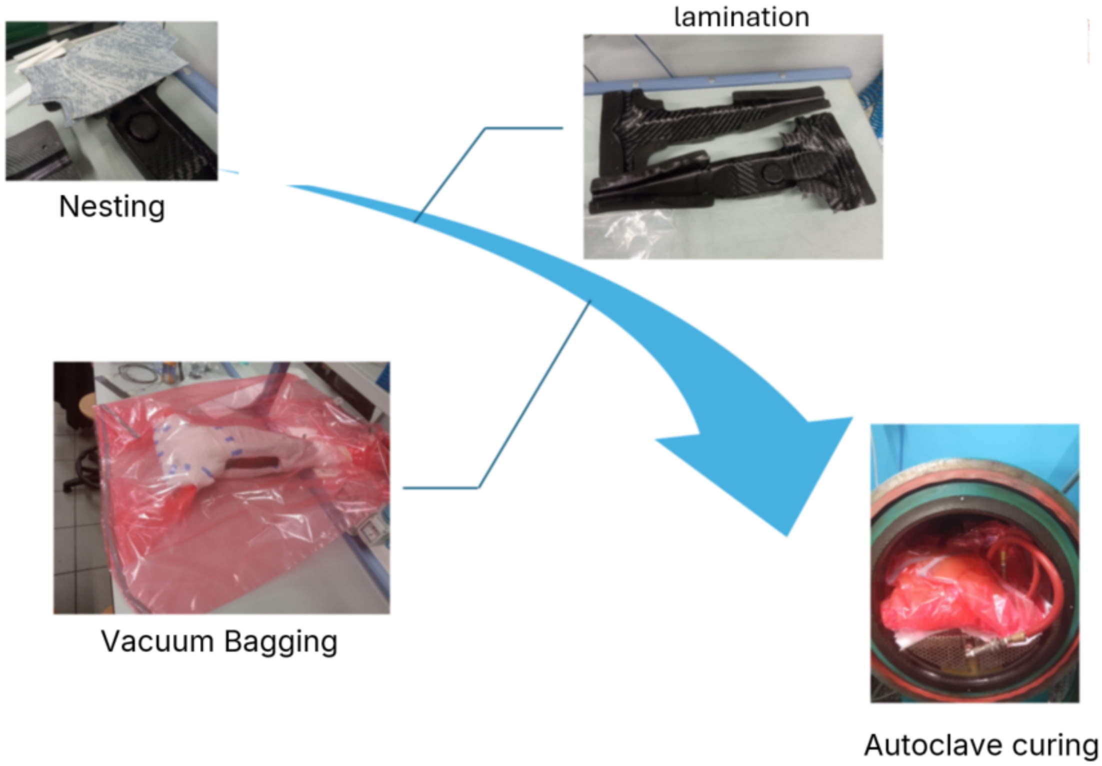

Figure 5. Manufacturing sequence: ply cutting, hand layup, vacuum-bag build-up and autoclave cure.

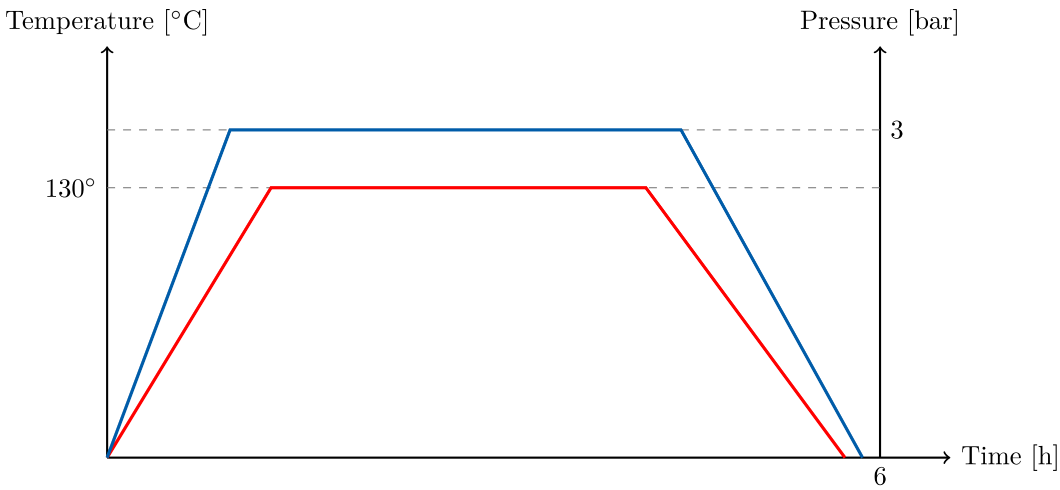

Figure 6. Autoclave cure cycle. Temperature (red): initial ramp 2 °C/min to a 130 °C dwell, final ramp 3 °C/min. Pressure (blue): held at 3 bar through the dwell. Total cycle ≈ 6 h.

Figure 7. Surface finishing and final weigh-in. Measured mass ≈ 477 g against a 480 g target.

Figure 8. finished drone frame photo

References

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