Project Summary

Hybrid Carbon Fibre Composites for Automotive Applications

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Background and Motivation

Carbon fibre reinforced polymers (CFRPs) offer significantly higher stiffness-to-weight and strength-to-weight ratios than conventional metals or polymers. Despite these advantages, widespread automotive use has been limited by high material costs, complex manufacturing processes, and challenges in recycling thermoset matrices. However, recent advances in automated layup, out-of-autoclave curing, and rapid-cure resin systems have reduced costs and production time, enabling their use in high-performance motorsport and student teams such as Cambridge's Full Blue Racing, which operates under an annual £10,000 budget.

Even so, the composite design cycle remains complex: predicting laminate behaviour requires ply-by-ply Classical Laminate Theory, while manufacturing demands autoclave processes to prevent defects. Validation through tensile or suction loading tests often exceeds the capabilities of student workshops. Currently, most composite intake systems are analysed via detailed finite element models due to the anisotropic and lay-up-dependent behaviour of CFRPs. This project addresses the gap readily accessible, back-of-the-envelope models for composite structures under uniform negative pressure, such as intake manifolds subjected to suction. The composite material's lay-up dependent orthotropic behaviour and statistical variability in fibre strength have thus far confined analysis to finite element studies employing layered shell definitions or solid elements with cohesive interlayers. Developing a simplified semi-analytical model, grounded in laminated plate theory and in-plane stress state approximations, would enable rapid preliminary sizing, lay-up iteration, and failure margin estimation without immediate reliance on detailed Finite Element Analysis (FEA), thereby streamlining the design workflow for Formula Student teams.

Coupon-level testing is used to inform validate the semi-analytical model and the design of an intake plenum for Full Blue Racing's 2025 Formula Student UK (FSUK) car. The model aims to support efficient, evidence-based composite design for current and future plenum systems across FSUK teams.

The intake plenum, acting as an air reservoir, plays a critical role in distributing airflow evenly to each cylinder and minimising throttle lag. To optimise volumetric efficiency, plenum geometry must be compact and smooth, which makes near-net-shape composite fabrication particularly well-suited. Compared to metal or thermoplastic alternatives, composite manufacturing offers advantages in weight reduction and material efficiency, key considerations in both competition and industry. The semi-analytical model enables rapid iteration of lay-up strategies and failure predictions without full-scale FEA, helping teams navigate the complexity of composite design with limited resources.

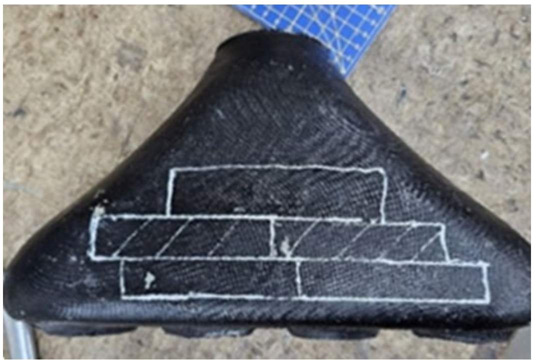

Figure 2: Old intake plenum

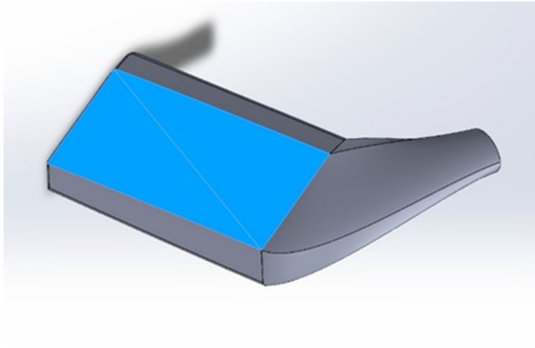

Figure 1: CAD model of the new plenum design

Design Requirements

The design targets start with an aggressive weight reduction: the intake plenum needs to weigh under 2 kg to improve acceleration. For a pressure target, the plenum is designed for a peak suction of –60 kPa (that's –40 kPa measured on-car multiplied by a 1.5 safety factor). To ensure optimal engine performance, the internal surface must be smooth to minimise turbulence and pressure loss, yet still manufacturable via student-friendly methods. Finally, we must keep raw material costs under £700 to stay within the team's allocated budget for this project, as the team has to run on tight sponsorship money.

Semi-Analytical Modelling

Recognising the largest surface on the plenum is the one with the highest deflection and stress, that surface is approximated to a 330 × 133 mm flat panel modelled as a clamped-clamped bending beam under uniform suction, giving an out of plane bending moment Mx. Then stitching that to thin-wall pressure-vessel theory, the in-plane line forces Nx and Ny is obtained. This is done because the through thickness stresses are significant due to the out of plane deflection/ bending moment.

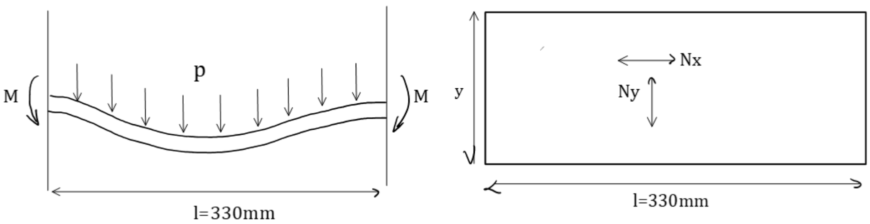

Figure 3: Bending beam model

Those in-plane line forces and out of plane bending moment into software solver for classic laminate theory CCSM, using AS4/3501 unidirectional prepreg data as input for material data. By iterating ply orientations and thickness, CCSM indicated that a 14-ply lay-up of fourteen 0.2 mm UD carbon plies in a stack totalling 2.8 mm, with stacking sequence [$0°_3$, $90°_4$], yields forces and bending moments about –52 kPa with a safety factor of 1.3.

$$M_x = \frac{pl^2}{12}\ N \qquad N_x = -\frac{p \times 9284}{459}\ N/m \qquad N_y = -\frac{p \times 34506}{910}\ N/m$$

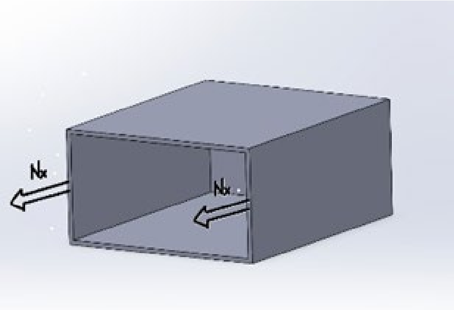

Figure 5: longitudinal line force

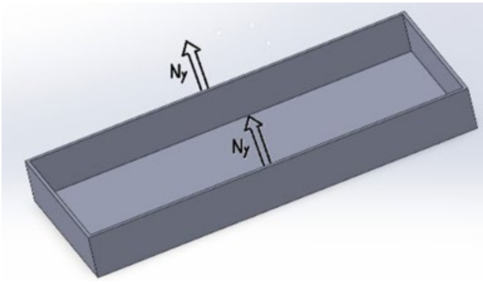

Figure 4: transverse line force

4-Point Bending Tests

The modelling was validated with ASTM-standard four-point bend tests on both the old plenum coupons and coupons of off-the-shelf CFRP panels of two thicknesses. 5 samples of each were tested, and the CFRP were tested in orientation parallel to top ply fibre direction and at 45 degrees.

The old plenum material has a stiffness of only about 1.95 GPa in flexure, failing at 45.7 MPa. By contrast, the stiffness of 1.95 mm CFRP is 22x and strength 12x that of the old plenum coupons. The 2.74 mm CFRP panels was only slightly less stiff and strong than the 1.95mm coupons.

Figure 8: 4-point bend test rig showing the 2.7mm CFRP sample

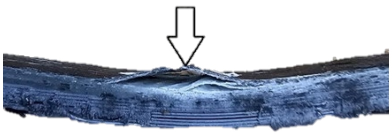

Figure 7: old plenum coupon, ply wrinkling shown

Figure 6: CFRP coupon, fibre breaks/ cracks shown

Combining models and experiments, using beam + thin vessel theory, we sized a 2.8 mm laminate, which is within 3 % of the thickness predicted by zonal FEA from research of a similar plenum, but 50 % conservative versus full 3D ply-based FEA. In four-point bends, the purchased quasi-isotropic 1.95 mm CFRP fails at equivalent stresses below –40 kPa and 2.74 mm fails below –60 kPa, so only optimised UD stack works. Measured densities were ≈ 28 % above manufacturer datasheets, highlighting the need to test real coupons. ABS/GFRP of the old plenum delaminates unpredictably via debonding and top ply wrinkling, which deters us from using a hybrid lay-up, whereas CFRP fails by ply buckling and fibre fracture, matching CCSM predictions. All CFRP strips also met damping targets ($\zeta \approx 0.15$–0.27) from a vibrations test carried out, so engine vibration is less of a concern.

Manufacturing Approach

To manufacture the plenum, unidirectional carbon fibre will be hand-laid into a simple two-part female mould. We chose a high-temperature TGMDA epoxy, with low viscosity for good wet-out, and glass transition above 175 °C to handle engine bay temperatures. Using VARTM, low void content and proper fibre wet-out can be achieved without an autoclave. Once cured, the two halves of the plenum will be bonded using film adhesive

Figure 9: top half of mould

under vacuum bagging pressure—no mechanical fasteners, reducing machining, stress concentrations and weight. The final assembly weighed about 1.9 kg and cost roughly £650 in raw materials, meeting our mass and budget requirements