STRUCTURAL OPTIMISATION OF MARINE HAT STRINGER STRUCTURES

C.A. Pearson[1]*, M.A. Battley[1] and T.D. Allen[1]

[1] CENTRE FOR ADVANCED MATERIALS MANUFACTURING & DESIGN (CAMMD)
- CORRESPONDING AUTHOR (CPEA689@AUCKLANDUNI.AC.NZ)
- (https://www.linkedin.com/in/connor-pearson-78b32218b/)

INTRODUCTION

Hat stringers are components used to stiffen and strengthen composite hull panels of high-performance racing yachts. Lighter boats travel faster, so minimising the weight of hull structures increases the chance for victory. Weight savings are possible through optimisation of stringer-stiffened hull structures. This may be achieved through modification of stringer cross-sectional profiles and composite laminate. Genetic algorithms (GA) are often used to optimise composite structures as they are easily applied to problems with incomplete definitions, relaxed accuracy requirements and large investigation scopes.

In this work, a GA was coupled with an Abaqus/CAE finite element analysis (FEA) to optimise hull stringers. The complex three-dimensional hull structure has been represented as a simple beam under uniform pressure and the geometric and laminate parameters of the marine hat stringer are optimised to minimise weight and avoid failure. Comparisons are made to a baseline stringer design found in existing generations of IMOCA60 racing yachts.

Minimise weight, avoid failure

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of PURE Design & Engineering Ltd and Guillaume Verider Architecture Navale (GVAN) for providing technical advice and guidance. The authors also wish to acknowledge the use of New Zealand eScience Infrastructure (NeSI) high-performance computing facilities as part of this research. This work is funded by the University of Auckland Doctoral Scholarship.

PROBLEM DEFINITION

DESIGN VARIABLES

The stringer is characterised by 35 parameters which define the geometric and laminate details of the structure, as shown in Figure 1 and Figure 2.

- The main areas for optimisation come through modification of the stringer cross-sectional profile and laminate design.
- Optimisation of a hat stringer was carried out using a constant panel span, stiffener spacing and panel laminate
- Constraints - Profiles must be horizontal at the centreline and tangential to the fillet coves.

SOLUTION PROCESS

Prospective designs are solved using a linear perturbation static solver and eigenvalue buckling solver through Abaqus/CAE.

The model setup is presented in Figure 3 and Figure 4 and is made up of 4 independent parts.

- Stringer
- Panel
- Bondline
- Buckhead

Simulations were carried out using a NESI cluster. Wall clock solution time using a 3 mm global mesh is 570 seconds using one core and 6000 MB of memory on a Broadwell node cluster (E5-2695v4, 2.1 GHz, dual-socket 18 cores per socket).

EVALUATION

The fitness of potential designs is evaluated based on mass, fibre strains, deflections, laminate failure criteria and buckling eigenvalues. Based on defined limits, each design is allocated safety factor which is used to determine its overall fitness.

PERFORMANCE REQUIREMENTS

Max Deflection	1%
Max Tensile strain	0.92%
Max Compressive strain	0.86%
Max Failure criteria	1.0
Max Bondline stress	22.0 MPa
Min Buckling eigenvalue	1.15

OBJECTIVE FUNCTION

$$F_i = \left[\frac{\left(\min(SF)_{ij}\right)^2}{(m)_i}\right]$$

where F_i is the fitness score, $\min(SF)_{ij}$ is the lowest safety factor for performance requirement j and m_i is the component mass for individual i.

FIGURE 1: BASELINE GEOMETRIC PARAMETERS

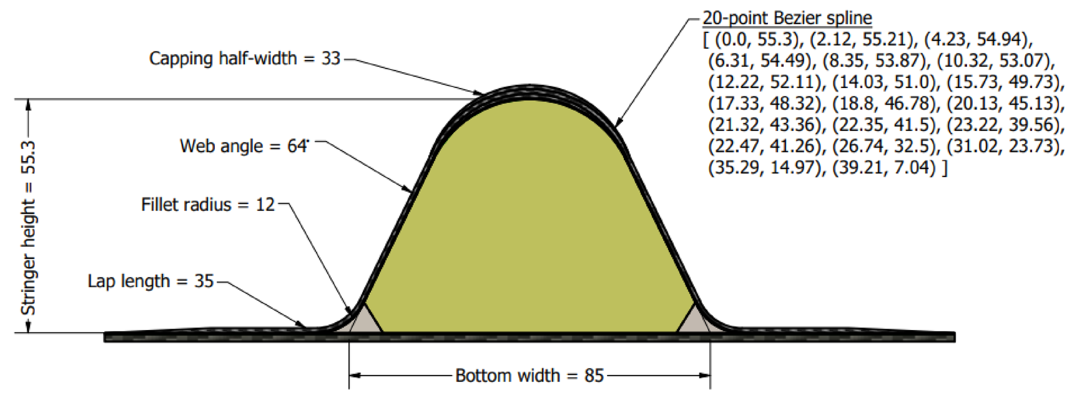


FIGURE 2: BASELINE LAMINATE PARAMETERS

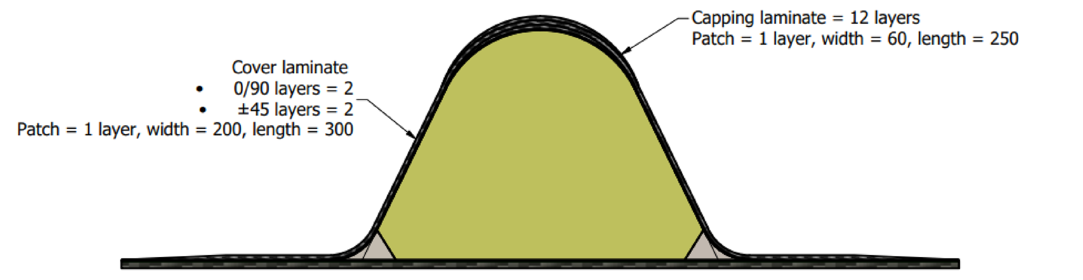


FIGURE 3: MODEL ASSEMBLY

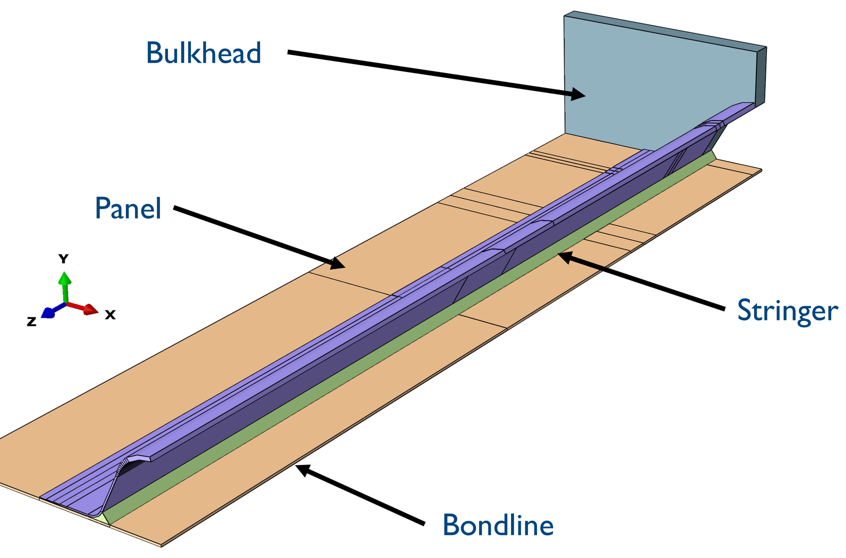
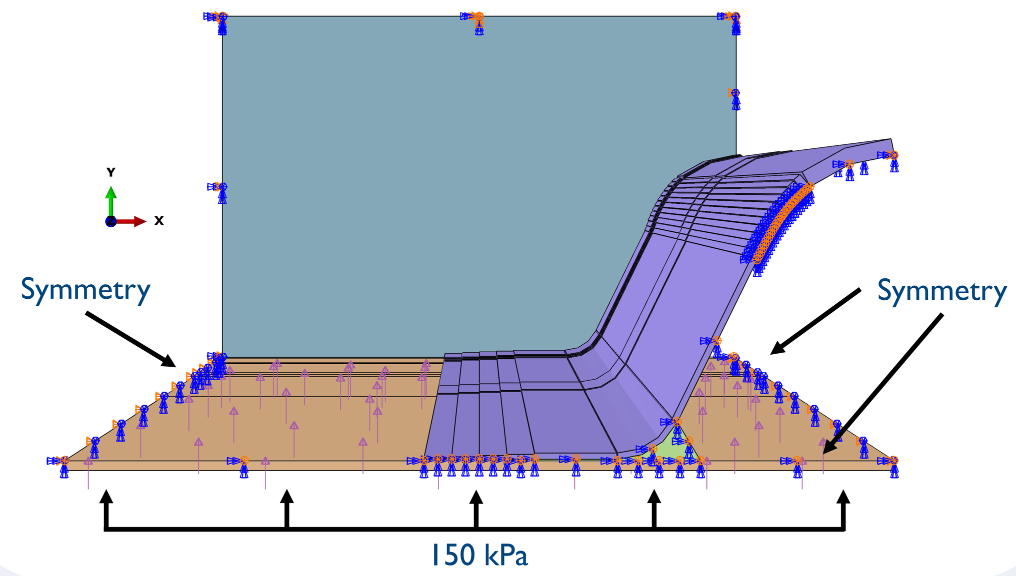


FIGURE 4: MODEL BOUNDARY CONDITIONS



GA IMPLEMENTATION

The GA used in this work features 3-way tournament selection, uniform and random linear crossover and random re-assignment mutations (Figure 5). A certain percentage from each generation are allowed a chance for breeding selection, while a smaller percentage survives to the next generation with no gene modification.

An adaptive crossover and mutation operator were used to increase the efficiency of the optimisation process. The probability of a crossover event is based on the average and maximum fitness of the entire population and parents.

GA OPERATING PARAMETERS

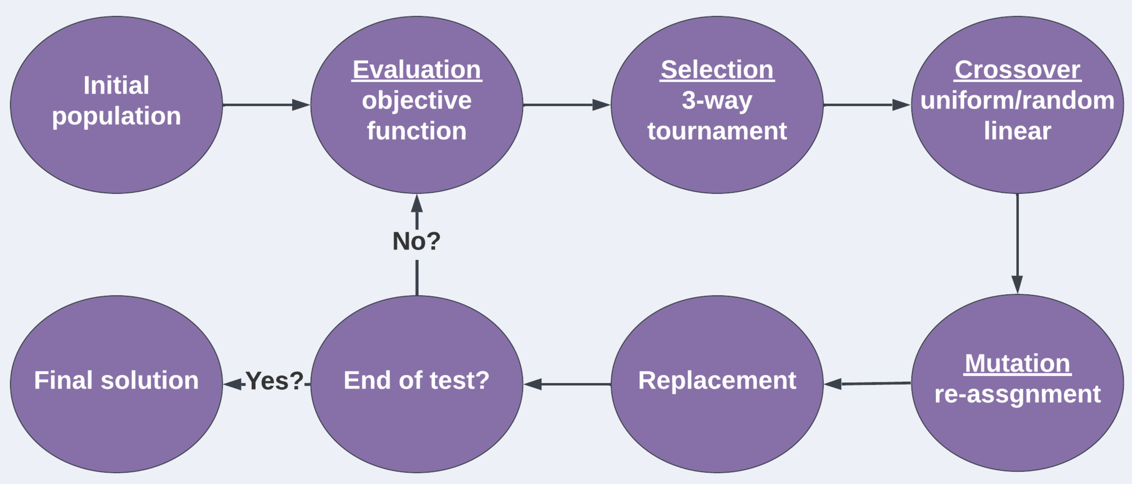
Crossover probability	$P_{C1} = 1.0$, $P_{C2} = 0.5$
Mutation probability	$P_{M1} = 0.5$, $P_{M2} = 0.1$
Breeding	Top 80% of generation
Survival	Top 2 individuals of generation

ADAPTIVE CROSSOVER / MUTATION

$$P = \begin{cases} \dfrac{P_1(F_{Max} - F')}{F_{Max} - F_{Avg}} + P_2, & F' \geq F_{Avg} \\ P_1 + P_2, & F' < F_{Avg} \end{cases}$$

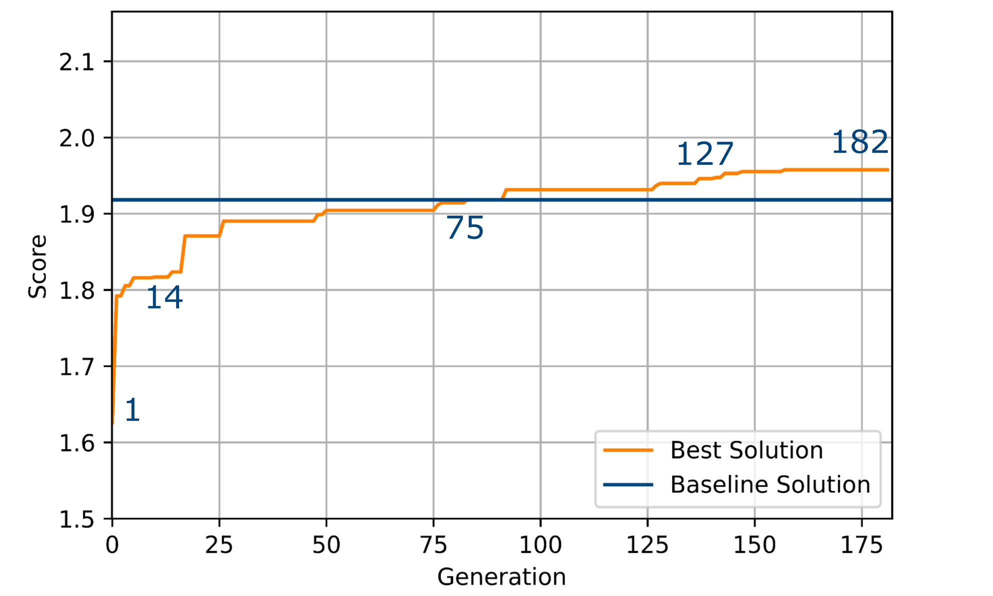
where P_1 and P_2 are the probabilities for crossover/mutation, F_{Max} and F_{Avg} are the maximum and average fitness scores for the generation respectively and F' is the maximum fitness of the two parents.

FIGURE 5: GA SCHEME



A total of 182 generations were solved using a population size of 500 individuals, taking approximately 10 days of wall clock time. Solution convergence is shown in Figure 6.

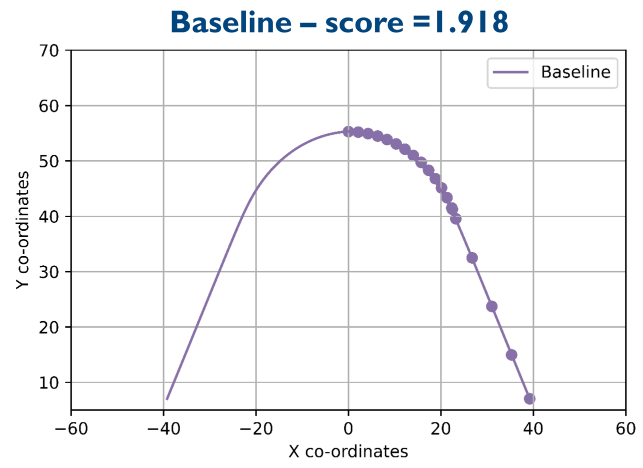
FIGURE 6: GA CONVERGENCE



RESULTS

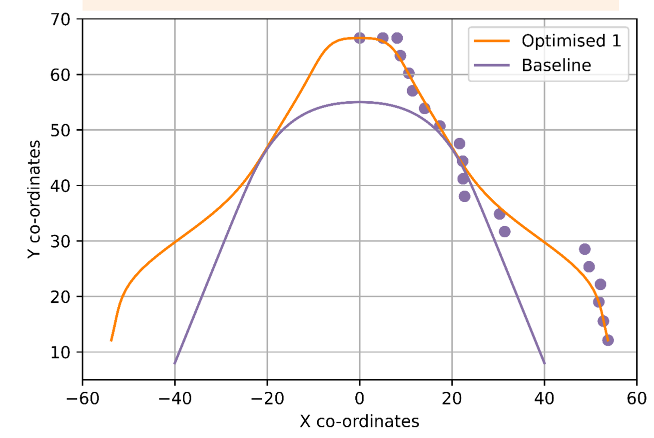
SOLUTION PROGRESSION

Baseline – score =1.918



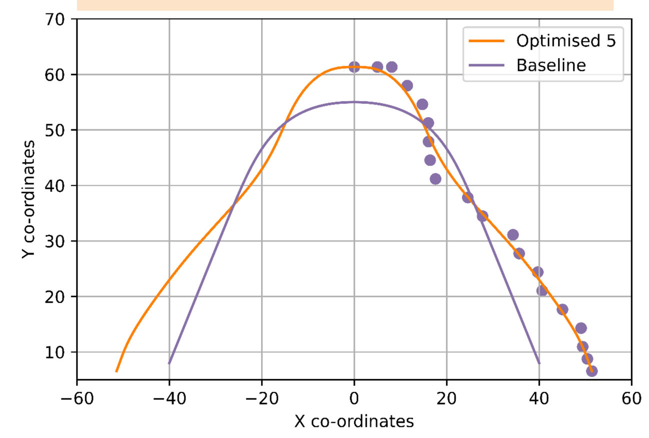
- Capping – 12 layers, 70 mm
- Cover – 3 layers @ 45°, 0 layers @ 0°, No patching
- Cap patching – 1 layer (250x120 mm)
- Cover patching – 1 layer (300 mm)

Generation 1 – score =1.626



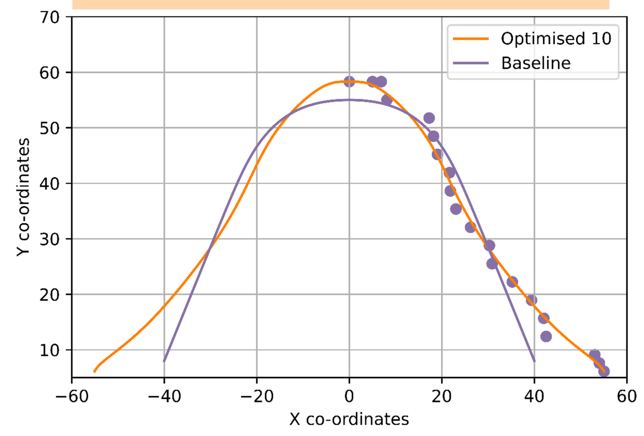
- Capping – 14 layers, 72 mm wide
- Cover – 2 layers @ 45°, 2 layers @ 0°, No patching
- Cap patching – 4 layers (68x162 mm)
- Cover patching - None

Generation 14 – score =1.817



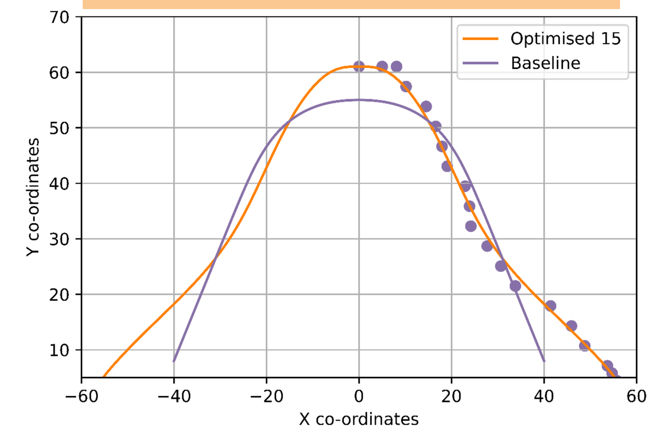
- Capping – 13 layers, 60 mm wide
- Cover – 1 layers @ 45°, 4 layers @ 0°
- Cap Patching – 4 layers (145x154 mm)
- Cover patching - None

Generation 75 – score =1.904



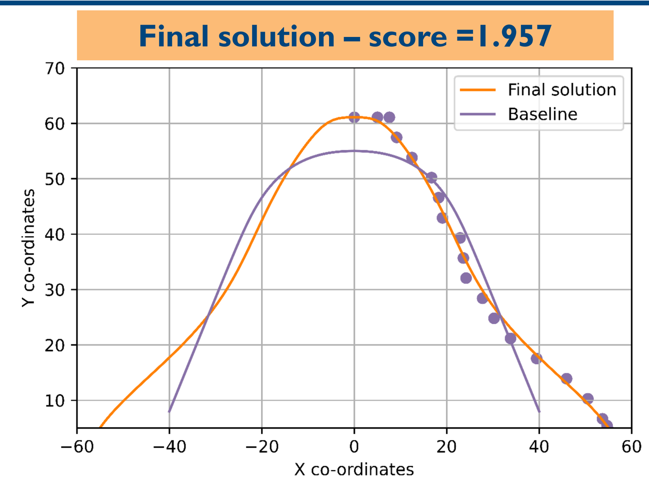
- Capping – 12 layers, 56 mm wide
- Cover – 3 layers @ 45°, 0 layers @ 0°
- Cap Patching – 2 layers (187x88 mm)
- Cover patching - None

Generation 127 15 – score =1.937



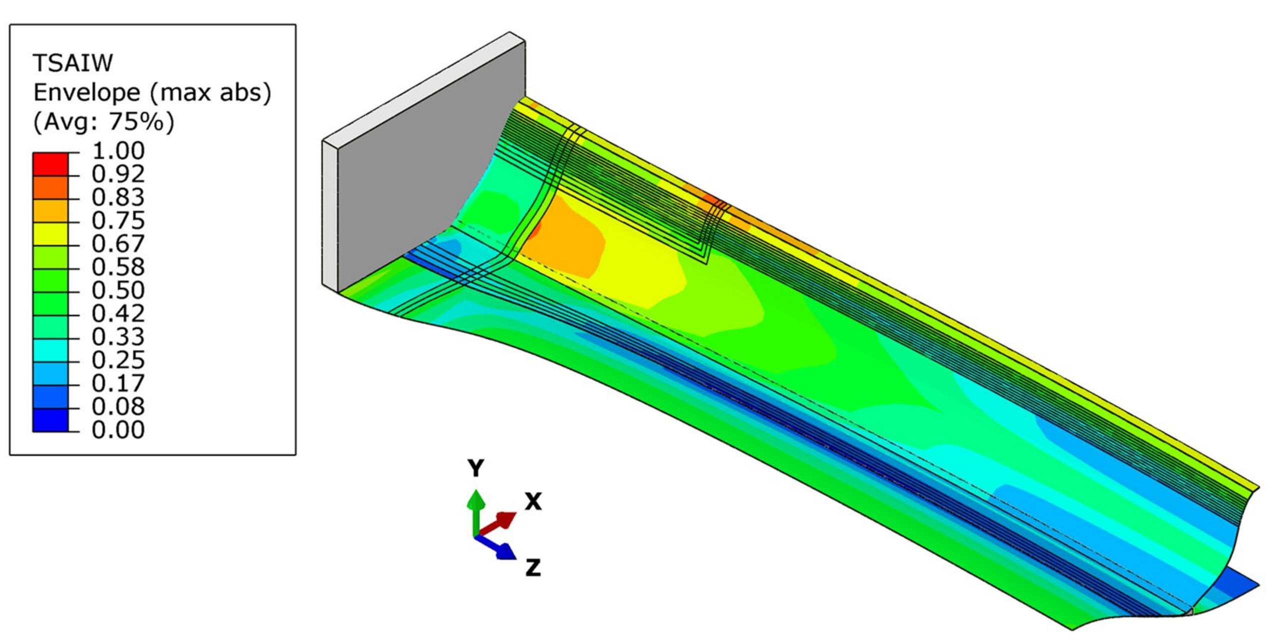
- Capping – 12 layers, 54 mm wide
- Cover – 2 layers @ 45°, 1 layers @ 0°
- Cap Patching – 4 layers (186x86 mm)
- Cover patching – None

Final solution – score =1.957



- Capping – 12 layers, 54 mm wide
- Cover – 2 layers @ 45°, 1 layers @ 0°
- Cap Patching – 4 layers (178x76 mm)
- Cover patching – None

FIGURE 7: FINAL SOLUTION TSAI-WU FAILURE CONTOUR



CONCLUSIONS

- A 2% reduction in mass was achieved while maintaining similar levels of performance.
- The optimised solution features a narrower profile and higher peak than the baseline. Stringer height increased by 11% over the baseline. This maintains flexural stiffness while using 14% less CFRP in the capping laminate.
- The stringer profile features a concave curve and a shallower angle at the fillet cove. This provides increased resistance to buckling and decreases bondline stress by 44% over the baseline. This also reduces stress concentrations in the vicinity of the fillet cove and web due to abrupt changes in stiffness.
- Patching in the cover laminate is removed entirely. Despite the larger surface area of the optimised stringer profile, cover laminate mass only increases by 0.8%.
- Reduction in fillet cove radius and web angle decreases the mass of the bondline by 46%.

CAMMD.co.nz