Simulation Driven Design for Manufacture of a Pressed Composite Automotive Tailgate

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Abstract: *A current key automotive industry initiative is delivery of mass savings through the use of lightweight materials, to reduce vehicle C02 emissions. Penso were commissioned by a European automotive OEM to design and manufacture a continuous fibre reinforced composite tailgate prototype. The new carbon fibre design had to meet all existing strength and stiffness targets, whilst maintaining existing A-surface geometry and all hardware. The three main parts of the tailgate considered for light weighting were the tailgate inner panel, tailgate outer panel and spoiler mechanism carrier. An optimised laminate design was developed by the engineering team using a non-linear static FE analysis performed with Abaqus/Standard. The Tsai-Wu failure measure and a user defined inter-laminar failure criterion were used as design metrics in post processing. The design was then evaluated with Penso's composite manufacturing team to develop preliminary ply shapes and overlap joint locations suitable for manual draping and Penso's pressed composite technology. These ply boundaries and material directions were updated in the FE model for further refinement of ply joint locations, prediction of finalised mass/performance and generation of layup manuals. The A and B-surfaces of the parts were then updated within CAD and used to create tool geometry for pressed composite. The final design of parts gave a combined mass save of over 65% whilst having comparable structural performance to the production design.*

Keywords: *Carbon Fibre, Composites, Design Optimization, Failure, Finite Element Analysis, Laminate, Manufacture*

1. Introduction

Penso were commissioned to design and manufacture a continuous fibre reinforced composite tailgate. This would be a lightweight alternative to the current production tailgate which is moulded from Sheet Moulding Compound (SMC), a discontinuous-fibre reinforced composite material.

2. Tailgate design

The production tailgate structure comprised of a bonded sub-assembly of inner and outer SMC panels, with a steel spoiler mechanism carrier bolted to the outer panel, as illustrated in Figure 1. Metallic reinforcing mounting plates for the hinges, gas struts and latch were bonded to the inside of the inner panel, with the rear screen glass bonded to the outer panel. The mass of the three main panels were 5.67 kg, 3.25 kg and 1.13 kg for the tailgate SMC inner panel, tailgate SMC outer panel and steel spoiler mechanism carrier respectively, giving a total mass of 10.05kg for the three panels.

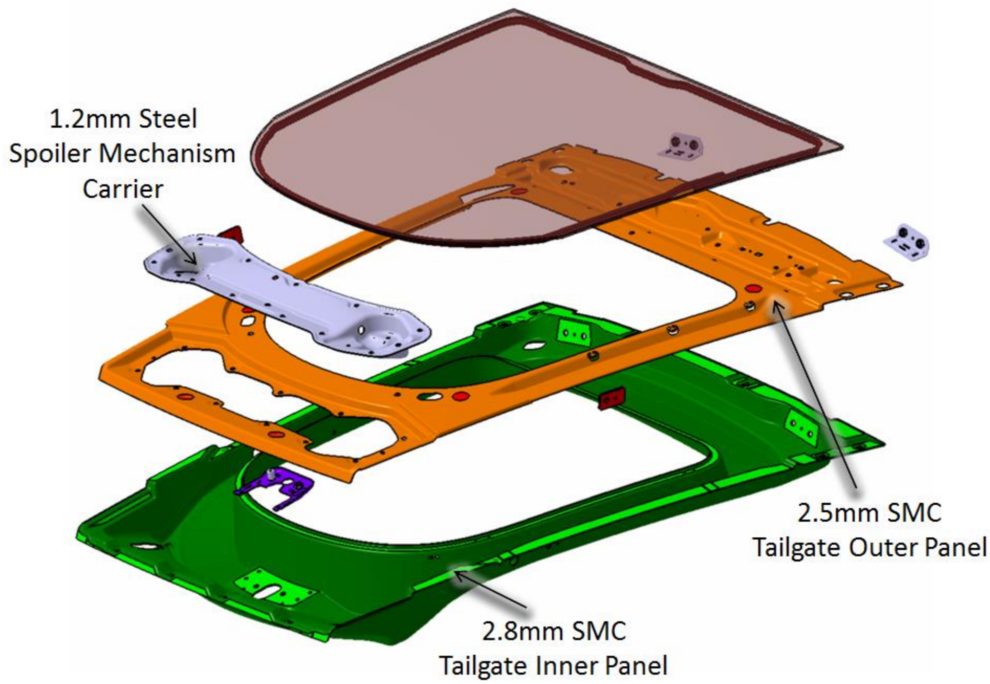

Figure 1. Tailgate parts considered for light weighting.

Three main parts of the tailgate were considered for light weighting; these were the tailgate inner panel, tailgate outer panel and spoiler mechanism carrier. The new carbon fibre design had to meet all existing strength and stiffness targets, whilst maintaining existing A-surface geometry, hardware and functional requirements. The structural performance targets against which the tailgate would be evaluated were torsion, cantilevered bending, latch load and margin & flushness.

The composite parts comprised a continuous fibre reinforced polymer material, using pre-impregnated (prepreg) epoxy resin carbon fibre reinforcement. The composite parts were laminated from a single prepreg composite sheet material supplied by Cytec Industries. The reinforcement material was a Toray T300 carbon fibre in a 6k tow size, a standard strength/modulus fibre used in a number of industry sectors. The matrix material was Cycom 2020 epoxy, a traditional autoclave cure resin developed by Cytec for structural motorsport applications, with a nominal resin weight fraction of 40%. This carbon fibre was woven into a 2x2 Twill fabric having a nominal areal weight of 400g/m^2. The nominal fibre volume fraction and cured ply thickness for this prepreg material were 52% and 0.44mm, respectively. Mechanical properties for this prepreg were obtained from static coupon tests performed by the material supplier in longitudinal (warp) and lateral (weft) fibre directions, with an average tensile modulus of 58 GPa, tensile strength of 550 MPa and compressive strength of 650 MPa. These orthotropic elastic material models were validated through simulation of coupon testing performed according to various ASTM test methods (Arnold et al, 2014).

The prototype composite parts of the tailgate were manufactured using Penso's pressed composite technology. Pressed composite technology is a process in which the prepreg composite material is placed into an open matched metal mould cavity. The tool is then closed under pressure to encapsulate the fibre and resin compound within the mould cavity. Heat and pressure are maintained until the composite material has cured.

3. Laminate optimisation

3.1. Finite element model

The CAD geometry was imported into the ANSA pre-processing software and converted into a surface suitable for shell meshing. The visible surface was chosen as the A-surface of each panel. The mesh was created on the A-surface which corresponded to the preform tool surface, such that the laminate plies stacked from A to B surface. Each panel was meshed with first order conventional S4 and S3R shell elements, having a nominal element edge length of 5mm.

Abaqus/Standard was used for the non-linear static finite element analysis for the tailgate load cases. The composite panels were modelled with laminate properties defined using *SHELL SECTION, COMPOSITE, where the Material identifier (MID), cured ply thickness (T) and orientation angle in longitudinal direction (PHI) of each ply are defined within the stacking sequence. Material orientation for each element was defined using a combination of *ORIENTATION, *DISTRIBUTION TABLE and *DISTRIBUTION such that the material X axis was orientated predominately in the fore/aft direction of the panel. Orthotropic elastic material models were defined for the macroscopic behaviour of the woven fabric prepreg using *ELASTIC, TYPE=LAMINA with *FAIL STRESS. The modulus of elasticity for warp and weft directions were both set to the minimum of these two values obtained from tensile test data, however it was noted that these values differed from those derived by compression tests. The tensile strengths in warp and weft directions were both reduced to the open hole tensile strength. The compressive strengths in warp and weft directions were similarly reduced to the open hole compressive strength. This was a method proposed by Niu (1992) to incorporate hole and defect tolerance. The resulting knock down factors for tensile and compressive strengths were 0.75 and 0.45, respectively.

To complete the tailgate model, the metallic mounting plates were modelled as shell elements referencing non-linear elastic-plastic material properties, whilst the rear screen glass was modelled with shell elements referencing isotropic elastic material properties. The adhesive was modelled using solid elements referencing isotropic elastic materials properties. The adhesive elements connected to neighbouring panels using the distributing coupling constraints.

3.2. Optimisation

Two methods of optimisation techniques were carried out on the tailgate, a manual method and a design optimisation software were utilised. Strain energy output was plotted to assist with manual optimisation of the layup. Figure 2 illustrates a combined strain energy envelope plot for all load cases of the tailgate; the areas of high strain energy indicate the areas where the part is working hard. To improve the global stiffness of the part, either thickening the laminate by adding extra reinforcement plies or else altering the fibre orientation is necessary.

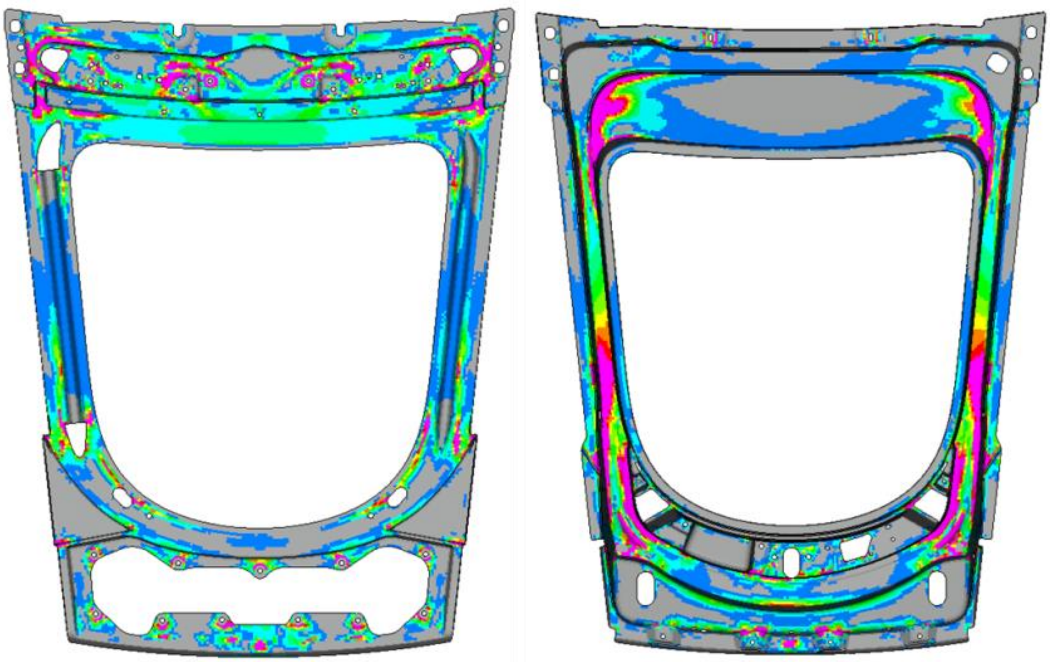

Figure 2. Strain energy plot for torsion load case.

A design optimisation software, VR&D GENSIS, was also used for topometry optimisation of the tailgate composite laminate. This is a method which indicates the layup required for each element to satisfy the defined objectives. The component is automatically split into patches having approximate dimensions of 50x50mm, to reduce the number of design variables and to simplify rationalisation. A candidate laminate was assigned to the global laminate and propagated to the separate patches. The candidate laminate had a layup of [45/0/45]s, so that the thickness could vary between a specified minimum and maximum thickness for each angle. The results gained from the topometry optimisation are continuous, not discrete ply thicknesses. Results are shown in Figure 3. These continuous topometry results were used to create rationalised patches which group similar thicknesses and orientations together to define the size and shape of each patch. Once the rationalised patches have been defined a sizing optimisation can be carried out on the patches, the results gained are now discrete rather than continuous.

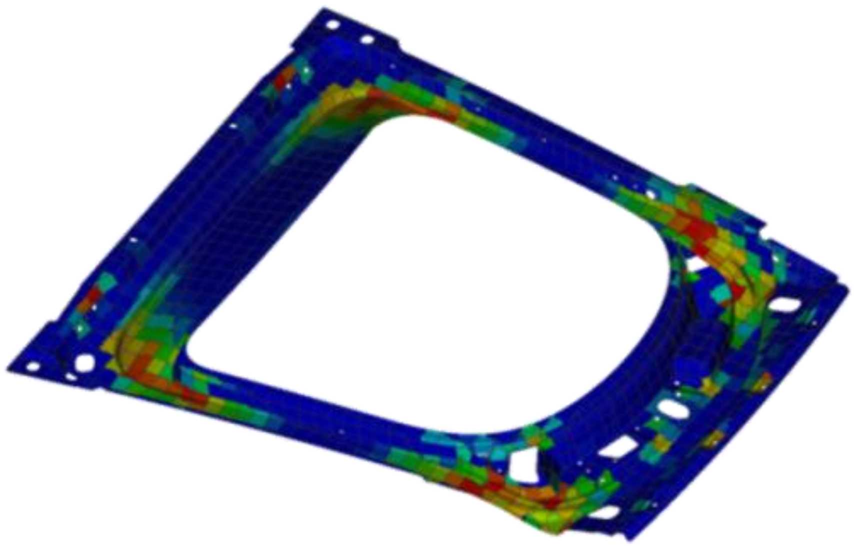

Figure 3. Topometry optimisation results for tailgate inner panel.

An optimised layup for the composite panels, which disregarded joints between all-over plies, was derived to comply with the structural performance targets, whilst also minimising mass. The optimised layup was derived by using knowledge gained from both the manual and design optimisation method. Each panel was constrained to have a minimum thickness of two all-over plies and a symmetric balanced laminate, to reduce the possibility of distortion during the manufacturing process. A symmetric laminate is a laminate where all plies are symmetrical about the mid-plane with regards both material and fibre orientation. A balanced laminate is a laminate where all the fibres that are oriented at angles other than 0° or 90° occur in pairs of $+\theta$ and $-\theta$, but are not necessarily adjacent. Although 2x2 Twill fabrics have slightly different mechanical properties in warp and weft fibre directions, the use of one or more of such plies orientated at 45° was considered balanced.

The laminate for the outer panel comprised two all-over plies oriented at 45° relative to the material orientation axes, with an additional local reinforcement ply oriented at 0° and positioned local to where the spoiler mechanism carrier is mounted. The laminate for the inner panel comprised three all-over plies oriented at 45°, 0° and 45°, with three additional local reinforcement plies oriented at 45°, 0° and 45° enclosed within the main laminate. These reinforcement plies were positioned at the four corners of the panel to improve global stiffness, and also at the hinge, latch and gas strut mounting face to improve the strength locally within these areas. Figure 4 illustrates a thickness plot of the optimised layup for the inner and outer tailgate panels. The laminate for the spoiler mechanism carrier simply comprised three all-over plies oriented at 0°, 45° and 0.

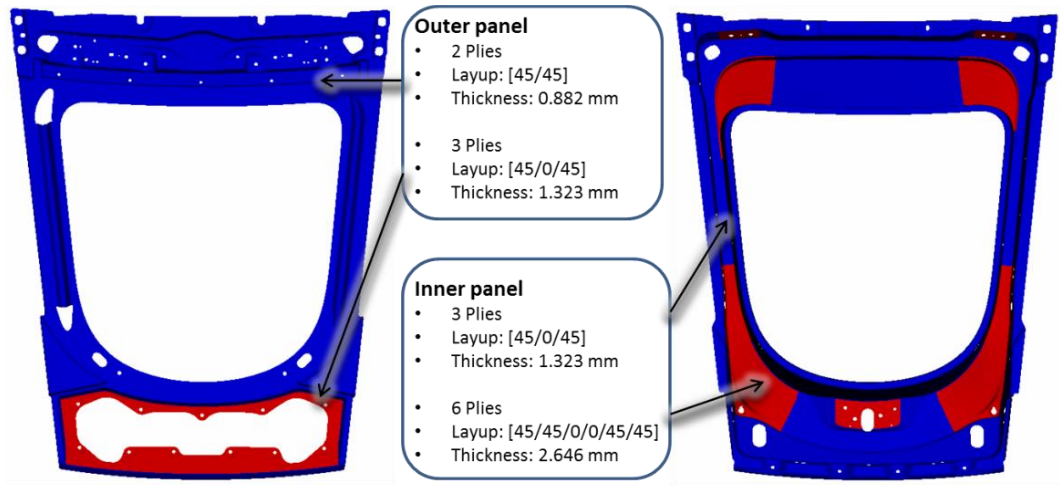

Figure 4. Optimised laminate design for tailgate inner and outer panel.

3.3. Finite element results for optimised laminate design

The Tsai-Wu Failure Measure and a user defined Inter-Laminar Failure Criterion were used as composite design metrics in post processing, to determine if ply failure or inter-laminar shear failure would occur between the laminate. Failure measure results were plotted using the μETA post-processor. The in-plane integration points at the middle section point of each ply were used to output values of the Tsai-Wu Failure Measure. Integration point results were used since these are the locations where results are typically more accurate (Cook et al, 1989). It was also thought that extrapolation of the results at the integration points to the corners may introduce additional uncertainties in failure measures. For the user-defined Inter-Laminar Failure Index, the output values were taken at surface section points of each ply. Nodal displacements were taken at certain pre-defined nodes, depending on the load case, to ensure compliance with stiffness targets.

3.3.1. Failure index

For the post processing of the laminate, the Tsai-Wu Failure Criterion was used. The Tsai-Wu Failure Index (FI) is used with composite materials under loading, with a FI ≥ 1 indicating failure. Failure index is not proportional to applied load for more complex, interactive failure criteria (i.e. Tsai-Wu), so is of limited use in design optimisation. The Tsai-Wu Strength Ratio (SR) is a related failure criterion for composite materials under loading, with a SR ≤ 1 indicating failure. Strength ratio is inversely proportional to applied load, regardless of failure criterion used, and therefore preferred for design optimisation. The disadvantage of using strength ratio in post processing is that the minimum value is of most interest to identify high stress regions, which is less intuitive for the user. Therefore, an alternative derivation is provided in Abaqus/Standard called Tsai-Wu Failure Measure, which is proportional to applied load since it is derived from the reciprocal of Tsai-Wu Strength Ratio (Dassault Systémes Simulia Corp, 2012). To account for load variability, a safety factor of 1.5 was considered for strength assessment (Niu, 1992). Rather than incorporate this safety factor into the material strength terms, as with the hole and defect tolerance, this was instead incorporated during post processing by ensuring the maximum Tsai-Wu Failure Measure value was <0.67. This was also believed to provide some robustness against variation in material allowables and uncertainty in FEA methods. Figure 5 shows a Tsai-Wu Failure Measure plot for the torsion load case. For this load case, a vertical Z-direction load of 267N is applied at the right hand bump stop, while the left hand bump stop is constrained in z-direction and the hinges constrained in all DOF. The max Tsai-Wu Failure Measure found is 0.36, indicating ply failure will not occur.

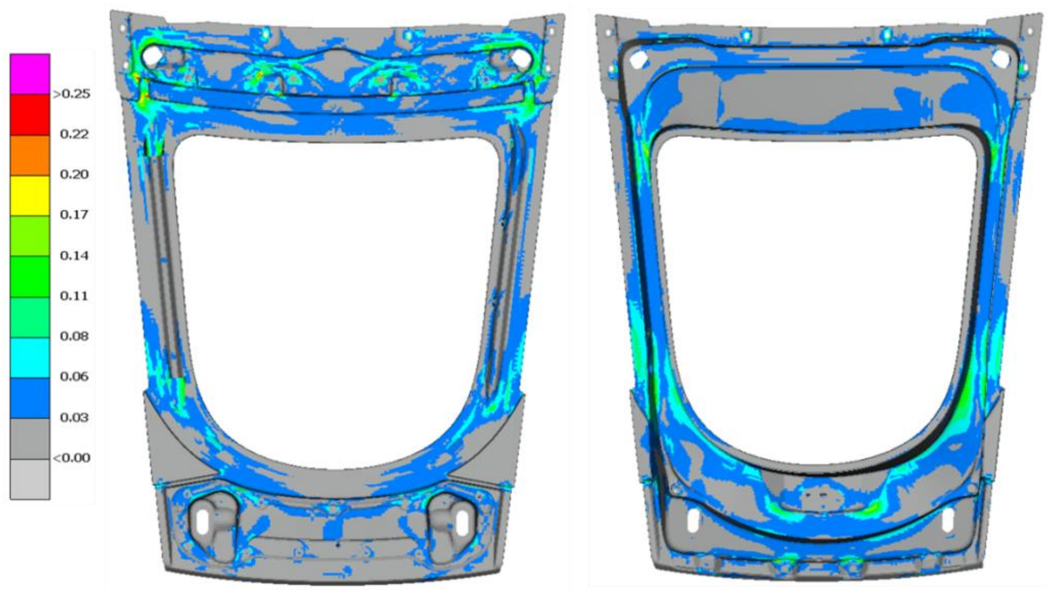

Figure 5. Tsai-Wu failure measure plot for torsion load case.

3.3.2. Interlaminar shear

Interlaminar shear stress, an indication if delamination would occur, is analysed through the use of the output variable transverse shear stress. Transverse shear stress (TSHR) was requested in Abaqus/Standard to request results for transverse shear stress in the 13-component, $\tau_{13,}$ and transverse shear stress in the 23-component, τ_{23}, for each ply boundary for every element. These are defined in the ply local coordinate system. To convert the transverse shear stress from the local material coordinate system to the global coordinate system the resultant of transverse shear stress was calculated. This can then be used in a user defined equation shown in Equation 1 to calculate the Inter-Laminar Failure Index (Bednarcyk et al, 2008). The allowable Inter-laminar shear strength Fsu13 and Fsu23 was assumed to be the same for the woven fabric.

$$Inter - Laminar\ Failure\ Index = \sqrt{(\frac{\tau_{13}}{Fsu_{13}})^2 + (\frac{\tau_{23}}{Fsu_{23}})^2} \quad (1)$$

Figure 6 shows a resultant transverse shear stress plot for the torsion load case. The max resultant transverse shear stress was found to be 9.79 MPa, which gave an Inter-Laminar Failure Index of 0.20, indicating delamination would not occur.

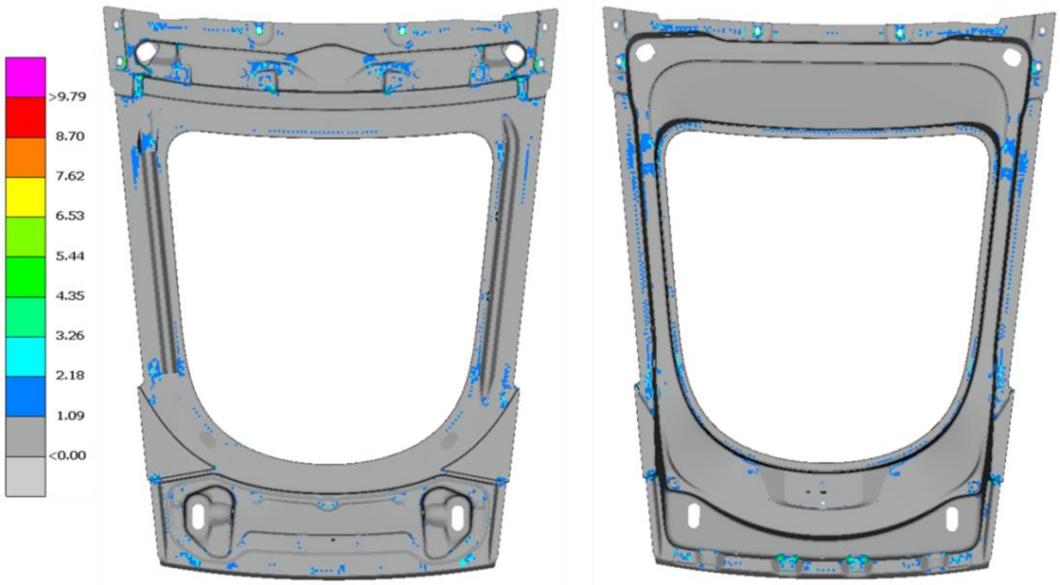

Figure 6. Resultant transverse shear stress plot for torsion load case.

3.3.3. Adhesive

Major Principal Stress and Max Shear Stress were evaluated for the failure of the adhesive. These stresses along with the corresponding allowable stresses for tensile and shear, were used to calculate a failure index to determine if tensile and shear failure would occur. This method, when combined with the linear elastic material model, gives a conservative result. As the stresses found within the analysis for the adhesive were very low, a more rigorous assessment was deemed unnecessary.

3.3.4. Displacement

Figure 7 shows a displacement plot for the torsion load case. Using the z-deflection at the unconstrained right hand bump stop and the distance between the two bump stops, the twist angle can be calculated by trigonometry. The calculated twist angle was 1.63 degrees.

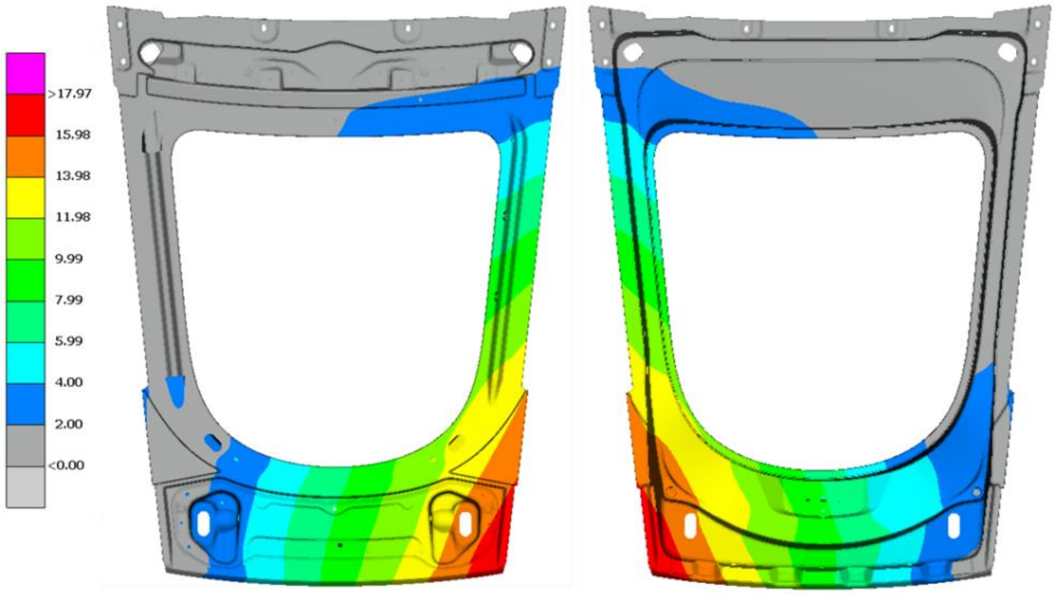

Figure 7. Displacement plot for torsion load case.

3.3.5. Results summary

Table 1 shows the results of the optimised laminate design for torsion load case discussed in sections 3.3.1, 3.3.2 and 3.3.4, along with results for the remaining three load cases that the tailgate was analysed against. It can be observed that the stiffness results comply with the targets set for their production tailgates, apart from the torsion load case where the twist angle marginally exceeded the target of 1.6 degrees by 2%. This was considered to be acceptable in the knowledge that adding overlaps into the final model will increase the torsional performance. The strength results also comply with Penso’s target of <0.67 for Tsai-Wu Failure Measure and Inter-laminar shear failure index. It was found that the design was driven mainly by the stiffness requirements, particularly for the torsion load case, which is a key reason the tailgate outer and inner panel laminates are biased to plies oriented at 45 degree.

Table 1. Optimised tailgate load case results.

Load case	Deflection Target	Deflection Result	Max Tsai-Wu Failure Measure	Max Interlaminar Shear FI
Latch Load	< 1 mm	0.11 mm	0.14	0.05
Torsion	< 1.6 degrees	1.63 degrees	0.36	0.20
Margin & Flushness	< 2 mm	1.29 mm	0.53	0.28
Cantilevered Bending	< 0.85 mm	0.02 mm	0.24	0.12

4. Design for manufacture

The optimised laminate design was evaluated with Penso's composite manufacturing team to develop preliminary ply shapes and overlap joint locations, suitable for manual draping and pressed composite. A preform tool was manufactured to the preliminary A-surface geometry and used for layup trials. Due to the complex geometry of the inner and outer panels, each of the all-over plies was subsequently divided into approximately twelve separate overlapped pieces to enable draping of the prepreg. The overlap distance between any two plies was typically 10mm, with the step in laminate thickness located on the B-Surface to ensure a smooth A-Surface. Figure 8 shows an example of a staggered overlap joint used, where the lower ply of an overlap joint is butt jointed to the upper ply of the previous overlap joint. Consideration of the detailed joint architecture was vital as the use of butt joints alone does not allow the transfer of loads from one ply to another. Overlap joints were deemed to be more effective, as this method reduces the thickness variation across the joint and will simplify the layup during the manufacturing stages.

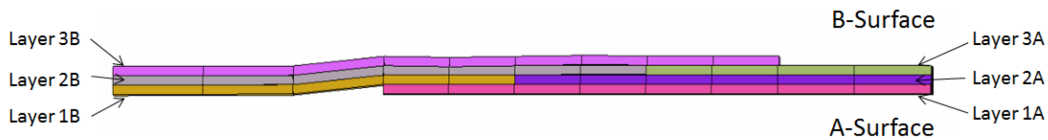

Figure 8. Staggered overlap joint between three plies.

Once the ply layup and overlap locations had been developed for manufacture, the ply boundaries documented by the laminator in their draped configuration were sent to Penso's analysis team along with information regarding fibre distortion. These ply boundaries, overlap locations and material directions were updated and modelled in the FE model for further refinement, for prediction of finalised mass/performance and generation of layup manuals. Material directions gained from layup trials were compared to that in the analysis model and corrections made where large inconsistences existed between the two sets of data. Since the parts were to be manufactured using layup books generated directly from the FE models the laminates needed to be accurately defined.

The laminate tool within ANSA was utilised for the ease of building, handling and modifying of all the layers of the composite model, which exploits a special ANSA laminate property. This ANSA laminate property simplifies the number of layers the user has to manage during pre and post-processing e.g. the outer panel comprised 1 laminate having 3 layers compared to the 2 composite shell section properties having a total of 5 plies when written out to the Abaqus/Standard FE solver. As draping simulation was not performed during the development of the prototype tailgate, the material orientation was defined within ANSA by projecting a vector of the fore/aft direction onto every element.

Figures 9 and 10 show thickness plots for the updated FE model of the tailgate outer and inner panels respectively, incorporating the ply boundaries and overlap locations determined by the manufacturing team.

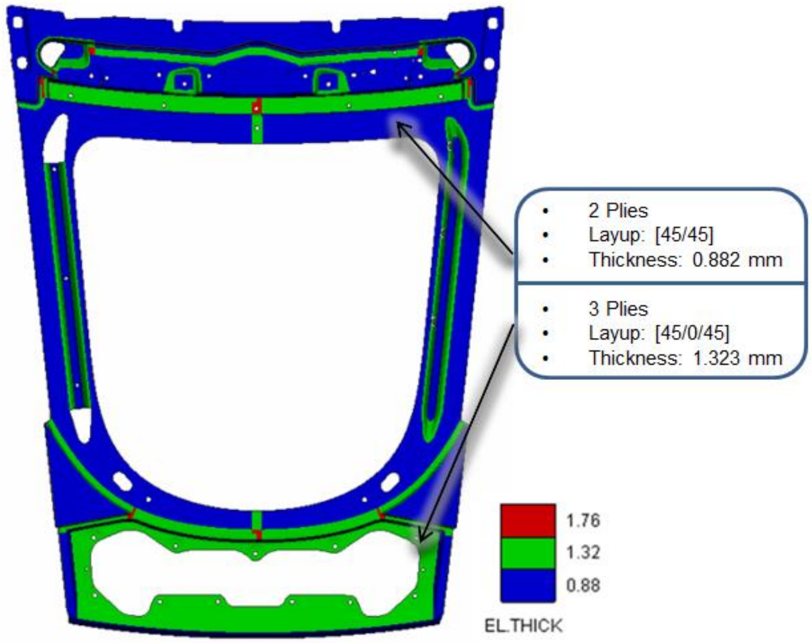

Figure 9. Thickness plot of final tailgate outer panel including overlap joints.

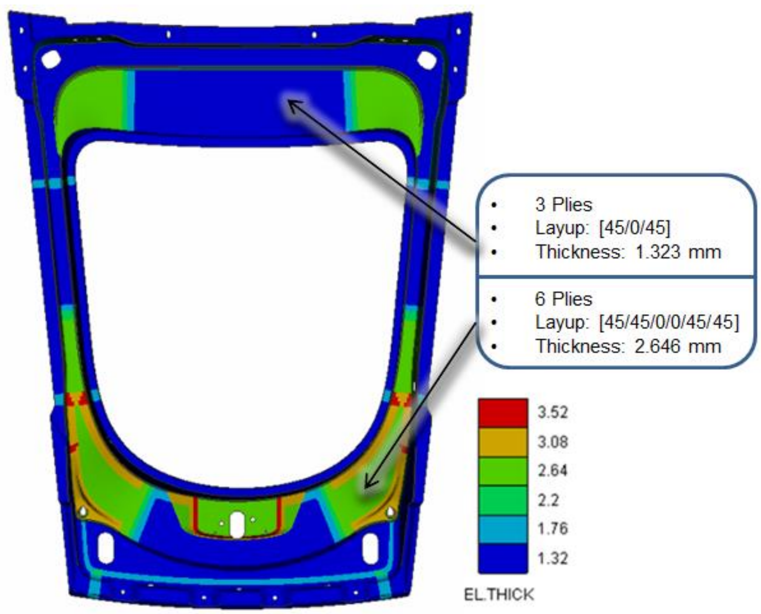

Figure 10. Thickness plot of final tailgate inner panel including overlap joints.

The previous four load cases were rerun with the tailgate model including overlap joints. The performance of the structure increased marginally, as shown in Table 2. This is due to the thicker regions added for the overlaps; though this also made the mass of the parts increase. As classical laminate shell theory is being used to represent the laminate, the performance is predicted to increase due to the increase in thickness at these overlap regions. However this does not accurately represent the joint as, under certain load conditions, it doesn't factor in the reduction in strength due to the discontinuity of the fibres at the joints.

Table 2. Final tailgate load case results.

Load case	Deflection Target	Deflection Result	Max Tsai-Wu Failure Measure	Max Interlaminar Shear FI
Latch Load	< 1 mm	0.10 mm	0.12	0.04
Torsion	< 1.6 degrees	1.30 degrees	0.25	0.14
Margin & Flushness	< 2 mm	1.83 mm	0.48	0.20
Cantilevered Bending	< 0.85 mm	0.02 mm	0.21	0.10

Ply shapes of the final tailgate design were transferred to Penso's design team by outputting ply boundaries as curves within an IGES file. By taking into account the ply shapes and ply thickness the B-Surface was generated for the composite parts of the tailgate, by modelling the layup from the A-Surface. The A and B-surfaces of the composite parts can then be used to create tool geometry for manufacturing.

4. Conclusion

The main purpose of this project was to show that weight reduction can be achieved by considering the production tailgate (Tailgate inner, tailgate outer and spoiler mechanism carrier) manufactured from the existing SMC material into carbon fibre, whilst maintaining similar results to the targets/baseline. Results gained from FE analysis of the tailgate showed that all strength and stiffness targets were achieved, whilst having equivalent or better structural performance to the production design. The total mass of the prototype carbon fibre tailgate panels was 3.04kg, giving a mass saving of 6.65kg, compared to the equivalent SMC/steel panels. The overall mass saving of the tailgate assembly was greater than this, due to the use of a new lightweight rear screen glass and removal of components such as the anti-pinch strips and interior trim.

Further improvements could be made by redesigning the geometry for carbon fibre specific application and reducing the section depth of the assembly, rather than use carry over geometry designed for materials with lower strength and stiffness. This would improve optical quality of the finished composite parts due to less possibility of the material stretching during draping and reducing the complexity during the pre-forming phase. Also the locations of the ply joints were positioned to optimise the stiffness, whereas ideally they should be located in areas where they are less visible to give the best aesthetics. Carry over metallic mounting plates, such as at the hinge, latch and gas strut, could be replaced by metallic inserts to reduce the assembly part count and total mass.

Further work has been carried out since; firstly robustness studies have been carried out to produce a practical method for quantifying the variability of continuous fibre-reinforced composite structures to uncertainty in ply orientation. Draping simulation software has been evaluated to see how accurately they predict the ply orientation due to draping. Their use would ensure analysis models reflect the design intent data and would evaluate ply producibility during the design phase to avoid any potential manufacturing difficulties downstream. Also on-going work is being carried out with Penso's laminators to optimise the tailgate layup to reduce laminating time, yet still achieve equivalent structure performance.

5. Acknowledgements

This project was co-funded by Innovate UK as part of the IDP7 Low Carbon Vehicles programme, in which Penso were a lead manufacturing partner.

6. References

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