Development of carbon fibre floor structure for NIO premium electric SUV

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1 Abstract

NIO are a global automotive startup producing electric vehicles for the China market. Our second vehicle, the ES6, was unveiled in December 2018 in Shanghai. It features a lightweight carbon fibre floor body structure, which will become the first high volume CFRP production part in ASIA.

This presentation describes the CAE activities undertaken to develop the composite body structure. It explains the approach that was taken to construct the DYNA material cards and the various material tests used to validate them. It explores the various CAE activities used to develop and optimise the design of the parts and the layups of composite layers, and then the successful validation of the parts.

2 Introduction

The body in white (BIW) of the NIO ES6 vehicle is mostly an aluminium structure, constructed from an optimised mix of extrusions, castings and pressings. The rear floor structure is constructed from an assembly of four carbon fibre reinforced polymer (CFRP) composite panels.

2.1 Requirements

The first step in developing these CFRP parts is to understand the requirements placed upon them.

The seatpan structure, illustrated in figure 1, needs to support the rear occupants at the back of the vehicle. It needs to provide a high level of rigidity for their NVH comfort and be strong enough to support their weight during vehicle use, misuse, or crash scenarios. The seatpan also needs to be a removable part, able to be removed and replaced in order to access various hardware packaged underneath.

The cross beam structure, illustrated in figure 2, is a closed section cross-member constructed from two composite panels. It forms the main cross car structure at the rear of the car and so its requirements are driven by a wide variety of global loadcases such as full body stiffness and various crash events. However, there are also a number of more specific requirements on the cross beam; It provides anchorages for the rear occupants seatbelts and thus must withstand very high localized point loading from the restraints. It is also where the folding seat back is mounted, which means that it must meet the required NVH local stiffness targets and withstand impact loading from unrestrained luggage.

The trunk floor structure, illustrated in figure 3, primary requirement is to reinforce all of the other surrounding structural members. It is responsible for a significant proportion of the total stiffness of the rear body structure. Additionally it must be able to withstand the weight of an operator standing on it during vehicle assembly, and it must not fracture in rear crash in a manner that might endanger the rear occupants.

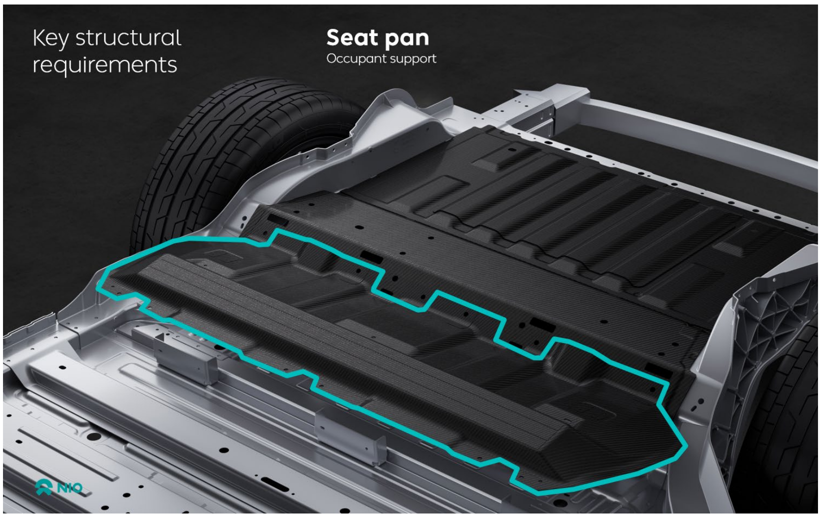

Fig.1: Seat pan

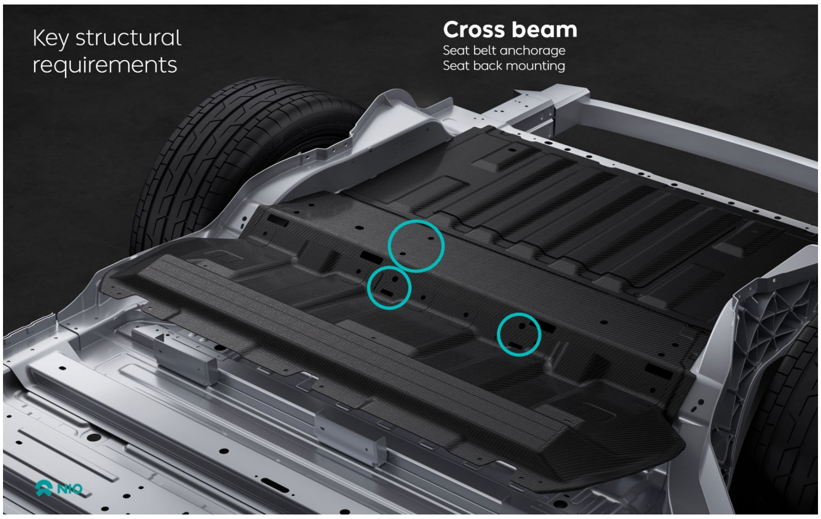

Fig.2: Cross beam

Fig.3: Trunk floor

3 Material card development

3.1 Construction of material card

A set of flat test panels were moulded from the desired resin and carbon fibre fabrics. This was done at a pressure and thermal curing cycle suitable for the production process to ensure that the material mechanical properties were representative of the production parts. From these panels a series of test coupons were cut and tested, table 1 below lists the tests that were used to construct the material cards.

From these tests the modulus and strength at 0°, 90° and +45°/-45° were understood, both in tension and in compression. These values were input directly into a *MAT_58 material card. The blue cells in table 2 illustrates the fields that were populated by direct entry of raw test data.

	Tension	Compression
0°	ASTM D3039	ASTM D3039
90°	ASTM D6641	ASTM D6641
+45°/-45°	ASTM D3518	ASTM D6641
Quasi Isotropic	ASTM D3039	ASTM D6641

Table 1: CFRP material coupon tests

MID	RHO	EA	EB	EC	PRBA	TAU1	GAMMA1
GAB	GBC	GCA	SLIMT1	SLIMC1	SLIMT2	SLIMC2	SLIMS
AOPT	TSIZE	ERODS	SOFT	FS	EPSF	EPSR	TSMD
XP	YP	ZP	A1	A2	A3	PRCA	PRCB
V1	V2	V3	D1	D2	D3	BETA	
E11C	E11T	E22C	E22T	GMS			
XC	XT	YC	YT	SC			

Table 2: MAT58: Laminated composite fabric

3.2 Validation of material card

This material card models the behaviour of a single ply of fabric, and then needs to be used multiple times within a *PART_COMPOSITE card in order to model the overall behaviour of a complete laminate, with multiple plies stacked together at different orientations. In order to validate that the material card works appropriately at a laminate level a second set of coupon tests was conducted, this time using a test panel with a quasi-isotropic (QI) layup. These QI coupon tests were then used to validate the material card, rather than as direct data to construct it. Figure 4 shows an example of this QI validation exercise.

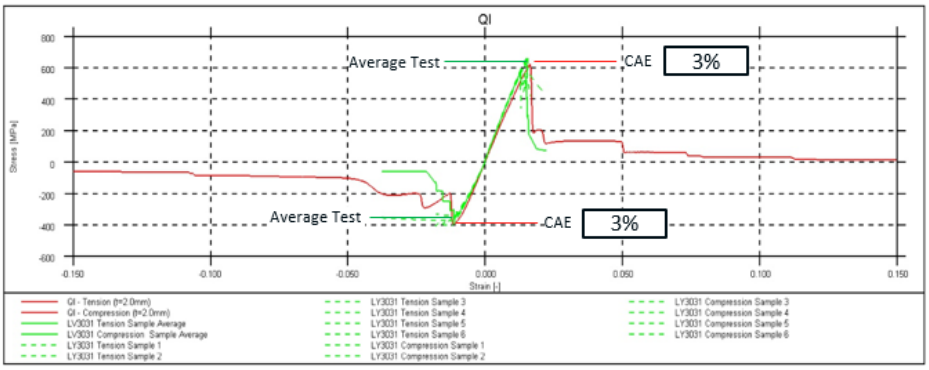

Fig.4: Correlation between test and CAE for quasi-isotropic material coupon

The QI coupon correlation demonstrates correlation for peak strength of the laminate, but further confidence in the non-linear post failure behavior is desired, especially for rear crash, seat mounting and restraint anchorage requirements. In order to assess this behavior a set of bolted joint pull through tests were conducted.

The tests consisted of a CFRP panel clamped round all four sides in a bolted frame, with a bolted joint at the centre of the panel, which is then pulled normal to the panel until ultimate failure of the joint. Two different test conditions were tested, one with a 50mm square steel backing plate under the nut, and one with a 70mm square plate, see figures 5 and 6 for an illustration of the test setup.

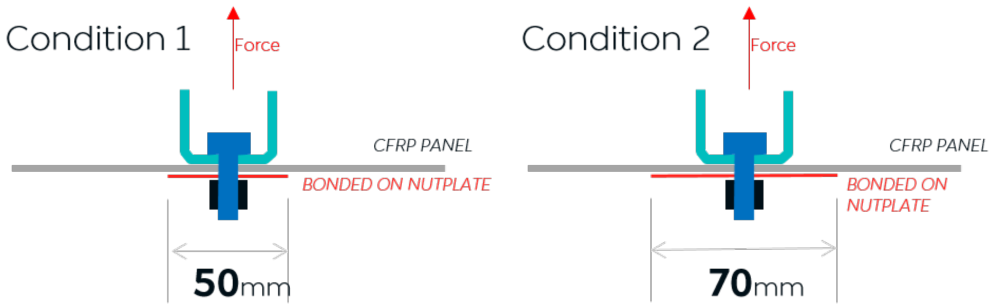

Fig.5: Bolted joint pull through test schematic

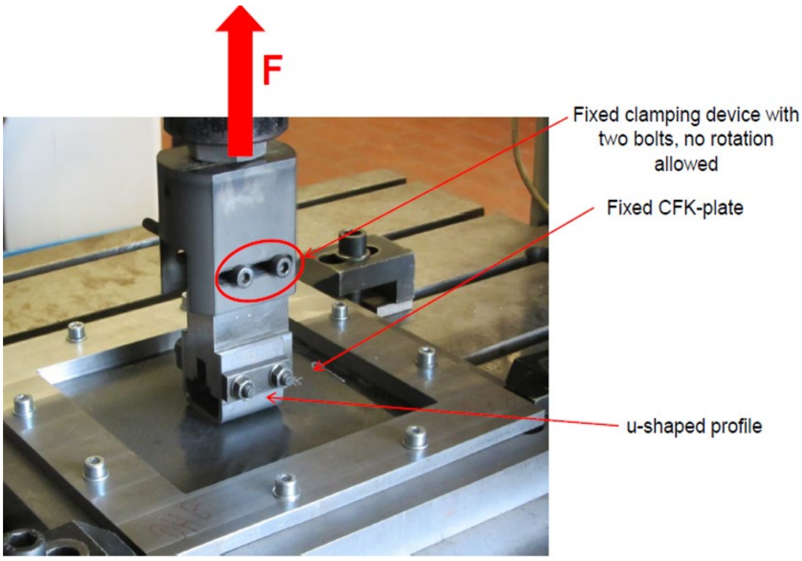

Fig.6: Bolted joint pull through test apparatus

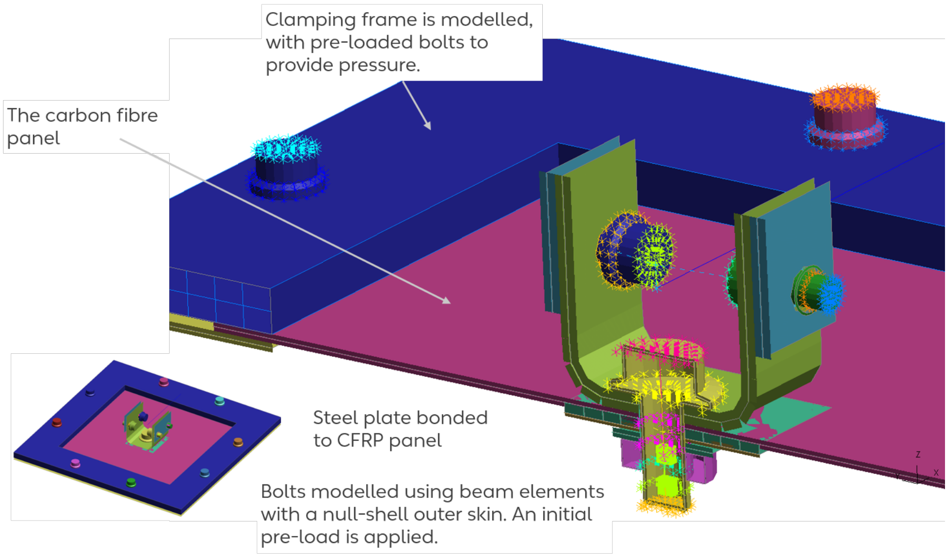

Fig.7: CAE model of bolted joint pull through test

Figure 7 shows the DYNA model constructed of the test. In order to properly represent the boundary conditions the clamping frame was modelled with deformable elements, with pre-loaded bolts to provide clamping pressure. In order to ensure that this correlation study provides useful validation for vehicle scale simulation the CFRP panel was modelled using the same specifications used to the model the composite parts in the full ES6 vehicle models.

All three tests with the 50mm square backing plate condition showed a consistent behavior, cracking of the CF panel from the bolt hole, followed by eventual pull through of the steel backing plate. In general these cracks developed at 45 degrees from the bolted joint. The DYNA model also showed the same overall macro-scale behavior, with the CF panel breaking via element erosion followed by pull out of the backing plate. The damage propagation in the model was not at a clear 45 degree pattern like the tests, but this capability is limited by the use of element erosion to model complete laminate failure and the relatively coarse 0-90 degree regular quad mesh pattern.

The 70mm square plate tests all showed a different failure mode from the 50mm tests. They failed via global cracking/folding of the panel and eventual failure/pull-out of the panel from the clamping frame at the edge of the panel. The DYNA model again gave a good match to the overall macro scale behavior, with the panel folding followed by the edges pulling out of the clamps and the corners tearing off, like in the tests. In the three tests the panels showed folds in different directions, showing a mix of 0 and 45 degrees. In the model the panel folded only at 45 degrees.

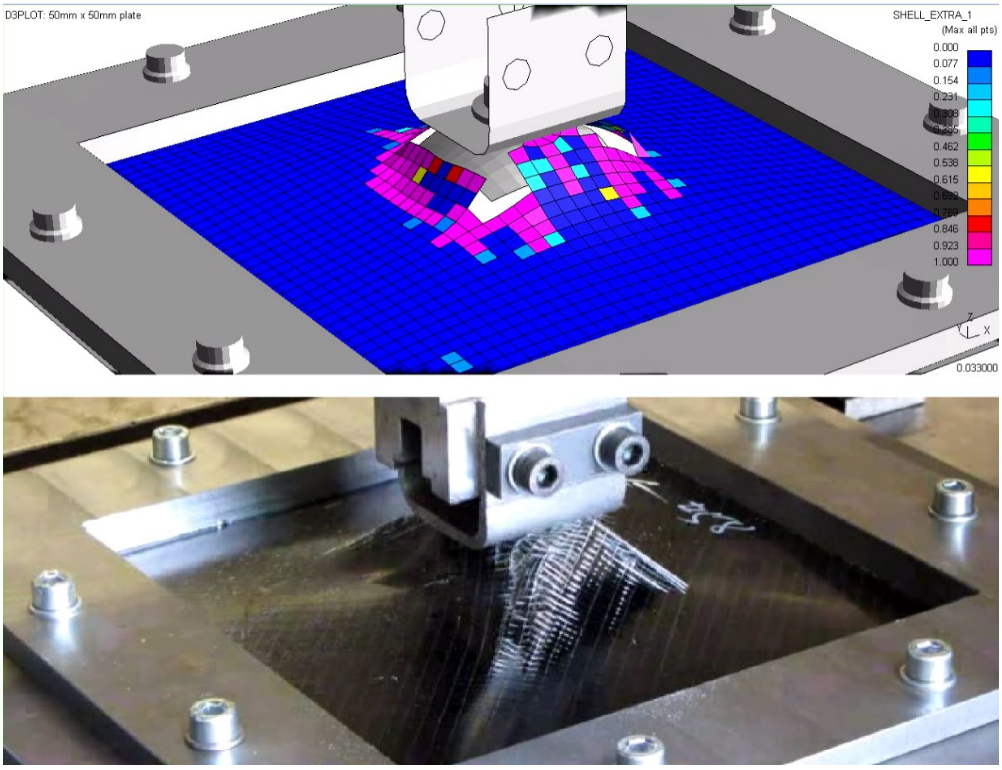

Fig.8: Test and CAE for 50mm square backing plate – mid test

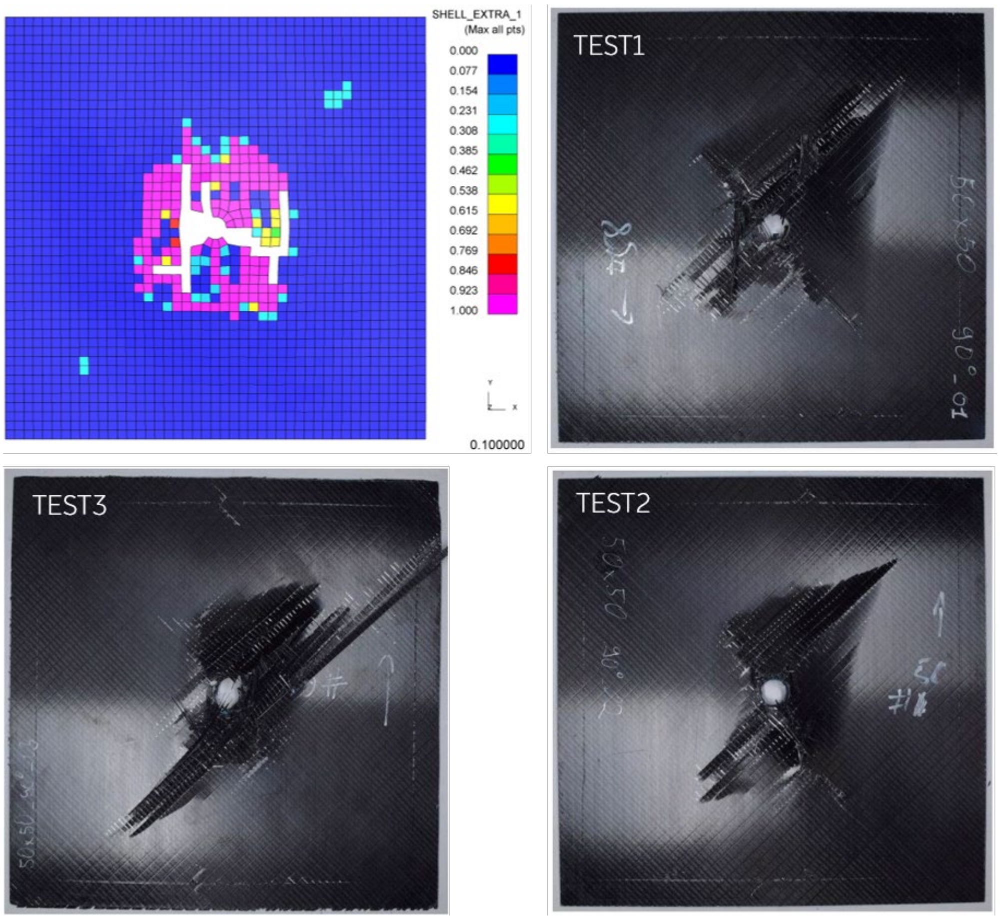

Fig.9: Test and CAE for 50mm square backing plate – post test

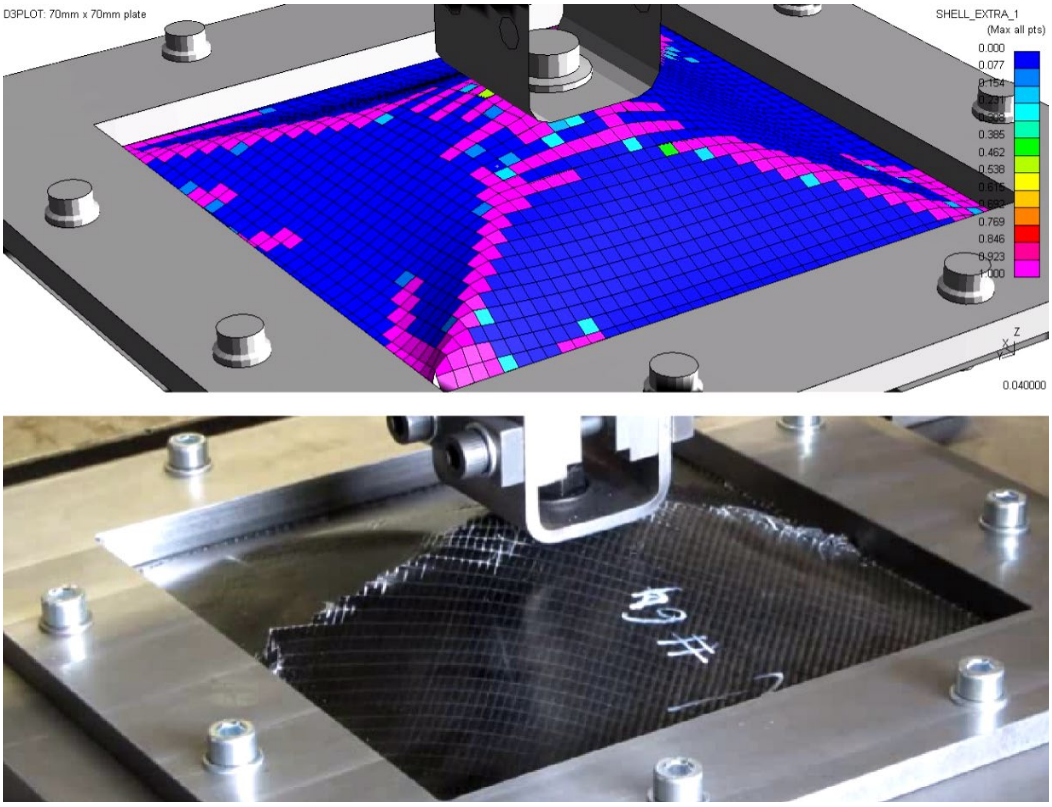

Fig.10: Test and CAE for 70mm square backing plate – mid test

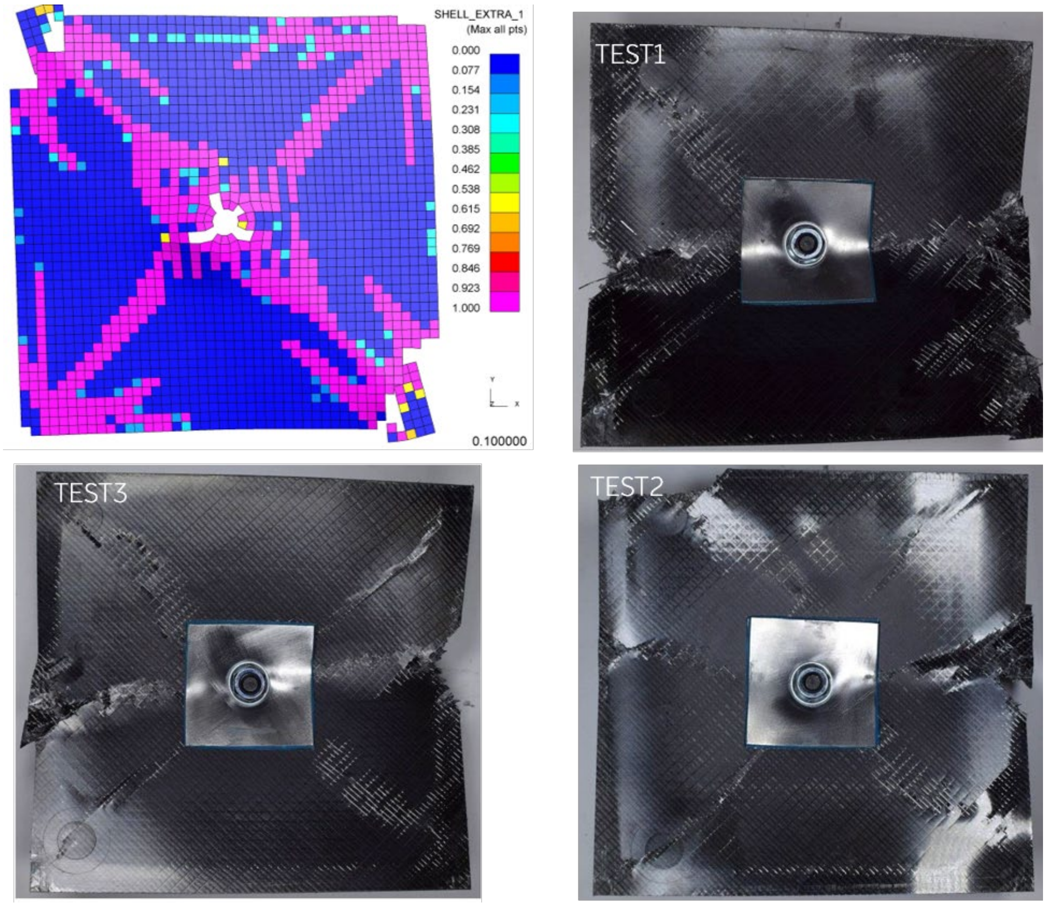

Fig.11: Test and CAE for 70mm square backing plate – post test

Figure 12 shows the force vs displacement results for the tests and the DYNA model. The initial ramp up in the model is stiffer than test. However we have high confidence in the stiffness of the CFRP material card from the coupon validation, so this effect is attributed to differences in slippage at the clamping around the boundary, given that the coefficient of friction between panel and frame is unknown.

The 50mm plate model gives good correlation to test, with peak load matching test and the post failure behavior matching too. The 70mm plate model shows an onset of damage at a very similar load to the tests, thereafter the post failure load shows the correct trend but at a lower load than the tests.

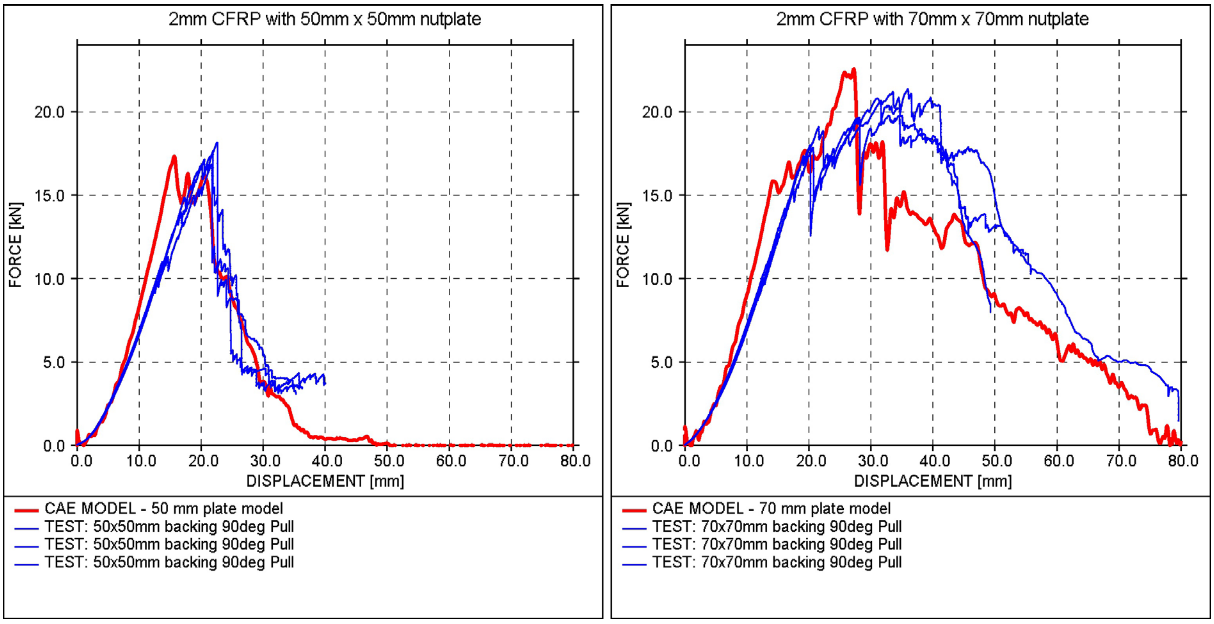

Fig.12: Force vs Displacement profiles for 50mm & 70mm plates, test and CAE

4 CAE optimization of components

With confidence in the material cards, the layups of the parts themselves could then be developed and optimised for maximum efficiency through CAE methods.

This was achieved through topometry optimisation of the four parts in a linear static model of the whole structure. An initial candidate laminate with a balanced and symmetric 0/90/45/-45/s layup was applied, with the thickness of each ply defined as an optimisation variable. The optimisation was constrained to meet strength and stiffness targets for all the critical loadcases discussed in section 2.1, and an optimisation objective for minimum mass was applied.

First the optimisation was run with each element freely sizing the layer thicknesses independently, to highlight local weaknesses in the parts, and thus provide feedback to the designers where the topology could be improved to smooth the required laminate. Next, the optimisation was run with whole plies being sized at once, constrained to work to discrete available fabric thicknesses and to keep 45 degree plies balanced.

The resulting layup was then checked in the full explicit DYNA models for each loadcase.

5 Conclusion

The finished components were successfully validated during the ES6 vehicle development tests. The production of the parts themselves is fully automated and will enter the market in mid 2019 to become to first high volume CFRP parts manufactured in Asia.

Fig.13: Fully automated assembly

6 Acknowledgements

This project was successfully delivered as a collaboration across multiple sites within NIO Vehicle Engineering; Oxford, Munich and Shanghai. The author would like to thank Sarabjit Bhooee, Dr Bin Wei, Karsten Tschierschke, Martin Li, Ethan Wang, Ellevern Chen and Haiko Heller for their valuable contributions to the project.

7 Literature

[1] LSTC: “LS-DYNA Keyword User’s Manual Volume II Material Models R10.0”