DEVELOPMENT OF A CFRP CAR UPPER BODY WITH NOVEL HOLISTIC STRUCTURE

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ABSTRACT

Based on the lightweight development requirements of a certain car model, a holistic CFRP car upper body was developed by performing structure design, non-linear CAE analysis and optimization, using Prepreg forming technology. The structure has passed the physical roof crush test, which shows that the car upper body produced by holistic CFRP manufacturing technology provides better stiffness and strength, satisfies the requirements of roof crush test standard. Moreover save additional 30% of weight compared with upper body structure with Aluminum frame and GFRP upper body shell.

CFRP composite materials are featured with higher specific strength and specific modulus. Compare with traditional metal material, CFRP could provide a better lightweight result. Benefit from the better structure and function integrity of composite materials, it may include multiple function and parts onto minority structures, further reduce the number of parts, number of connections, simplify the assembly process, and reduce the cost of assembly. Because of the orthotropic property of composite material, it is possible to optimize according to specific performance requirement, which provide a bigger optimization space and flexibility. In this study, the CFRP car upper body was produced using low-temperature Prepreg, and passed the roof crush test. The low-temperature Prepreg requires cure temperature about 80 ˚C, requires lower temperature resistance of the mould, which leads to a lower cost of the mould. The roof crush test was passed in first test, achieving a reaction force of 20KN, compare with the predicted reaction force of 21kN from CAE, the scatter is within 5%, which shows a good consistency between the CAE and test.

1 INTRODUCTION

Along with the development of the automotive industry, light weighting is one of the key elements of a successful vehicle development not only for traditional vehicle but also for new energy vehicle. It is a common understanding that a 10% of vehicle weight reduction can save 6%-8% of fuel consumption potentially [1] [2]. For electrical cars one of the current issues is the short mileage because of the limited battery capacity and weight of the battery. It is clear that a further light weight

BIW will greatly help with the mileage of the electrical vehicles. Carbon Fiber Reinforced Plastic (CFRP) is one of the best material which can tremendously reduce the weight without sacrificing the performance and safety.

Working together with BAIC Beijing Electrical Vehicle to develop one of their products, KDC has developed a car upper body with a holistic structure using CFRP. In this study, the upper body was developed according to typical CFRP development process in automotive industry including CAE simulation and physical test for verification.

2 PRODUCT DEVELOPMENT

CFRP product development process is similar to the traditional automotive product. Before concept design, feasibility study and program commencement was performed to reduce risk. Topology concept, material, process concept and assembly concept were addressed in concept phase according to project definition followed by detailed design. The product was verified by both CAE analysis and physical test as requited. Design loop of verification and redesign was involved for several times for optimization. **Figure 1** shows the development process.

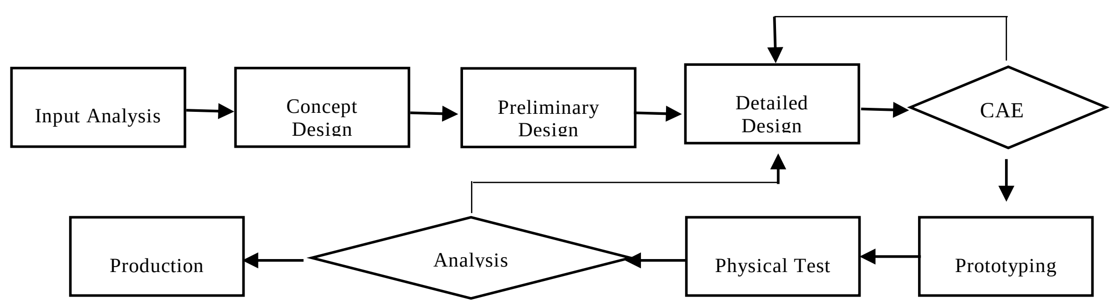


Figure 1: Typical development process of CFRP part for automotive application

2.1 STRUCTURE DESIGN

2.1.1 DESIGN PRINCIPLE

CFRP has high functional and structural integration potential due to its unique forming process. Maximizing integration is one of the design principles of the project, which bringa several benefits. Firstly, part number can be reduced dramatically to simplify the assembly process; secondly, connection of parts can be reduced to save weight; thirdly performance and safety can be maximized due to the holistic structure. CFRP is orthotropic material [3], it has very good performance along the fiber direction. In order to maximize the usage of the carbon fiber material, the load path of the vehicle was investigated and laminates were designed considering the load path [4].

2.1.2 STRUCTURE DESIGN

The original design includes three GFRP parts to form an upper body shell (Figure 2), then the upper body is mounted on an Aluminum space frame to take various loads. So the GFRP parts are not structure parts but functional parts. Figure 3 shows the original design.

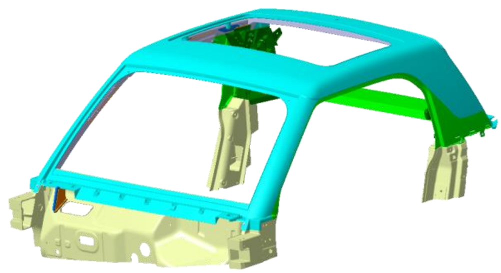


Figure 2 GFRP shell in original design

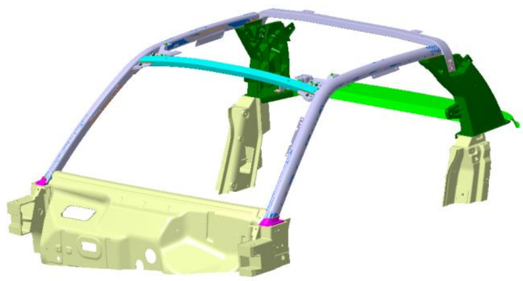


Figure 3 Al space from for structure parts

The optimized holistic CFRP upper body consists a one piece shell, which integrates the fire wall upper beam, A-pillar, Upper body side, B-pillar and roof etc. A front cross member bonded onto the inner side of the upper body links the left and right a-pillar. Rear cross member bonded on the inner side of upper body rear region links the left and right b-pillar. B-pillar inner panel bonded onto the inner side of b-pillar to form a closed section and provide connection structure for safe belt. Al structures were designed to form the connection between the Al lower body and CFRP upper body. Al connection parts can provide a uniform and much accurate connection interface which helps the positioning and bonding of the CFRP upper body (**Figure 4**). Other accessories to install other parts including interior, cables, roof window etc. were achieved using either stainless steel or Al and bonded onto the CFRP shell.

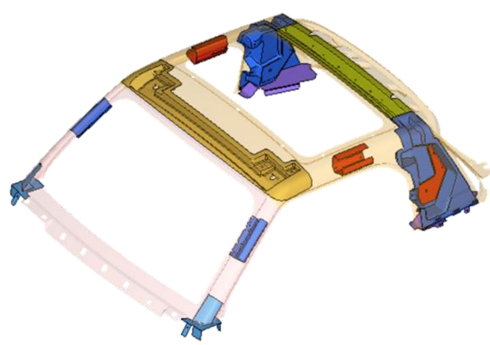


Figure 4 Structure of the CFRP upper body

2.1.3 MATERIAL AND LAMINATE

It is chosen to use prepreg out of autoclave as the forming process for all CFRP parts. 3 types material were used: 200gsm twill weave prepreg, 200gsm unidirectional prepreg and 300gsm unidirectional prepreg [4]. The mechanical properties are shown in **Table 1.**

Material Properties		**Unit**	**RC200**	**UDC200**	**UDC300**
Reinforcement Mass	m	[g/ m^2]	200	200	300
Long Modulus	E11	[Mpa]	62500	115000	120000
Transverse Modulus	E22	[Mpa]	62500	8000	7000
Through thickness Modulus	E33	[Mpa]	7000	8000	7000
Shear Modulus 12	G12	[Mpa]	4000	4000	4000
Shear Modulus 13	G13	[Mpa]	3500	4000	4000
Shear Modulus 23	G23	[Mpa]	3500	3000	3000
Poissons Ratio 12	v12	[Mpa]	0.04	0.27	0.27
Poissons Ratio 13	v13	[Mpa]	0.3	0.3	0.3
Poissons Ratio 23	v23	[Mpa]	0.3	0.4	0.4
Tensile Strength	XT	[Mpa]	688	1520	1560
Compressive Strength	XC	[Mpa]	500	1020	1020
Shear Strength	SC	[Mpa]	60	40	40

Table 1 Mechanical properties of prepregs used in project

Laminate table is as followed:

Outer Shell Laminate:

Outer Shell	**Ply No.**	**Material**	**Fiber mass**	**Thickness**	**Fiber Direction**	**Coverage**
			[g]	**[mm]**	**[deg]**	
Mould	1	RC200	200	0.23	±90	Total coverage
	2	UDC300	300	0.33	0	Total coverage
	3	UDC300	300	0.33	45	Total coverage
	4	UDC300	300	0.33	-45	Total coverage
	5	UDC300	300	0.33	90	Total coverage
	6	UDC300	300	0.33	0	Total coverage
	7	UDC300	300	0.33	0	Total coverage
	8	UDC300	300	0.33	90	Total coverage
	9	UDC300	300	0.33	-45	Total coverage
	10	UDC300	300	0.33	45	Total coverage
	11	UDC300	300	0.33	0	Total coverage

Table 2 Laminate table for outer shell

Laminate for inner panels:

Inner Panel	Ply No.	Material	Fiber mass	Thickness	Fiber Direction	Coverage
			[g]	[mm]	[deg]	
Mould	1	UDC200	200	0.22	0	Total coverage
	2	UDC200	200	0.22	45	Total coverage
	3	UDC200	200	0.22	-45	Total coverage
	4	UDC200	200	0.22	90	Total coverage
	5	UDC200	200	0.22	0	Total coverage
	6	UDC200	200	0.22	0	Total coverage
	7	UDC200	200	0.22	90	Total coverage
	8	UDC200	200	0.22	-45	Total coverage
	9	UDC200	200	0.22	45	Total coverage
	10	UDC200	200	0.22	0	Total coverage

Table 3 Laminate table for inner panels

2.1.4 CONNECTION DESIGN

The upper body is connected to lower body by bolt and structural adhesive, which can ensure sufficient connection strength. The structure is shown in Figure 5. The transition connection structure is with material of AlMg6061.

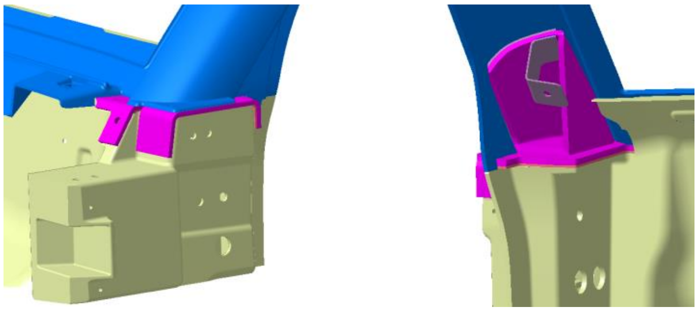


Figure 5 A pillar connection structure

A: Looking form outside; B: Looking from inside

To achieve the rear connection, the upper body was bonded onto the Al connection parts by structural adhesive, then Al connection parts were bonded onto the lower body. **Figure 6** shows the details of the structure.

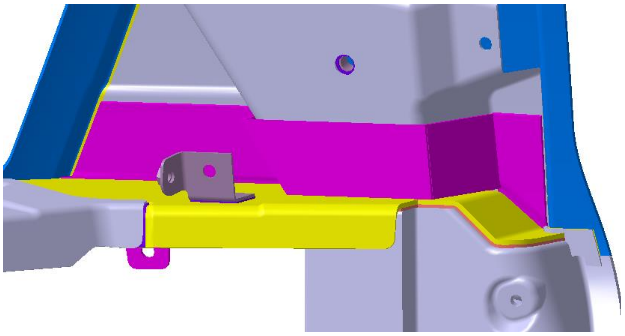


Figure 6 B pillar connection structure

2.1.5 ASSEMBLY DESIGN

The metal connectors, front cross member and rear cross member are shown in **Figure 7**. The assembly of these parts meet the tolerance requirements of the car. An assembly fixture which used the mould as a foundation was designed. The assembly accuracy can be guaranteed with this method.

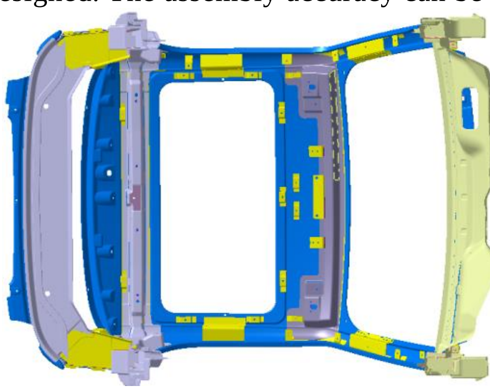


Figure 7 The Metal Connectors

2.1.6 KEY ISSUES AND SOLUTION

The galvanic corrosion could be an issue, if the connection between CFRP and metal were not well treated. For this reason stainless steel and coated Al were used for metal parts to prevent corrosion. Meanwhile it is important to ensure there is no direct contract between CFRP and Al parts. The structural adhesive layer can perform an insulator to prevent corrosion in some extent [5] [6].

2.2 CAE ANALYSIS

LS-DYNA was used for the non-linear quasi-static finite element analysis for the upper body roof crush load case. Orthotropic elastic material models were defined for the macroscopic behavior of the uni-direction non-crimped fabric and woven fabric prepreg using *MAT_LAMINATED_COMPOSITE_FABRIC. The modules of elasticity for warp and weft direction were both set to the minimum of these two values obtained from tensile test data, however it was noted that these value differed from those derived by compression tests. [7]

To complete the upper body model the metallic connectors and reinforced panel ware modeled as shell element referencing non-linear elastic-plastic material properties, whilst the four connection parts were modeled with solid elements referencing isotropic elastic material properties. The adhesive was modeled using solid elements referencing isotropic elastic materials properties. And the adhesive elements connected to neighboring panels using the distributing coupling constraints. [8]

An optimized layup for the composite panels, which disregarded joints between all-over plies, was derived to comply with the structural performance targets, whilst also minimizing mass. A symmetric balance laminate was designed to reduce the possibility of distortion during the manufacturing process [5].

For the roof crush load was applied according to the requirement of national standard of china, GB26134-2010[9], where defined the loading condition and specified the acceptance standard. The positioning of testing device as **figure 8**, the loading device was modeled as rigid wall property.

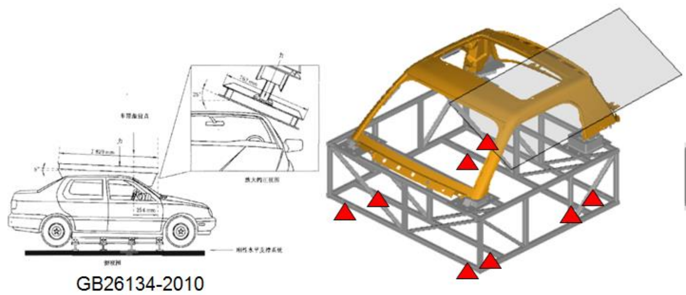


Figure 8 Roof crush test loading condition

The failure criteria of max stress and strain in fiber and matrix direction was used in post processing to determine if ply failure or inter-laminar shear failure would occur between the laminate [10]. Rather than incorporate this partial factor into the material strength terms, with the defect and scatter of materials, this was instead incorporated during post processing by ensuring the maximum stress value was 67% of theoretical value. Figure 9 shows a stress value in fiber and matrix direction on layer 4, which indicating ply failure will not occur in this moment.

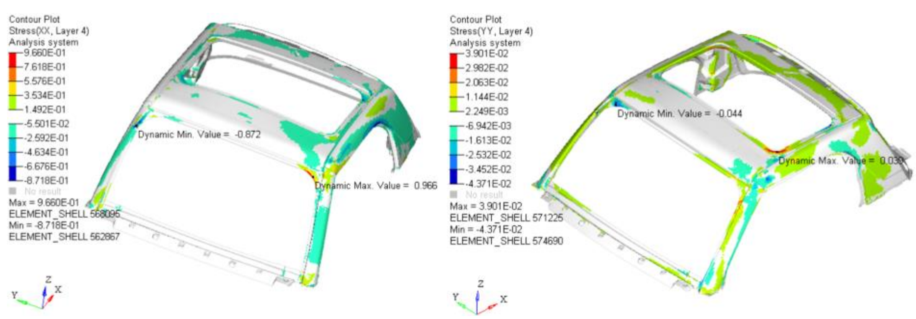


Figure 9 stress in two directions on layer 4

Major Principal Stress and Max Shear Stress were evaluated for the failure of the adhesive. According to the calculation results, **figure 10**, the adhesive elements under B pillar are dangerous. The connection design needs to be optimized.

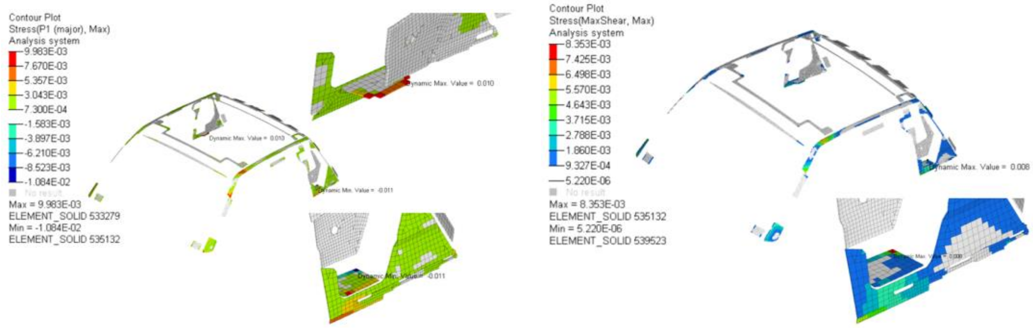


Figure 10 Adhesive stress results

The final target of roof crush test is to achieve a reaction force of rigid wall exceeded 18KN. According to the output of reaction force, figure 11, the target is achieved.

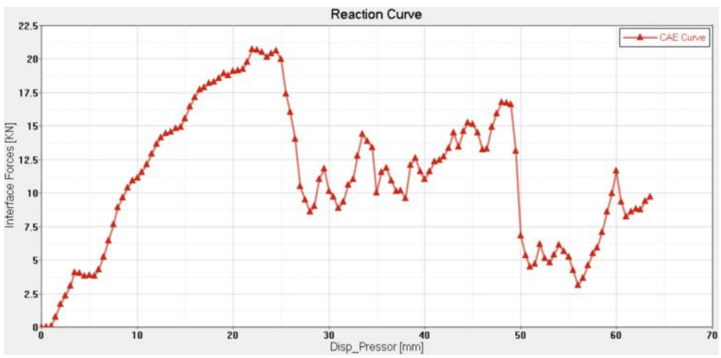
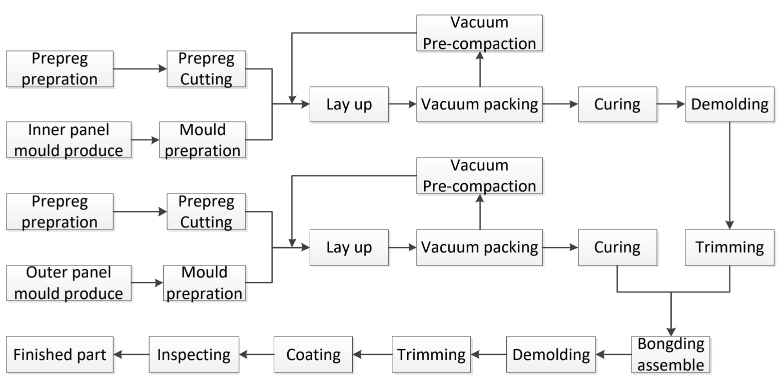


Figure 11 Reaction Curve

3 MANUFACTURING

3.1 PROCESS SELECTION

Considering of cost and mechanical property, the CFRP parts use prepreg vacuum bag molding. Figure.12. shows the manufacturing process of the holistic CFRP upper body.



Figureure 12 Manufacturing process of the holistic CFRP upper body

3.2 MOULD AND TOOLING

In order to reduce production costs, GFRP mold was used for forming. Due to the undercut of the upper frame of the car upper body, the formed part can't be demoded if the mould is in one piece. In order to solve the problem of demolding, the mould is designed with pieces, which includes a main mould and the two side moulds.

Figure 13 GFRP mould of the car upper body outer panel

3.3 MATERIAL

The thickness of car upper body outer panel is 3.5mm, and the thickness of other parts is 2.2mm. Considering the laminate design flexibility, it used unidirectional carbon fiber prepreg of 300 g/m^2 and 200 g/m^2 respectively. The first layer of car upper body exposed fiber texture for appearance is made of carbon fiber twill weave. Because of the low working temperature of GFRP mould, Prepreg with low curing temperature of 80 ˚C was chosen for the part. The car upper body outer panel and other parts are bonded with PU adhesive with high elongation to break ratio [11].

3.4 FORMING AND ASSEMBLY

The prepreg was cut by the automatic cutting equipment according to the input drawing. Cutting accuracy can reach 0.2mm. Using automatic cutting equipment can reduce the waste of prepreg. Figure.14. shows automatic cutting equipment and prepreg cut.

Figure 14 Automatic cutting equipment and prepreg cut

Assemble the mould, stack layers of prepreg according to designed laminate table.

Figure 15 Cured parts

The front cross member was trim and polished, same for rear cross member, B pillar inner panels. Then position the parts on the assembly fixture, bond the parts on the car upper body outer panel with PU adhesive.

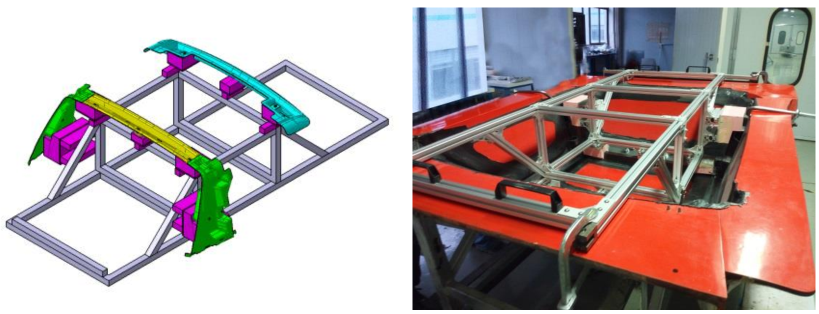


Figure 16 Assembly fixture

3.5 SURFACE TREATMENT

Demold and trim the car upper body, then the surface treatment, repairing, polishing, and coating. See Figure.17 for the surface finish of the holistic CFRP car upper body, which meets the requirements.

Figure 17 Finish product of holistic CFRP car upper body

4 TESTING AND VERIFICATION

To verify the design, we have worked with China Automotive Technology & Research Center (CATARC) to perform the roof crush test. The testing is shown in figure 18.

Figure 18 Testing picture

The comparison of reaction force during the test in experimental and CAE prediction is plotted in

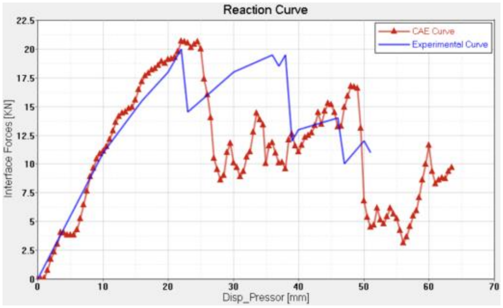


Figure 19 The comparison of experimental curve and CAE predicted curve

From the figure it was found that the CAE simulation was accurate before the failure occurred. The maximum predicted reaction force was 21KN, comparing to 20KN for experimental value. And the slope during loading stage matches well. However with current simulation methods the behavior after first failure was difficult in this case [4].

5 CONCLUSION

A holistic CFRP upper body for electrical vehicle was developed following a typical automotive industry development process. The upper body contains one monolithic shall structure and other cross members, inner panels and metal accessories. During the development, the structure was optimized considering performance, manufacturing feasibility, safety and cost. CAE simulation was performed to ensure the safety and predict the behavior of the part during roof crush test. Result was found fu ll fill the requirements of National Standard. After the first prototype was made, a physical roof crush test was performed to further verify the analysis results. And it is shown that the physical test consist with the CAE analysis very well. Which gives a reaction force of 20KN, compare with the CAE result of 21KN, a difference of 5% was found. The study also indicates further investigation and optimization is needed for some areas.

Acknowledgments

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