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Investigation on the Property of Injection Molded Steering Column Support Assembly Composite

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Keywords：Carbon fiber reinforced Polymers (CFRPs), Steering column support assembly, Injection molding, Lightweight, Electric vehicle.

ABSTRACT

Carbon fiber reinforced polymers (CFRPs) are used in automotive and aerspace application due to their lightweight advantages. In order to improve productivity and reduce cost, it is necessary to develop composite complex functional component efficiently and effectively using injection molding. In this study, a complex functional CFRPs steering column support assembly was developed using injection molding. It was found that 30 wt% carbon fiber reinforced PA66 (PA66-30 wt%CF) was appropritae. Through topology optimization and mold flow analysis, the main warpage and shrinkage deformations could be controlled within 3mm. The CAE analysis results could be good agreement with the text results. The manufactured component can satify these performance requirments. Due to the excellent damping properties, the mode of the composite component can be lower at least 7 Hz than that of metal component. The weight of the component was 4.1kg, and the weight reduction was 4.2kg compared to the steel part. The rate of weight reduction was above 50% percent.

INTRODUCTION

Lightweight technologies have been deemed essential for vehicles to achieve energy savings and emission reductions, and it is particularly urgent for electric vehicles (EVs) to improve their cruise range and battery life. Replacing heavy metallic materials with plastic is one of the most effective ways to reduce vehicle weight (Liu et al., 2013). Due to their specific high stiffness and strength, carbon fiber-reinforced polymers (CFRPs) have greatly expanded the use of fiber-reinforced plastic components and have been the predominant composite material in structural applications (Wan et al., 2021). CFRPs have been applied in many vehicles, such as the BAW i3 body and Aston Martin Vanquish chassis components. The application of CFRPs is much more complex than that of metal materials due to the complex mechanical relationships between carbon fibers and resins. Carbon fibers and matrix resins are not independent of other aspects of the component, nor are they necessarily independent of each other (Yao et al., 2018; Ma et al., 2019). Various forms of carbon fibers, such as continuous filaments, weaves, or knits, as well as various kinds of matrix resins, including thermoset resins and thermoplastic resins, have been developed for CFRPs (Seifans et al., 2021; Liu et al., 2019; Nantina et al., 2022; Kuo et al., 2019). Various manufacturing technologies such as injection molding, resin transfer molding (RTM) and compression molding (He et al., 2011; Nerea et al., 2019; Kuo et al., 2022) have been developed over the decades. Due to its many advantages, such as high productivity, good flexibility to complex structures and economic efficiency, injection molding has been one of the most widely used manufacturing technologies. Numerous studies have been conducted on this technology. These run through every link in the new solutions for injection molds (Kuo et al., 2019; Kuo et al., 2022; Cunha et al., 2022; Kuo et al., 2022), computer-aided engineering (CAE) for optimization (Kitayama et al., 2022; Zhao et al., 2022; Zhou et al., 2021; Formas et al., 2022), and materials investigation (Kubra et al., 2022). These studies positively expanded the application of injection molding and improved the

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quality and geometric structural complexity. As a very important functional component of the vehicle, the steering column support assembly mainly manufactured by metal materials is usually welded by 20 metal components, mainly including a cross-car beam tube, 2 end brackets (to secure instrument panel (IP) to the body in white (BIW) on each side of the car), steering column bracket, and side vertical brace (Figure 1), which holds the components housed in the cockpit area, such as the air-conditioning system, the central console and airbags (Ding et al., 2017). On account of its load bearing the steering-column and the steering-wheel system, the component requires high noise, vibration and harshness (NVH) and mechanical performance. Obviously, this component has great requirement for lightweight. Recently, the lightweight steering column support assembly has been studied by many researchers. Li et al. (2005) introduced a casting magnesium cross-car beam (CCB) for the Ford GT 2005, which enabled the Ford GT to meet vehicle performance and safety targets in a timely fashion and budget and achieve 30% weight savings compared to an equivalent aluminum version. Li et al. (2015) maximized the benefit of design optimization and achieved considerable savings in the design time and the associated costs by carrying out topology optimization in the conceptual design stage of aluminum CCBs, followed by size and shape optimization in the subsequent detailed design stage. Gao et al. (2011) redesigned the extruded magnesium alloy CCB to achieve lightweight. The magnesium alloy substitution design met the requirements on lightweight, crash safety and manufacturability. Due to the excellent damping and mechanical properties of CFRPs, a higher degree of integration and more weight reduction can be achieved (Ding et al., 2017). However, it remains a challenge to develop a composite steering column support assembly that can satisfy the mechanical requirements, primarily owing to the difficulties in material selection, parts and mold design and so on.

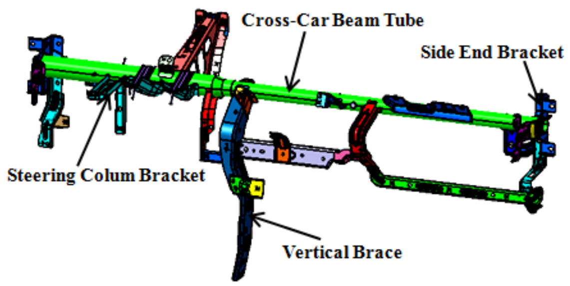


Fig. 1. The traditional metal steering column support assembly.

Developing complex functional components, such as steering column support assembly, is one of the key problems that must be resolved in the lightweight automotive and aerospace industries. In this study, a CFRP steering column support assembly was developed using injection molding. Topology optimization and mold flow analysis were carried out to investigate the main warpage and shrinkage deformation control as well as the optimum process parameters. CAE analysis and various tests, such as NVH and 3D scanning, were conducted to measure the performance of the composite component. Furthermore, the weight of the CFRP steering column support assembly was also evaluated.

CFRPS STEERING COLUMN SUPPORT ASSEMBLY STRUCTURE

The design methodology of CFRP steering column support assembly is definitely different from that of the steel part. Due to the drawbacks of high cost associated with raw materials and complex structures, the designed structure must be as rational as possible to achieve the most weight reduction and the lowest cost. Therefore, the structure design is one of the key challenges to CFRP steering column support assembly. A CAE-based design approach, combining various requirements of performance, manufacturability and engineering design is used at the conceptual stage of the design process for the design of CFRC steering column support assembly. These two steps of this design approach could achieve an optimum steering column support assembly design that may fulfill the performance and deformation controlling requirements.

Optimization design

Topological optimization based on the variable density method has been used to optimize the structure of steering column support assemblies to achieve lightweight design (Xie et al., 2020). The variable density method introduces an imaginary variable material with a relative density between 0 and 1. It is assumed that the elastic modulus of the design material has a nonlinear relationship with the density. A penalty function is used to constrain the unit with a density between 0 and 1, and the optimal distribution form of the structural material with the least flexibility is found under a certain amount of material. The variable density method without introducing the real material structures has simple procedures and high optimization efficiency and is widely used in structure optimization (Zhao et al., 2018). The mathematical model with the maximum flexibility of the structure as the design objective function and the volume as the constraint is as follows:

$$\text{Min: } C(X) = U^T K U = \sum_{e=1}^{N} (x^e)^p\, U_e^T k_0 u_e$$

$$\text{s.t.: } \frac{v(x)}{v_0} \leq f$$

$$KU = F$$

$$0 \leq x_{min} \leq x^e \leq x_{max} \leq 1 \quad (1)$$

where X is the design variable, x^e is the element design variable (e=1, 2..., N, N is the number of design variables), C(X) is the compliance of the structure, F is the load matrix, U is the displacement matrix, K is the overall stiffness matrix, U and K are the element displacement matrix and the element stiffness matrix, respectively, v(x) is the effective volume of the structure under the state of design variables, v0 is the effective volume of the structure under the state of design variables taking 1, f is the percentage of material consumption (volume factor), and P is the penalty factor. Topology optimization was performed based on the design space of the steering column support assembly. The analysis results demonstrate that there are two kinds of colors, red and blue, on the component (Figure 2). The red color means that these positions are crucial to performance and require a structural enhancement design, while the blue positions are relatively unimportant. The wall thickness of blue positions can be reduced appropriately. According to the results, structural design was conducted. To improve the performance of the red positions, those positions were designed into two components, called the IP carrier body and the steering column bracket assembly, to fix the steering-column (Figure 3). The thickness of the steering column bracket assembly is 4 mm and that of the IP carrier body is 3.5 mm.

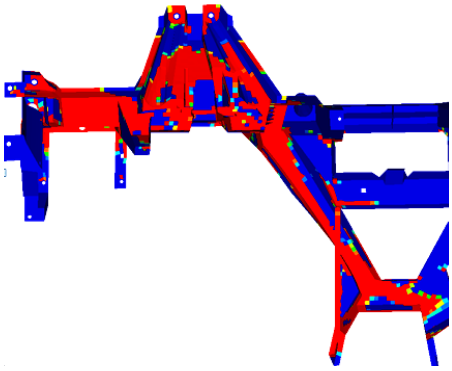


Fig. 2. Topology optimization diagram

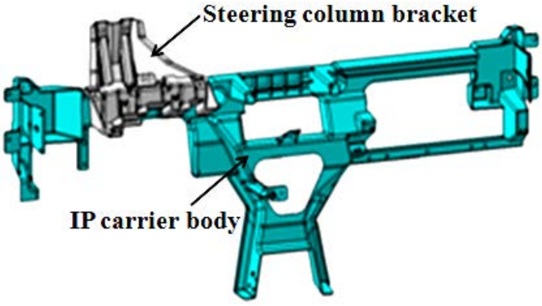


Fig. 3. The designed structure of CFRC steering column support assembly

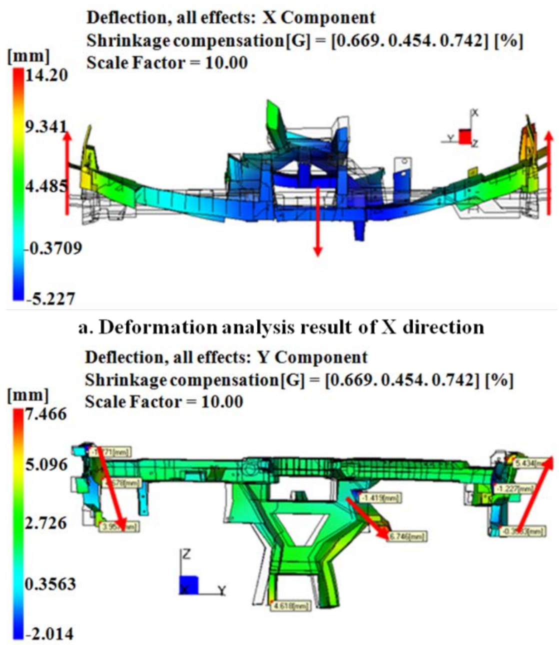
Deformation analyzation

Deformation control is one of the key challenges for large and complex injection molding components. Therefore, deformation analysis must be conducted for CFRP IP carrier body. Mold flow analysis can simulate a series of complicated processes that the material undergoes during the injection molding and can enable deformation analysis to be used to assess the deformation of the steering column support assembly body. The finite element (FE) model used for mold flow analysis was meshed into 16,795 3-D midplane elements. The parameters of the material used for the analysis are listed in Table 1.

Table 1. The parameters of carbon fiber reinforced PA66 for mold flow analysis

Parameter	Carbon Fiber Reinforced PA66
Density (g/cm3)	1.37
Melt Flow Index (g/10min)	31.5
Elastic Modulus (MPa)	26531/10704(PA66)
Maximum Shear Rate (1/s)	6000
Melting Temperature (℃)	280-310

The analysis results of the deformation are presented in figure 4. Both ends of the beam are warped in the +X direction and -Z direction, and the middle of the beam is warped in the -X direction and Z direction. The maximum deformation in the X direction is 19.4 mm (Figure 4a), and reaches 13.7 mm in the Z direction (Figure 4b). For the Y direction, the deformation is not uniform, and the maximum deformation is 9.5 mm (Figure 4c). The main deformation should be controlled within 3 mm. Obviously, the deformation of the steering column support assembly body cannot satisfy the requirement.



a. Deformation analysis result of X direction

b. Deformation analysis result of Y direction

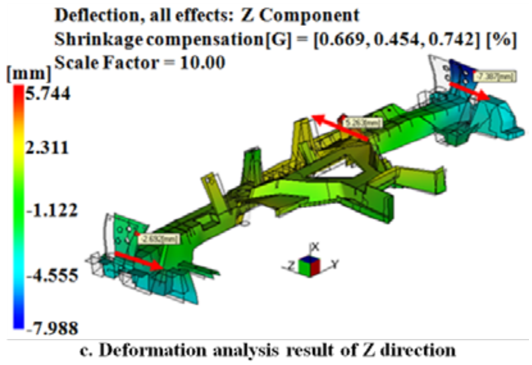
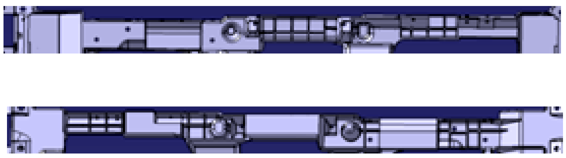
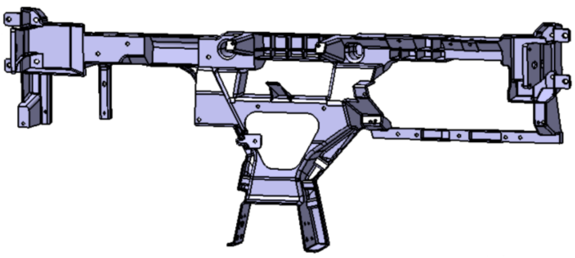


Fig. 4. The warp deformation of the primary structure(a)-(c)

It can be concluded that the deformation of the beam area is the largest by analyzing the deformation results. The abovementioned structure of the beam is mainly U shape, and the warpage is mainly along the opening direction of the U-shaped beam. Therefore, structural optimization was performed as shown in Figure 5. The U-shaped beam was divided into multiple sections with opposite opening directions of the two adjacent parts (Figure 5a), and then the deformation of the beam could be neutralized to a great extent. For other positions, ribs and flanging structures were added to control the deformation (Figure 5b).



(a) The optimized structure of beam



(b) The optimized structure of body

Fig. 5. The optimized structure of steering column support assembly body(a)-(b)

To verify the optimization, mold flow analysis was performed for the new structure (Figure 6). Only one bracket deformed 5.8 mm in the X direction, which exceeds the requirement (Figure 6a), while the deformations in the Y and Z directions are within 3 mm (Figure 6b and 6c). Therefore, the optimized structure can satisfy the requirement. The final structure of the CFRC steering column support assembly is determined as shown in Figure 7.

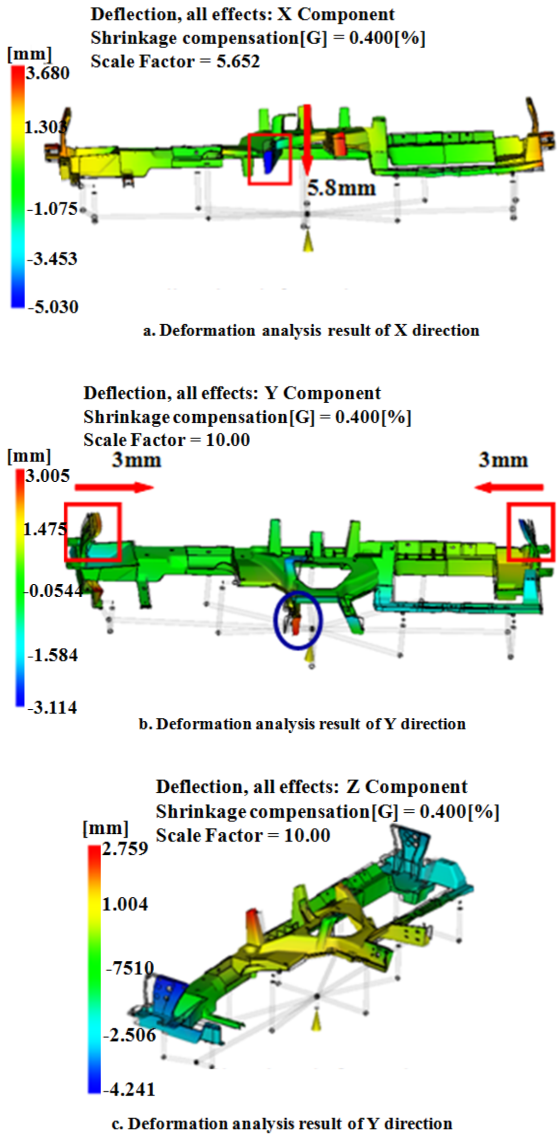


Fig. 6. The warp deformation of the final structure(a)-(c)

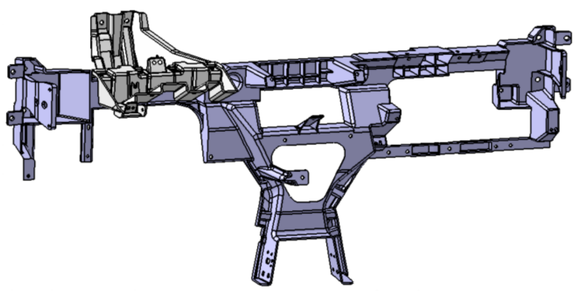


Fig. 7. The final structure of CFRP steering column support assembly

MATERIALS

The types of fibers used range from simple overlapped plies of carbon or glass fiber to very complex braided textiles. The matrix material also varies from vinyl esters, thermoplastics and epoxies.

The material selection must be based on the performance requirement, structure and so on. Due to the attached components, especially the steering column, stiffness and modulus performance are of great importance for the materials used. Therefore, according to the requirements of materials, process and structure, 30 wt% carbon fiber reinforced PA66 (PA66-30%CF) was selected to develop the steering column support assembly. The properties of the materials for selection are presented in Table 2.

Table 2. Mechanical property of composite materials

Composite Material	Density (g/cm^3)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
PA66-30 wt%CF	1.32	323	32.8	506	30.8
PA66-20 wt%CF	1.22	230	17	320	14
PA66-40 wt%LGF	1.4	260	13	/	/

CAE ANALYSIS

CAE analysis is necessary to predict the performance of the final structure. In addition to the NVH requirements, the composite steering column support assembly must satisfy the safety standard for the interior fittings of passenger cars. Then, NVH analysis and interior fitting analysis of the IP system were performed to validate the composite steering column support assembly.

NVH analysis

For steering column support assembly, NVH performance essentially concentrates on the analysis of the assembly natural frequency, reflecting the oscillation of the steering wheel in the driver’ s hands. Therefore, a steering system model analysis was performed. Moreover, a vibration transmission function (VTF) analysis was conducted to evaluate the oscillation of the steering wheel.

Steering system mode analysis: For carbon fiber-reinforced PA66 of the steering column support assembly using injection molding, the material properties were anisotropic. The properties at different positions may be significantly different depending on the material flow direction. An analysis model of the composite steering column support assembly was obtained using mold-flow analysis, and then the model was attributed to the BIW model. The system mode analysis result (Figure 8 and Table 3) was as follows.

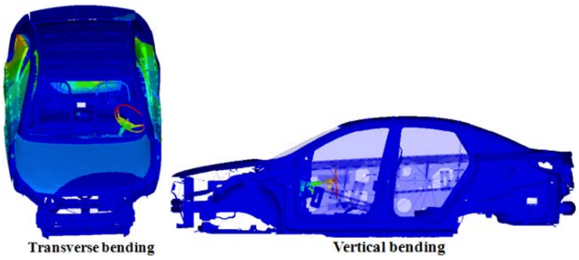


Fig. 8. Steering system mode analysis result

Table 3. Steering system mode analysis result

Analysis mode	Result	Compared steel part
First order vertical bending/Hz	22.6	34
First order transverse bending /Hz	33.2	38

The analysis results demonstrates that the modal values of the composite steering column support assembly were lower than those of the steel part. However, the damping of the composite material is higher than that of the steel material. Therefore, the modal requirement of the composite part should be lower than that of the metal part. Modal tests must be conducted to determine if the modal performance and the accuracy of the modal analysis can satisfy the requirements.

VTF analysis: To evaluate the vibration response sensitivity of the steering wheel, VTF analysis was conducted. These key points of the BIW were excited, and the vibration response of point 1 (X and Z direction) and point 2 (Y direction) on the steering wheel (Figure 9) was calculated. The analysis results (Table 4) show that the vibration response of the steering wheel is within the requirement.

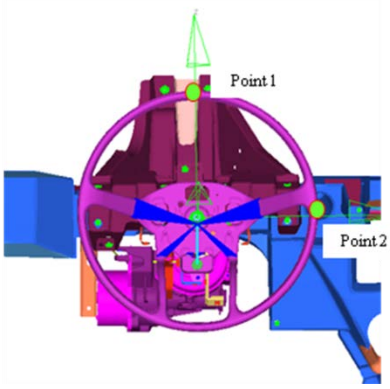


Fig. 9. The analysis point of steering wheel

Interior fittings analysis: Interior fitting analysis was conducted to predict whether the IP system with the composite steering column support assembly can satisfy the safety standard of passenger cars interior fittings.

Table 4. VTF analysis result

Excited point	Max accerleration (mm/s^2)			requirement
	Point 1		Point 2	
	X	Z	Y	
Left front support mounting point	42	19.4	37.4	<100
Right front support mounting point	21.2	20.3	30.3	
Left front suspension arm front mounting point	22.5	36.8	45.3	
Right front suspension arm front mounting point	43.6	25.3	27.6	
Left front suspension arm rear mounting point	36	18.3	28.2	
Right front suspension arm rear mounting point	24.7	16.4	24.5	
Left rear coil spring mounting point	27.2	26	31.8	
Right rear coil spring mounting point	20.5	11.2	28.1	
Left rear shock absorber mounting point	29.6	22	28	
Right rear shock absorber mounting point	20.8	12.3	26.2	
Left rear vertical arm mounting point	31.3	23.2	28.3	
Right rear vertical arm mounting point	22.3	13.2	19.3	
Engine left mounting	39.6	44.2	27.8	
Engine right mounting	28.7	21	19.5	
Engine front mounting	26.3	36.9	18.5	
Engine rear mounting	29.3	23.8	26.9	

Ball drop testing analysis was carried out for three key points (Figure 10), with a ball impact velocity of 24.1 km/h and an impact direction normal to the IP surface. Then, the acceleration vs. time curve within 30 ms was calculated. The results (Table 5) show that the maximum acceleration of the ball for these three points within 30 ms can satisfy the requirements.

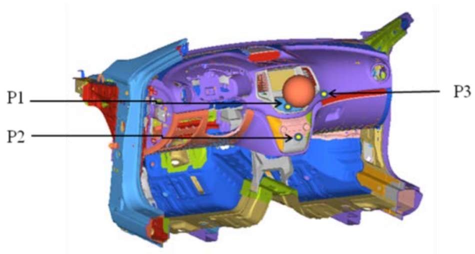


Fig. 10. The interior fitting analysis of steering column support assembly system

Table 5. The interior fitting analysis result

Crashing point	Acceleration at 3ms (g)	Time of acceleration exceed 80 g (ms)
P1	62.1	0
P2	47.6	0
P3	66.1	0
Requirement	<80	<3

MANUFACTURING OF CFRP STEERING COLUMN SUPPORT ASSEMBLY

Because of these advantages in terms of high styling freedom, high productivity and low cost, injection molding has been selected to develop the CFRP steering column support assembly. By now, glass fiber composites and natural fiber composites have mostly been used for injection molding parts in the automotive industry. Only the screw needed to undergo some changes when 30 wt% carbon fiber-reinforced PA66 was used. By molding-flow analysis, the manufacturing parameters were obtained (Table 6).

Table 6. Molding process parameter

Process parameters	Value
Mold Temperature (℃)	105
Melt Temperature (℃)	295
Filling Time (s)	3.27
V/P Conversion	99%
Cooling Time (s)	20
Injection Pressure(MPa)	93.8
Packing Pressure(T)	>1716
Shot Size(kg)	4.2

The manufactured prototype is shown in figure 11, and the weights of the IP carrier body and steering column bracket assembly are 3 kg and 1.1 kg, respectively.

Fig. 11. The manufactured prototype of the CFRP steering column support assembly

TEST

Various tests were performed to evaluate the performance of the manufactured CFRP steering column support assembly and the rationality of the CAE analysis.

Tests for deformation control

To evaluate the deformation control of the optimized design, a 3D scanning test and vehicle assembly were conducted.

3D Scanning Test: After the prototype is manufactured, 3D scanning test is usually used to evaluate the dimensional accuracy. The test results demonstrates that the deformation of the main position is controlled within 3 mm, and larger deformation positions are at the edge (Figure 12). Deviations controlled within 3 mm are above 90% (Figure 13).

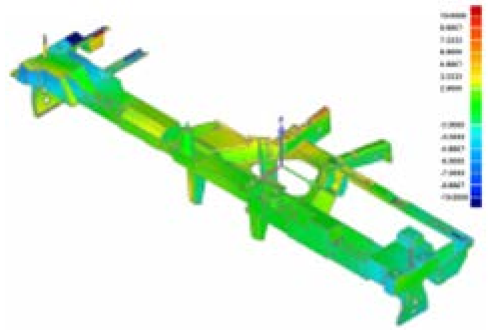


Fig. 12. 3D scanning test

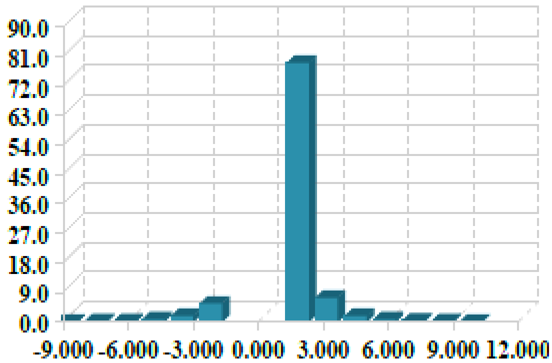


Fig. 13. Statistics of 3D scanning test result (Ding et al., 2017)

Vehicle Assembling: Although the deformation of some positions exceeds 3 mm, the deformation control can still satisfy the requirements. Therefore, the vehicle assembling test was conducted. The carbon fiber reinforced component can be assembled into a vehicle successfully (Figure 14).

Fig. 14. Vehicle assembly of steering column support assembly

The 3D scanning and vehicle assembling tests demonstrates that the structural optimization method is reasonable, and the final structure can satisfy the requirements. The structural controlling requirements for the composite part can be revised: The deformation of the main area should be controlled within 3 mm, and the deformation of the edge bracket part should be controlled within 6 mm.

NVH performance verification

The steering system mode test and NVH test were conducted to evaluate the NVH performance.

Steering system mode test: To verify the steering system mode analysis, the steering system mode test was performed on the four points of the steering wheel (Figure 15). The test result (Table 7) is in good agreement with the analysis result and demonstrates that the analysis mode used is reasonable.

Fig. 15. The steering system mode test

Table 7. The steering system mode test result

Vibration Mode	Test result	Analysis result
First Order Vertical bending (Hz)	22.6	22.6
First Order Transverse bending (Hz)	30.7	33.2

NVH test: As the air-conditioning system, central console, airbags and, and especially the steering-wheel system, were fixed on the CFRC steering column support assembly, vehicle NVH tests had to be conducted to verify the impact of the composite parts on the NVH performance of the vehicle. The test results demonstrates that the interior vehicle sound pressure level at most locations is better than that of the reference vehicle (Figure 16). Only in the sliding noise condition is the test value of the test vehicle is a little higher, but this is acceptable (Table 8). The wheel vibration and seat guide rail vibration amplitude of the test vehicle are lower than those of the reference vehicle (Figure 17).

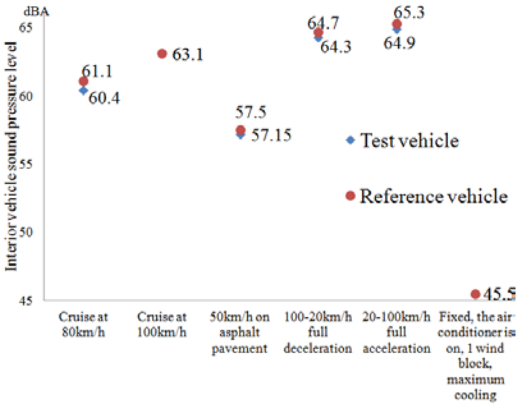


Fig. 16. Vehicle interior noise test

Table 8. Vehicle silding noise test

Noise Test	Sliding Noise, 30-80km/h	
	FLR (dBA)	FLR (AI%)
Test Vehicle	61.13-54.89	130.66-94.29
Reference Vehicle	61.1-53.7	131-94.2

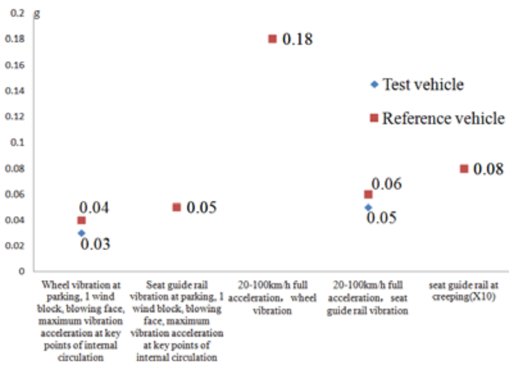


Fig. 17. Vehicle vibration test

The test results also demonstrate that the high damping of CFRC has a good effect on the NVH performance of CFRC steering column support assembly, and that for composite material, a significantly lower first natural frequency compared to metal can be accepted with an equivalent or better NVH performance, and it is not necessary to provide an equivalent stiffness.

The interior fitting test

The interior fitting test (Figure 18) was conducted by imposing 3 impact points as the analysis points. The test results (Table 9) demonstrates that the CFRP steering column support assembly can satisfy the IP system interior fitting requirements. Although the test results are not in very good agreement with the analysis results, the windage is acceptable.

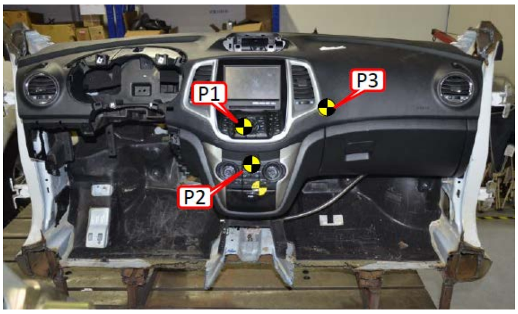


Fig. 18. The interior fitting test

Table 9. The interior fitting test result

Testing point	Ball velocity (km/h)	Max acceleration (g)	Acceleration at 3ms (g)	Analysis result (g)
P1	24.16	61.2	47.7	62.1
P2	24.55	52.8	40.9	47.6
P3	24.21	57.1	47.5	66.1

Four poster test

The strength and durability performance of the CFRP steering column support assembly should be verified and a vehicle 4 poster test was conducted. The driving signals for this test were derived from vehicle service road data. There were cracks and fractures were confirmed on the test specimen, and the CFRP steering column support assembly could satisfy the strength and durability performance requirements.

The manufactured CFRP steering column support assembly can not only satisfy the part verification tests but also the durability test. This means that the fabricated composite part can be mass produced with great potential. The development process can be extended to other complex functional components.

WEIGHT REDUCTION AND COST ANALYSIS

The weight of the 30 wt% carbon fiber reinforced PA66 steering column support assembly is 4.1 kg. Compared to the steel part (8.3 kg), the weight reduction is 4.2 kg, and the rate of weight reduction is 50.6%. The composite steering column support assembly can achieve more weight reduction than other lightweight technologies, such as aluminum alloy components with a weight reduction rate of 30%-40% and magnesium alloy components with a weight reduction rate of approximately 50%.

Due to the high cost of material, the cost of the 30 wt% carbon fiber reinforced PA66 steering column support assembly is much higher than that of the steel component and is comparatively to that of the magnesium alloy component. However, the cost of the material accounts for over 75% of the overall cost of the composite component. As the cost of the carbon fiber composite will decrease substantially in the future, the cost of the CFRP steering column support assembly will decrease accordingly. Thus, CFRP steering column support assembly using injection molding will be an ideal choice for original equipment manufacturers (OEMs) and will be widely used in the future.

CONCLUSIONS

Composite functional parts are increasingly used in automotive and aerospace due to their excellent performance. Injection molding is an ideal selection because it allows parts to be manufactured with extremely high productivity and low cost. In this study, a CFRP steering column support assembly was successfully developed using injection molding technology. According to the CAE analysis and experimental results discussed in this study, the following conclusions can be drawn: (1) The results obtained in this study are very practical and provide the great potential for application in the automotive industry for complex functional parts development since they can be used efficiently and effectively for manufacturing in relation to the development stage. (2) Detailed structure is obtained using topology optimization and mold flow analysis. The warpage and shrinkage deformations can satisfy the requirements. The CAE analysis results are in good agreement with the text results, which verifies that the CAE analysis methods are reasonable. (3) The weight of the manufactured composite steering column support assembly is 4.1 kg, and the weight reduction is 4.2 kg compared to the steel part. The component can satisfy these performance requirements. Due to the excellent damping properties, the mode of the composite component can be at least 7 Hz lower than that of the metal component. (4) The cost of the composite material and production using injection molding technology can be further reduced. The cost of CFRP steering column support assembly will be accepted by most OEMs, and this part will be extensively applied.

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複合材料轉向支撐系統總成注塑成型性能研究

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摘 要

本文旨在探討純電動汽車碳纖維增強複合材料轉向支撐系統總成的開發研究。鑒於碳纖維複合材料的優異的輕量化優勢，已被應用於汽車和航空航太領域。為了提升管生產效率和降低成本，應用注塑工藝開發複合材料複雜結構功能件是非常有必要的。本文首次完成了純注塑碳纖維複合材料轉向支撐系統總成複雜結構功能件的開發，發現PA66-30%CF 材料是合適的，綜合應用拓撲優化和模流分析，部件的主要變形可以控制在3mm 以內。CAE 分析結果能夠和試驗結果匹配。製造的部件可以滿足性能要求，由於複合材料優異的阻尼性能，複合部件的模態能夠比金屬部件至少低 7Hz 以上。部件重 4.1kg，實現了 4.2kg 的減重，減重率高於50%。