

Development of Rear Bumper Beam Using Thermoplastic Glass Fiber-reinforced Plastic

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ABSTRACT

Parts design technology that uses thermoplastic glass fiber-reinforced plastic with high-impact strength was developed to reduce the rear bumper beam weight. Both continuous fiber that provides good impact resistance and chopped fiber that is advantageous for molding complex shapes were applied to create the ideal impact-resistant design for the rear bumper beam. Short process molding technology was also developed that can simultaneously mold three types of materials with different fiber formats in the same mold in order to reduce parts weight and cost. In addition, the influence of the rib shape on product performance in this molding process was clarified, and design technology that reduces that influence was concurrently developed.

The developed technology was applied to the rear bumper beam that is part of the frame of a mass-production vehicle, and enabled a reduction of the weight by 46% and the number of parts, except for fastening parts, to 1/9 that of the previous model.

1. Introduction

Regulation of CO₂ emissions produced during vehicle operation is increasing in stringency worldwide as a means of addressing the issue of global warming. As a result, it is not enough to simply increase the fuel economy of powertrains, and reduction of the overall operating energy of vehicles is an urgent task. One means for achieving this is to reduce the body weight.

In particular, the bumper beams used in the front and rear of vehicles are heavy parts consisting of a beam that absorbs impacts by bending with torsional deformation and crush boxes that absorb impacts by axial collapsing. In addition, bumper beams are positioned at the front and rear of vehicles, so they have a large influence on not just fuel economy performance, but also handling stability. Automotive manufacturers are conducting R&D to reduce weights and cost⁽¹⁾, but there are limits to the weight reduction that can be achieved assuming the use of metallic materials such as steel plate (SP) and aluminum (AL).

There are cases of using fiber-reinforced plastic (FRP) material to reduce weight, but the applicable models are limited in terms of productivity and cost. Thermoplastic FRP that uses thermoplastic resin as the base material has better productivity and recyclability compared to conventional thermoset FRP, and extensive research is being performed on these materials⁽²⁾.

Thermoplastic FRP has a higher material cost than metallic materials such as SP and AL, or fiber-reinforced

pellets for injection molding. In addition, compression molding of continuous fiber-reinforced materials can form only simple shapes on the same level as SP pressed material, so it is necessary to assemble multiple parts. Furthermore, molding systems used to mold thermoplastic FRP entail great investment and need more dies to mold the same part configurations compared to SP. These factors all increase the cost.

Therefore, the authors investigated a combination of base material and reinforcing fiber from the viewpoint of cost relative to the bumper beam performance requirements in order to reduce material costs, and developed both a large integrated structure that enables a reduction in the number of parts and molding technology for manufacturing that structure. The thermoplastic FRP bumper beam developed using these technologies was used in CLARITY FUEL CELL (FCV).

2. Material Selection

Table 1 shows the results of axial collapse tests using various materials. This table shows that FRP has better specific strength and impact energy characteristics than SP and AL. Carbon fiber-reinforced plastic (CFRP) in particular exhibits a high performance but is also high cost. In comparison, glass fiber-reinforced plastic (GFRP) offers better cost effectiveness. Therefore, this development selected thermoplastic GFRP.

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Table 1 Performances and costs of various materials

Material	Molding method	Specific stiffness	Specific tensile strength	Specific energy absorption	Cost
		GPa/ ρ	MPa/ ρ	J/g	
SP (JSC270C)	Press	26	35	6	1
AL (A6063 T7)	Extrusion	26	89	17	3
GF/PA6 continuous FRP	Press	12	224	45	5
CF/PA6 continuous FRP	Press	38	560	61	30

ρ : specific gravity PA: polyamide

3. Structure and Manufacturing Method

3.1. Structural Concept

FRP that uses thermoplastic resin as the base material exhibits a different material performance according to the reinforcing fiber format. FRP fiber formats include continuous fiber material that has high strength and stiffness, and chopped fiber material that increases the degree of molding freedom by chopping the fibers, making it suitable for complex shapes. Figure 1 shows the relationship between the thermoplastic FRP fiber length and various performances (modulus of elasticity, static strength, impact strength)⁽³⁾. The fiber length is strongly related to static strength and impact strength. However, the degree of molding freedom decreases as the fiber length increases, which calls for a selection of materials suited to the application.

Continuous fiber-reinforced material was used in the main bumper beam member that needs both strength and stiffness in consideration of the property requirements. In addition, chopped fiber-reinforced material with a fiber length of 30 mm or more that can be used for compression molding was used in reinforcing shape locations with complex shapes, such as ribs, that need stiffness more than

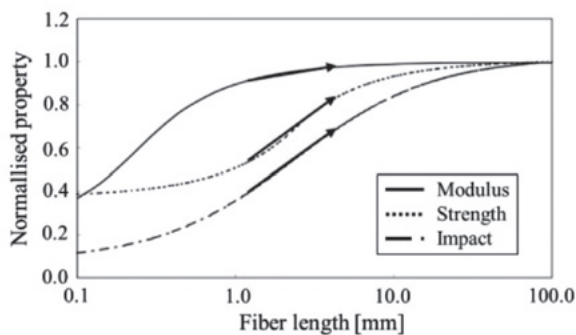


Fig. 1 Influence of fiber length on mechanical properties

strength. It was thought that this structural concept could satisfy the property requirements of each member. Open sections have lower stiffness and strength with regards to member bending deformation, so it was thought that the two-part configuration with a normally closed section could be integrated into a single part. Figure 2 shows an image of this concept.

3.2. Molding Concept

Integrated molding of parts, including the ribs, was achieved by simultaneously compression molding continuous fiber-reinforced material and chopped long fiber-reinforced material, with a fiber length of 30 mm to 50 mm, as the molding process for realizing the structural concept (Fig. 3). After compression molding, injection molding is performed to the parts periphery to add supplemental shapes that tolerate an elongation of portions that cannot be molded using continuous fiber-reinforced material, and to reduce secondary processing such as deburring of the parts periphery.

In addition, when molding 3-dimensional structures using the conventional method, it is necessary to set preformed reinforced-plastic material in the rib areas inside the die and perform re-molding. However, the developed method realizes one-shot molding after setting the necessary materials. This shortens the series of molding processes and helps eliminate incidental preforming dies, which also reduces costs.

3.3. Performance Requirements and Issues for Integrated Molding

3.3.1. Change in physical properties after compression molding of chopped fiber materials

To achieve the molding concept described above, it is necessary to understand the flow of chopped long fiber-reinforced material during compression molding and apply this to design. Therefore, a compression molding test was performed using chopped long fiber-reinforced material. Test pieces were cut from the rib molding test piece at different heights as shown by the red frames in Fig. 4, and tensile tests were performed. Comparison of the top and bottom areas of the rib showed that while there was little difference in the tensile test piece density, the tensile

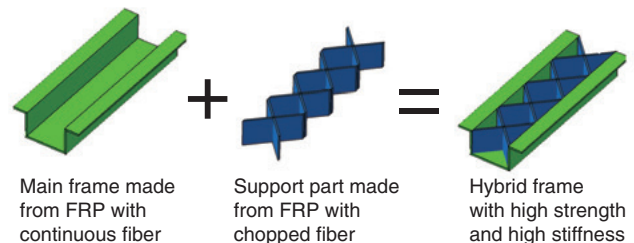


Fig. 2 Material composition concept

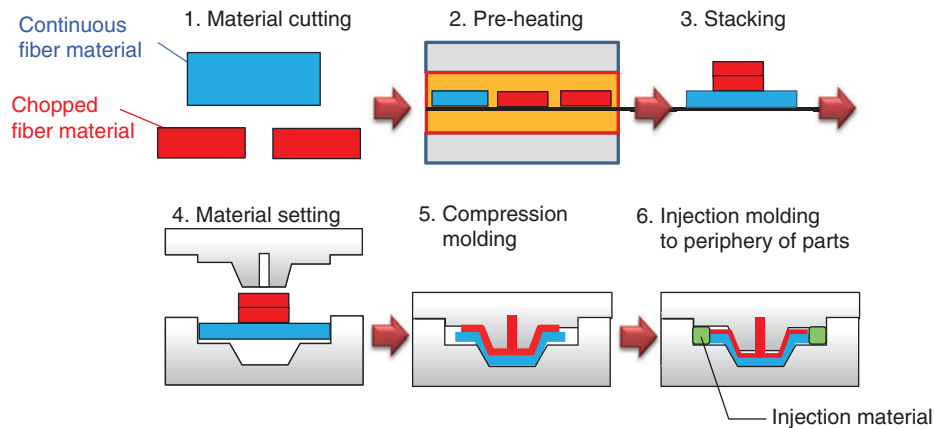


Fig. 3 Molding process

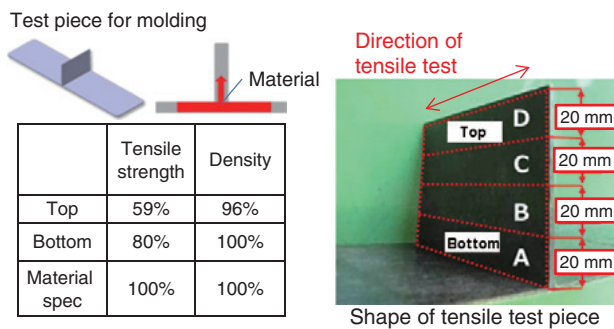


Fig. 4 Test of rib shape molded by compression molding

material flows due to compression molding, and performed molding tests. Figure 7 shows the compression molding test piece and the method of cutting out the tensile test pieces. In addition, Table 2 shows the relationship between two different rib shapes and the tensile strength. Figure 8 shows these two different rib shapes and the rupture start points. The test results showed that increasing the draft angle and the fillet R size, such as in Case 2, helps the plastic to flow more easily and reduces continuous fiber meandering, effectively increasing the strength. In this manner, both the fluid and mechanical properties were investigated when determining the product shape, and the results were reflected in the bumper beam shape design.

strength was lower at the top of the rib. Figure 5 shows the condition of the remaining fibers after heating the test piece to bake the resin. Long fibers remain at the bottom of the rib, but many shorter fibers can be seen at the top of the rib. Figure 6 shows the results of investigating the fiber length distribution at different heights of the above-mentioned rib molding test piece. This shows that fibers with a fiber length of 10 mm or less increase from the bottom towards the top of the rib. These test results revealed the rib height that can provide the needed base material performance, which enabled optimization of the shape.

3.3.2. Drop in strength when continuous fiber and chopped fiber materials are simultaneously molded

The developed manufacturing method simultaneously compression molds continuous fiber-reinforced material and chopped fiber-reinforced material. However, when the chopped fiber plastic flows due to the compression, the continuous fiber sometimes meanders according to the flow of the plastic. This phenomenon may result in a loss of continuous fiber-material linearity, leading to a drop in part stiffness and strength. The authors focused on the shear resistance generated when chopped fiber-reinforced

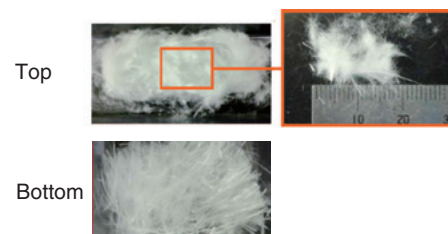


Fig. 5 Fiber distribution in rib after baking base resin

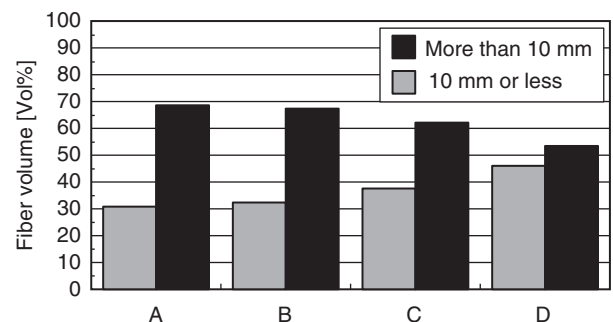


Fig. 6 Distribution of fiber contents in rib shape by compression molding

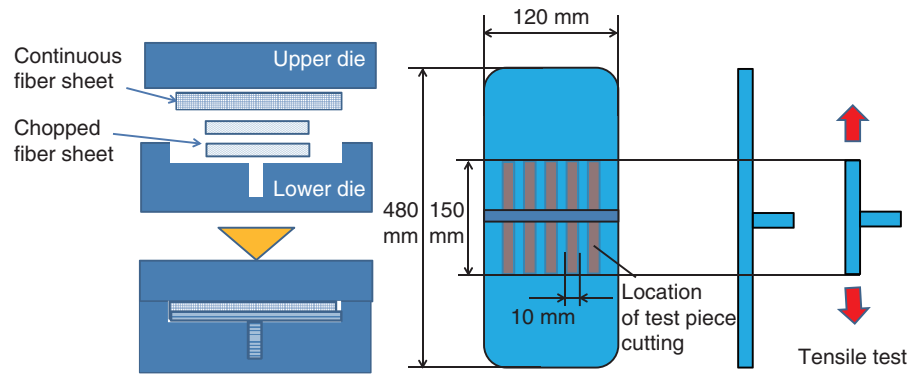


Fig. 7 Test piece molding method

Table 2 Relationship between fillet R at bottom of rib and tensile strength

	No rib	Case 1	Case 2
t : thickness [mm]	-	2.5	2.5
θ : draft angle [°]	-	0.5	1.5
R : fillet R [mm]	-	0.5	2
Strength index	1.0	0.41	1.06

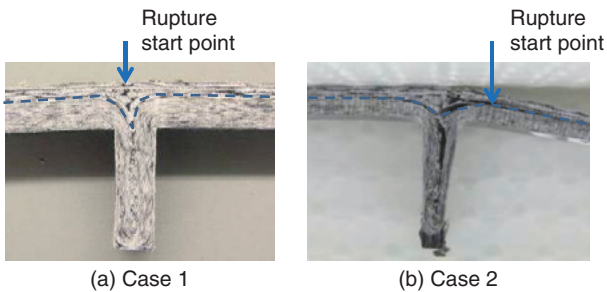
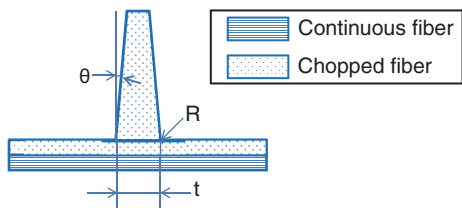


Fig. 8 Shape of rib test piece and location of rupture start in tensile test

4. Application to Rear Bumper Beam

Figure 9 shows the thermoplastic GFRP rear bumper beam, with the structure designed using the developed technology, and its location in CLARITY FUEL CELL. Figure 10 shows the structure and the material composition.

Figure 11 shows the relative positions of the bumper beam and the test jig in the Part 581 test of the U.S. Federal Motor Vehicle Safety Standards (FMVSS) for low-speed crashes. The structure positions hybrid structures consisting of high-strength continuous fiber-reinforced plastic and chopped fiber-reinforced plastic with a long fiber length at locations where a bending moment is generated. The test mode that applies a load from outside the vehicle can be addressed by the compression performance of the member instead of the moment. Therefore, supplementing the shape



Fig. 9 Thermoplastic GFRP rear bumper beam and location in CLARITY FUEL CELL

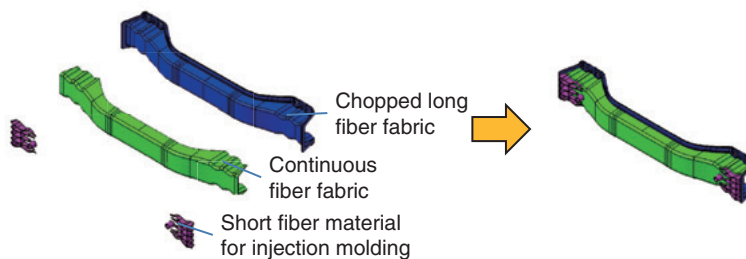


Fig. 10 Material composition of rear bumper beam

with injection molding materials that include low-strength glass-fiber filler can enhance the continuous fiber material yield, which helps to reduce the cost.

As a result of parts integration, the basic section of the bumper beam has a hat shape with an open section. When a beam with an open section receives a bending moment, the section opens further according to the input load, which lowers the stiffness and strength. This was addressed by positioning chopped fiber materials on the rear side of the beam and setting ribs as shown in Fig. 10. Figure 12 shows the test condition of the static load test, and Fig. 13 shows the rupture location at the peak load. The shape was optimized based on the rib investigation results in Section 3.3, and it was confirmed that there was no occurrence of final rupture resulting from a drop in strength at the bottom of the rib.

Figure 14 shows the Part 581 test in an actual vehicle, and Figs. 15 and 16 show the CAE results and the test

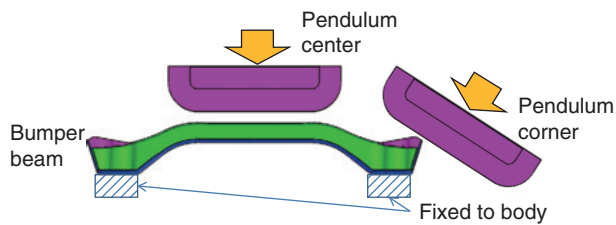


Fig. 11 Position of bumper beam and Part 581 pendulum test

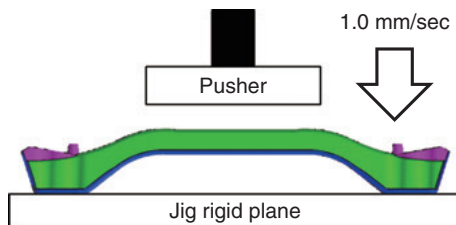


Fig. 12 Test condition of static load test

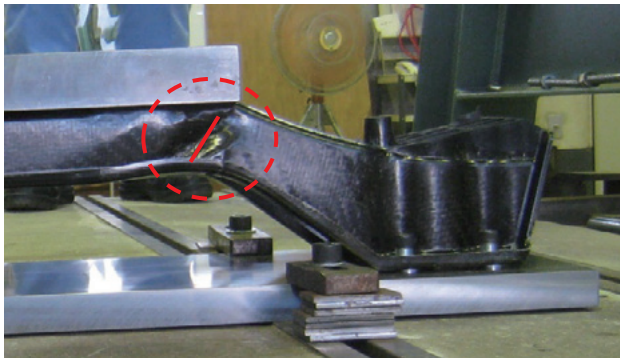


Fig. 13 Location of rupture at the peak load

results. These graphs show that the needed crash energy absorption amount can be obtained at the target deformation distance or less, which confirmed that the developed method provides the same level of performance as that of the previous part.

Figure 17 compares the number of parts with that of the previous rear bumper beam. The developed thermoplastic GFRP rear bumper beam has 1/9 the number of parts and achieved a weight reduction of 46% compared to the previous structure.

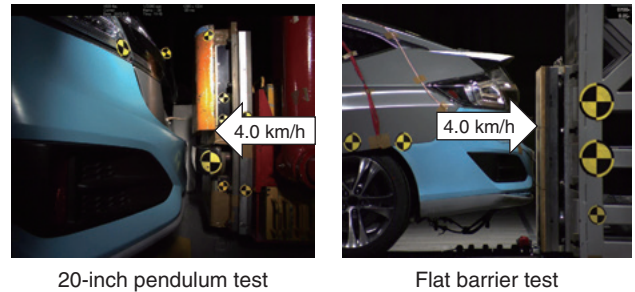


Fig. 14 Part 581 test

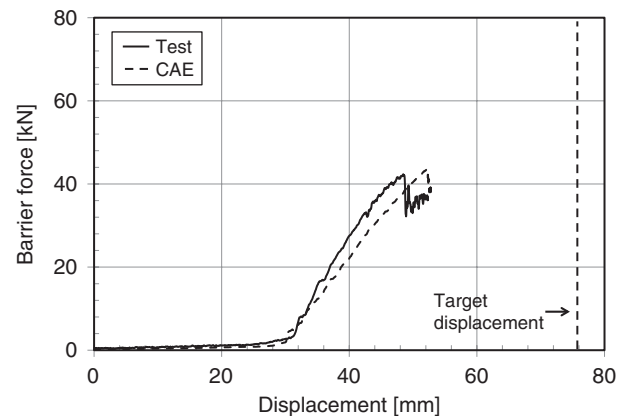


Fig. 15 Comparison of actual test and CAE simulation in Part 581 20-inch pendulum test

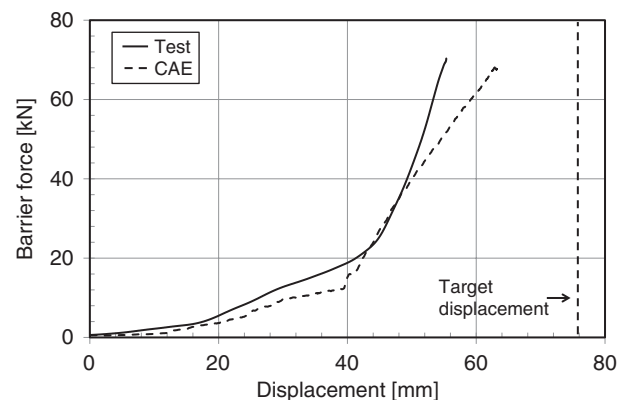


Fig. 16 Comparison of actual test and CAE simulation in Part 581 flat barrier test

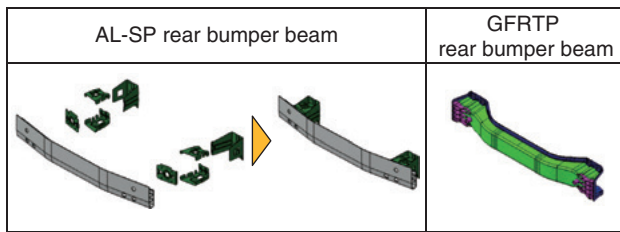


Fig. 17 Comparison of GF RTP rear bumper beam and AL-SP rear bumper beam

5. Conclusion

Parts design technology that uses thermoplastic glass fiber-reinforced plastic was developed to reduce the rear bumper beam weight, and the following findings were obtained.

- (1) A new hybrid molding method was developed that simultaneously compression molds continuous fiber-reinforced material and chopped long fiber-reinforced material, and flows chopped long fiber-reinforced material to the rib areas. This method realizes one-shot molding after setting the necessary materials, which shortens the series of molding processes and helps eliminate incidental preforming dies, which reduces costs.
- (2) Compression molding tests of chopped fiber-reinforced material were performed, and the results clarified the relationship between the rib height and the contained fiber length, which helped to optimize the shape.
- (3) It was found that when continuous fiber-reinforced material and chopped fiber-reinforced material are simultaneously compression molded, the resin flow may result in a loss of continuous fiber-material linearity, leading to a drop in part stiffness and strength. Therefore, the bottom of the rib was changed to a shape that helps the plastic to flow more easily, which reduced the drop in performance.
- (4) Parts integration was achieved by arranging three types of materials with different fiber formats in the appropriate locations and by making use of the degree of molding freedom inherent to plastic. This enabled weight to be reduced by 46% and the number of parts to 1/9 compared to the previous rear bumper beam, while still satisfying the U.S. low speed crash standards.

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