Design of GFRP Engine Mount Frame by Using Topology Optimization

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Abstract. With the help of topology optimization and coupling analysis, the virtual prototyping technology was first used in designing a GFRP engine mount frame. In this design, the topology optimization technology based on a variable density method was introduced in order to reduce the structural weight while having enough stiffness. Then, a design for manufacturability of GFRP engine mount frame was performed on the basis of the instruction of topology optimization. After that, a coupling analysis combined with the fiber orientation was carried out to verify the performance of the designed frame. The result shows that the designed GFRP engine mount frame not only meets the requirement of strength and frequency, but also reduces about half weight compared with the steel frame, which means a significant lightweight effort.

Introduction

The automotive industry is striving to meet targets for reducing fuel consumption and emissions by introducing lightweight vehicle components or even, more recently, by switching to lightweight materials for car body [1].

Glass Fiber-Reinforced Plastic (GFRP) has been used in vehicle industry since the early 60's [2]. Because of the lightweight, high strength and excellent plasticity of GFRP, it is wildly used to make various interior parts in vehicle. With the rapidly development of chemistry technology, the strength of GFRP has been greatly improved, and now it is capable to form the structure components of vehicle which include the frame of engine suspension—the engine mount.

Engine mount is one of the most important parts of the whole powertrain suspension system, and it is the only bridge between engine and chassis, which requires the high effective design of mount frame. To isolate the vibration between engine and suspension system as well as to keep the engine right on the position, the structure of engine mount should have enough stiffness and strength. What's more, the first order modal of engine mount must be at least 500 Hz in order to avoid the resonance with other components in vehicle [3].

The methodology of designing an engine mount by using metal material for front wheel drive vehicle has become very developed. But when it comes with GFRP, things are becoming much difference. Because of its high anisotropy of mechanical properties, the GFRP cannot be designed as usual. In consideration of its complex shape and indeterminacy in evaluating structural responses under service load, a new methodology is needed for designing GFRP components [2].

In this paper, a design method of GFRP engine mount frame is proposed by using topology optimization technology (TOT) and finite element method (FEM). Simultaneously, the fiber orientation is also taken into consideration in design. The goal of this article is to obtain a satisfied GFRP engine mount frame which can meet the requirements of mechanical property of engine mount and save the weight of 50% compared with the traditional steel frame. The present results not only provide a theoretical basis for the design of short glass fiber-reinforced plastic component, but also have great theoretical significance and practical value.

Definition of Original Design Space

Before performing a conceptual structure design based on TOT for GFRP engine mount frame, we first need a geometry model of basic design—an initial design space. The space should cover all possible spaces we can use between the chassis sub-frame and the engine in order to get full use of space in engine compartment.

According to the assembly relationship between mount structure and various components, offered by suppliers (Figs. 1, 2 and 3), we can get a design space by digging out the maximum volume that the engine mount can spare. After that, we can form a reasonable CAD (computer aided design) model for optimal purpose.

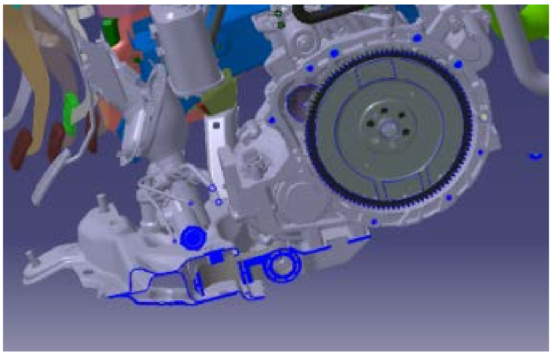


Fig. 1. Assembly relationship

Fig. 2. Initial design space

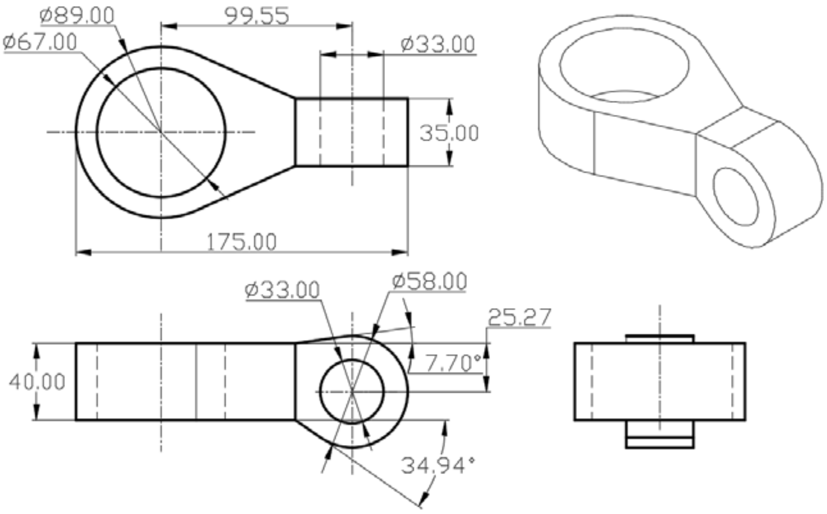


Fig. 3. Blueprint of design space

Topology Optimization Theory

With the above original design space model, we can start to design the detail of GFRP engine mount structure. The design is different from a fussy and sluggish traditional experience design method, while TOT method is faster and more sufficient in structure optimization. With the aid of modern computer technology, by using the numerical mathematic method depended on variable density, it can provide the most reasonable material distribution of structure under the predefined loading conditions, which, of course, not only saves our time in the product development step, but also simultaneously obtains an optimal structure.

The basic idea of topology optimization design is in a given design range to seek an optimal material distribution of structure subjected to load [4]. At present, the main TOTs are variable thickness method, peak function interpolation method, variable density method and homogenization method [5]. The SIMP method of topology optimization [6] assumed that the material density is constant within an element and can be taken as the design variable, while the material properties are simulated by an exponential function concerning element density. In this exponential model, it is assumed that there are some kinds of non-linear relationships between the density and elastic modulus of material, which are as follows:

$$E = \rho^{\alpha} E_0 \tag{1}$$

$$\nu = \nu_0 \tag{2}$$

$$\rho = \rho_i \rho_0 \tag{3}$$

where, E, ν and ρ respectively are the elasticity modulus, Poisson ratio and density of a material used in simulation; and ρ_0 is the inherent density, E_0 is the elasticity modulus of real material when $\alpha > 1$, and ρ_i is the relative density for each element and it is the design variable for TOT as well. The material data of GFRP used in simulation are listed in Table 1.

With the above relationships, by taking the weighted total flexibility of structure of minimization (stiffness and strain energy of maximization) as the optimal object function and the volume constraint of whole structure as the constraint condition of optimization, the mathematical model [7] of variable density method can be expressed as:

$$\underset{x=\{x_1, x_2, \ldots, x_n\}}{\text{Minmize}}\ C(x) = \{U\}^{\mathrm{T}}[K]\{U\} \tag{4}$$

$$s.t. \begin{cases} \sum_{j-1}^{n} V_j x_j - \overline{V} \leq 0, \\ 0 < x_{\min} \leq x_j < 1 \quad (j = 1, 2, \cdots, n), \\ Equilibriu \quad m \quad equations. \end{cases} \tag{5}$$

where, [K] is the stiffness matrix of system, {U} is the displacement vector of structure (in order to avoid the singularity of total stiffness matrix, taken $x_{\min}$=0.001), n is the number of elements, V_i is the volume of No. j element, V is the setting material volume, and $C(x)$ is the flexibility of structure.

With the above theory, following the rapid process of iteration, the number of elements that the density value is less than ε accumulates continuously. As result, the total volume structure decreases gradually. As long as the volume constraint reaches a predefined value, the iteration procedure of topology optimization is considered as convergence. In these results, all elements that the density value is greater than ε will be reserved. The region formed by these elements is just the result of topology optimization.

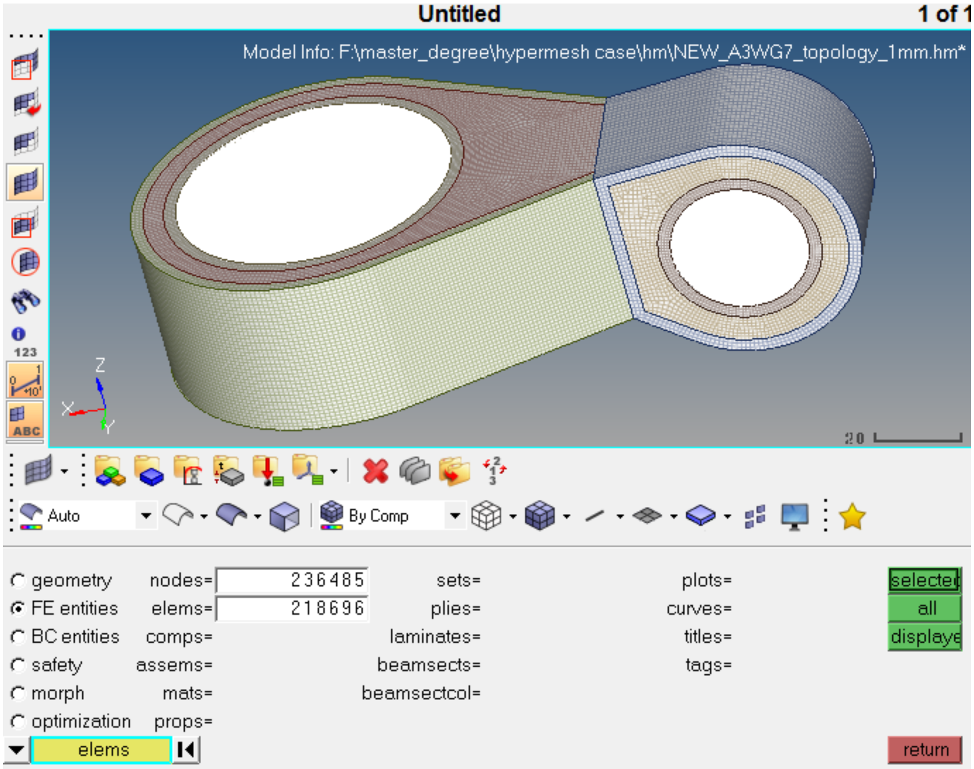
Table 1. Material data of GFRP

Polymer		Glass fiber	
ρ [g/cm^3]	1.14	ρ [g /cm^3]	2.54
E [MPa]	3000	E [MPa]	72000
ν	0.37	ν	0.22
μ-structure			
Mass fraction	30% of GF	Aspect ratio	25
Orientation	Fixed	Inclusion shape	Sphero-cylinder
RVE size [mm]	(5,5,2)		

Mesh Generation and Topology Optimization Solution

In order to obtain the accurate topology optimization results for GFRP engine mount frame, a hexahedral element is introduced to mesh the original design space (Fig. 4). To eliminate the random error brought by the oversized elements, the average element size is restricted to 1mm compared with the constraint of 3mm average width of engine mount. As we can see from Fig 4, we get 218696 hexahedron elements which meet requirements to operate the topology optimization and all operations below are performed in the software Optistruct®.

Assuming that the material of this frame is PA66GF35, whose density is 1.41g/cm^3. Before beginning to operate the optimization task, we should predefine the optimized regional space and the non-optimum space to distinguish that the materials of which regions will need to perform topology optimization and the others will need to remain (Fig. 5).



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Model Info: F:\master_degree\hypermesh case\hm\NEW_A3WG7_topology_1mm.hm*

○ geometry
● FE entities
○ BC entities
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○ morph
○ optimization

nodes= 236485
elems= 218696

Fig. 4. Mesh statue of original design space

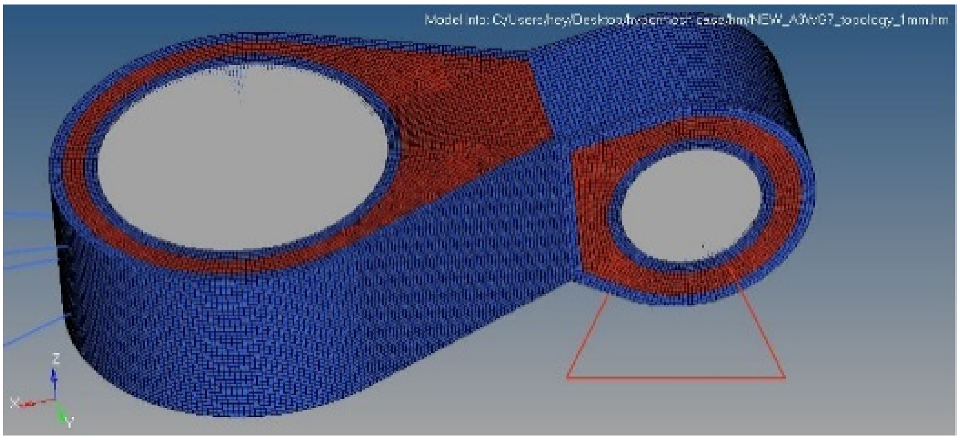

Fig. 5. The optimizing region (red)

Generally, there are three key factors of topology optimization, the design variable, the design object and the constraint. In this case, we take the density of each element as the design variable and constrain the optimized volume friction to 30% of the original design space. Considering the limits of the actual manufacturing technology, the draft direction constraint and symmetrical constraint have been added while the design object is defined as the minimum total strain energy of engine mount frame. Using MPC (multiple point coupling) method, the force is applied on the left internal cylinder according to the supplier's work demands, and the six degrees of freedom on right cylindrical surface are restrained. After completing above all steps, the iterative calculation of optimization is carried out. When completing 53 iterations, the object function shows convergence, and the results are shown in Figs. 6 and 7.

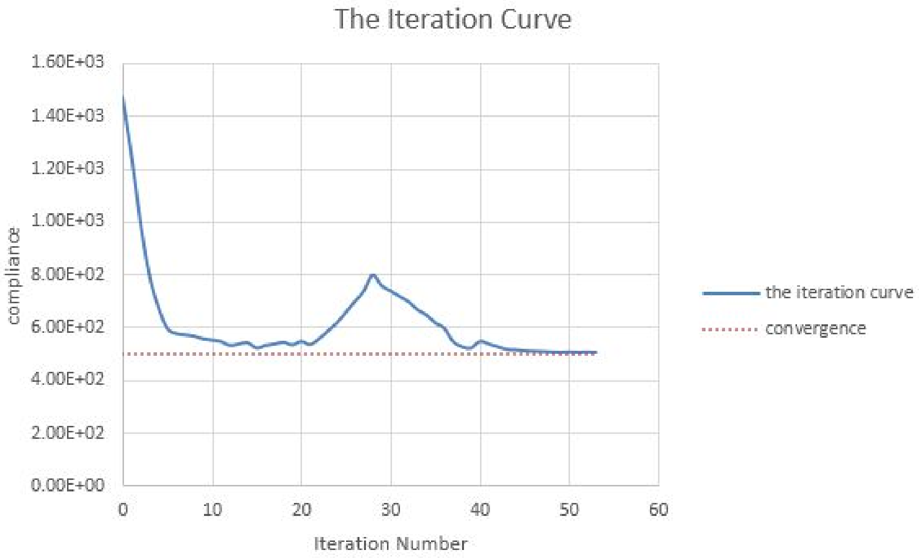

Fig. 6. Iteration curve

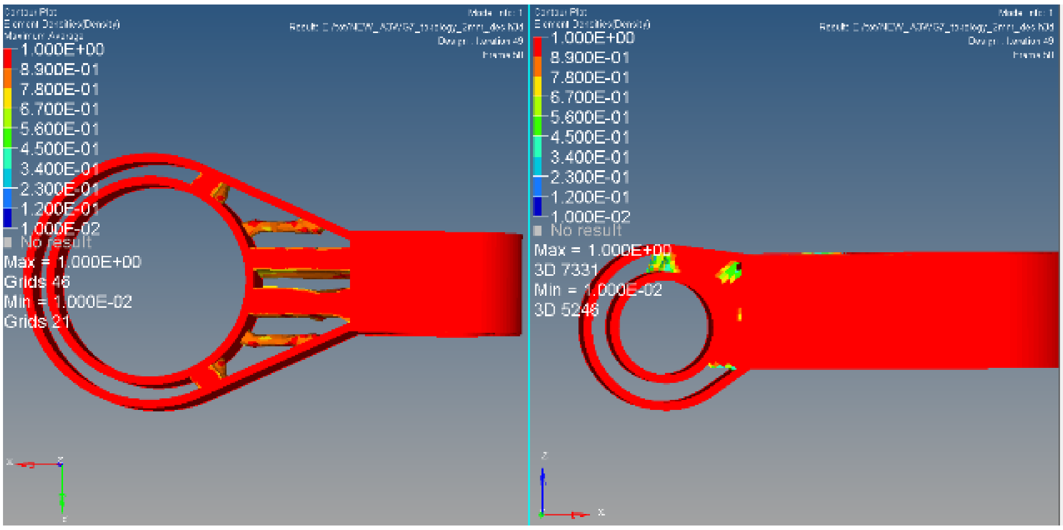

Fig. 7. Density distribution after optimization

Formable Design and Coupling Analysis

In order to make the frame design more formable, we need to redesign the GFRP engine mount frame based on the results of topology optimization. After all of manufacturable demands are considered, the formable structure of engine mount is redesigned, as shown in Fig. 8, and its stress distribution is shown in Fig. 9.

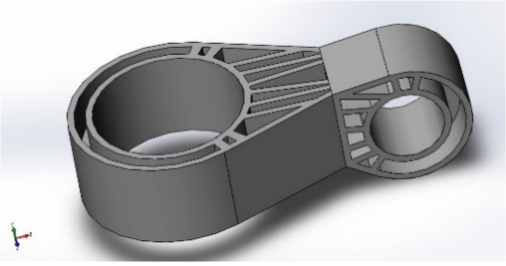

Fig. 8. Formable design

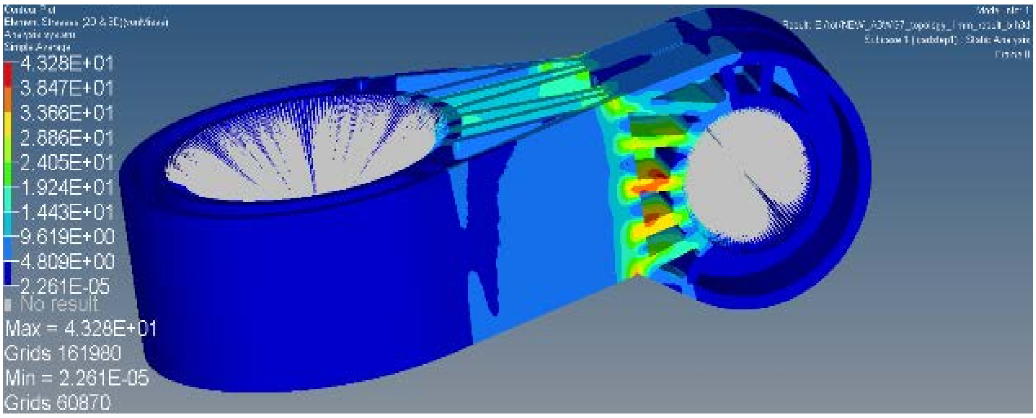

Fig. 9. Stress distribution of frame

Because the used GFRP is an anisotropic material, it shows a strong connectivity between the fiber orientation distribution and the mechanical performance [8]. It is very important to perform a coupling simulation for the designed frame according to inner fiber orientation shown in Figs. 10 and 11. Thus, when the fiber orientation is considered in FEA, we can obtain a more precise result of FEA of the GFRP engine mount by using coupling analysis. For this purpose, we use the software MoldFlow® to get the fiber orientation tensor while using Abaqus® software to do FEA for GFRP engine mount frame. The simulation is operated under the environment temperature at 50℃. The result is shown in Fig. 12.

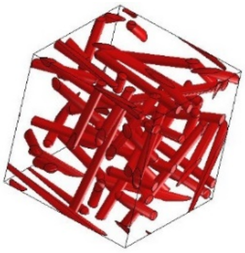

Fig. 10. Microstructure of GFRP

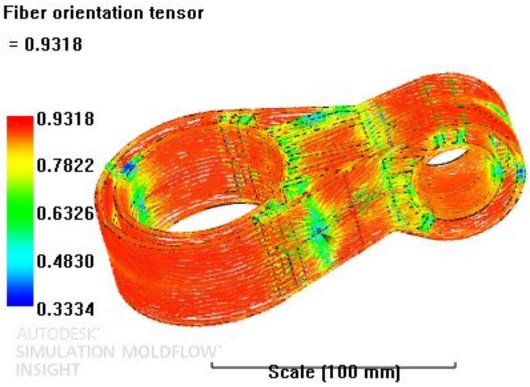

Fig. 11. Fiber orientation distribution

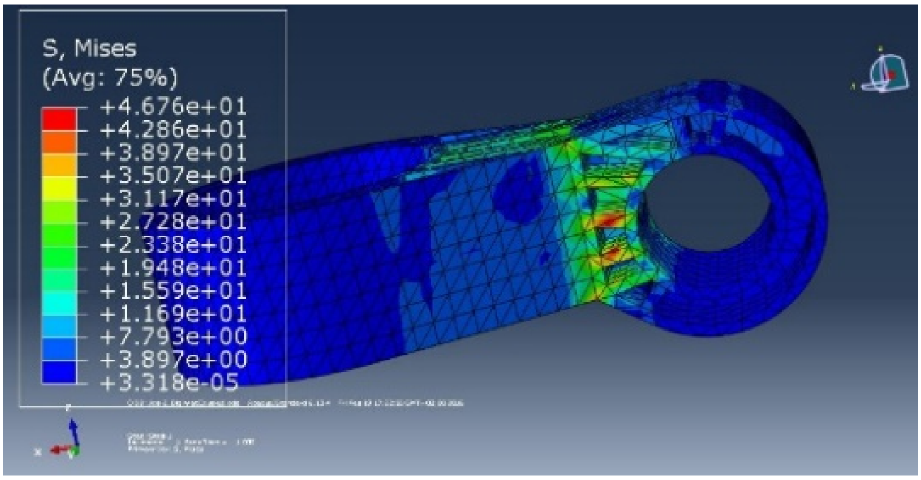

Fig. 12. Stress distribution after coupling analysis

As we can see above, the coupling analysis with the consideration of fiber orientation has more accurate simulation result than the general FEA for GFRP. The result shows that the stress is mainly concentrated on the middle reinforcing rib on the both sides of the engine mount frame. The maximum value is 46.8MPa. Compared with the ultimate strength of 50 MPa at 90° fiber orientation and the ultimate strength of 210 MPa at 0° fiber orientation [9], the strength of such GFRP engine mount frame fully meets the actual use requirements. The result also shows that the first order mode of the frame is 726 Hz which is much bigger than the required 500 Hz.

The mass of a traditional steel engine mount frame is about 558 g, while that of the optimized GFRP engine mount frame only is 193 g, which means that, with the aid of lightweight material and TOT, the mass of the designed GFRP engine mount frame only is 35% of steel frame mass, but it still meets the supplier's requirements, thus achieving the goal of lightening of engine mount frame.

Summary

The topology optimization design of GFRP engine mount frame is performed by using the advanced software Solidworks®, Optistruct®, MoldFlow® and Abaqus® in corporation with the topology optimization theory. The optimized GFRP mount frame not only meets the requirements of stiffness and strength, but also reduces the structure mass to 35% of steel frame. By using the coupling analysis method and taking the fiber orientation into consideration, we successfully predict the precise stress state of the GFRP engine mount frame, thus shortening the development cycle of business, improving the product performance and reducing the expensive production samples and the number of vehicle testing, which makes the design and manufacture costs reduce greatly.

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