Composite Optimization of Automotive Carbon Fiber Strut Bar Using Hyperworks Optistruct

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Abstract: Front strut bar is an automotive part commonly used for McPherson suspension system to minimize load on the strut tower by tying both left and right strut with a single bar. By distributing the force acting on a single strut to both strut tower, the strut bar minimizes the chassis flex which improves ride and handling especially during cornering. Therefore, strut bar should be stiffer but lighter at the same time to reduce vehicle weight towards fuel efficiency and lower carbon emission. This research attempts to design a lightweight carbon fiber reinforced polymer strut bar to replace conventional steel strut bar with equivalent stiffness. For validation, a steel strut bar model is analyzed by conducting experimental modal analysis to determine their natural frequencies and the corresponding mode shapes. These results were compared to simulation results. Later, the dynamic behavior of CFRP and the equivalent mode shapes were analyzed and correlated with static loading test results. Combination of different ply orientation and stack sequence results in the design of an optimized carbon fiber strut bar achieved 48% reduction in weight, up to 40% higher natural frequency while improving or preserving the static and dynamic performances compared to the steel strut bar.

Keywords: Composite Strut Bar; Composite Optimization; Finite Element Analysis (FEA); Ply orientation

1. Introduction
The competitive market in the automotive industry has led to higher demands for lower components price and increasing trends in reducing vehicle weight towards better fuel efficiency and lower emission [1]. Light-weighting activity has resulted in further development of the McPherson type suspension system, which eliminates the upper arm of double wishbone suspension and replaces it with an absorber-spring combination unit. This unit connects the knuckle on the lower end and the flexible mounting on the strut housing of unibody chassis on the upper end for weight reduction as well as minimizing the cost. However, the drawback of this type of suspension is the load acting on the strut tower or strut house, especially when passing over a bump or pothole on the road.

Furthermore, weight reduction on the unibody chassis often led to a decrease in stiffness, which is not a right combination to the McPherson strut regarding ride and handling. Development of hybrid composite strut tower had been conducted to increase structural rigidity. However, there are challenges in joining the part with the unibody [2]. Front strut bar or strut tower brace is designed to minimize loads on the strut tower by tying both left and right strut with a single bar. By distributing the force acting on a single strut to both strut tower, the strut bar reduces the chassis flex which improves ride and handling especially during cornering. The strut bar should be stiffer to overcome this issue [3]. Strut bar is generally made of steel or aluminum which is typically heavy or bulky. As such, a lighter component with similar or better performance is desirable. Currently, there are two types of strut bar in the market; single piece type and hinged type (Figure 1). Single piece type provides maximum rigidity compared to other types.
The lightweight design of metallic structures in vehicle body had been optimized to reduce material through finite element simulation which altered a component's topology, size, and shape. This method, however, has a limit in weight minimization where further weight reduction will compromise the structural rigidity and durability. Therefore, substituting steels with materials such as composite is an alternative for further weight reduction [4]. Carbon fiber with epoxy matrix (CFRP) is favored due to its higher strength–to–weight ratio and environmental resistance. CFRP can be significantly stronger than aluminum in term of tensile strength with about half of its weight [5]. CFRP has five times higher damping loss factor than steel, which is around 0.9 to 1.4% [6]. Having more carbon fiber will result in better properties in terms of tensile, bending and impact absorption, which can also be improved by changing the stack sequence and orientation for the same weight of carbon and glass fiber [7]. CFRP can be tailored for a specific purpose due to its anisotropic behavior [8]. Static and dynamic mechanical properties of CFRP can be customized according to the ply angles, ply thickness and stacking sequence [9–12].

The inertia of hitting a bump, cornering, and braking will cause a shift in the vehicle’s center of gravity and weight will be transmitted from McPherson suspension system to the body that influences the ride and handling performance of a vehicle [13]. Car manufacturers typically use steel strut bars to stiffen the chassis structure, but a significant disadvantage is the weight of steel strut bars. Therefore, this research project aims to develop a carbon fiber strut bar with stiffness value comparable to steel strut bar, with lighter weight.

Findings in the linear static analysis will be used as input in designing a carbon fiber strut bar to further optimizes using composite optimization method in finite element method (FEA) software Hyperworks Optistruct until desired characteristics are obtained.

2. Methodology

2.1 Reverse engineering of steel strut bar
Reverse engineering on an aftermarket steel strut bar should be performed to produce its 3D data. Hardware configuration of this process is shown in Figure 2.

![Reverse engineering hardware setup](image)

Figure 2: Reverse engineering hardware setup

Using Polyworks Modeler software, 3D scanning process to digitize the strut bar surface was conducted. Surface data is imported into CAD modeling software to reconstruct the 3D model of the component. ANSYS SpaceClaim is the CAD software used in this project. Figure 3 showed the scanned data in cloud point that was cleaned up and converted in the triangular mesh (*.STL) format while Figure 4 is the final
design of strut bar. CAD data is converted into mid surface for FE modeling. Mounting bracket thickness in 4.7 mm and bar thickness is 1.3 mm.

![Figure 3: Cloud of points in STL format](image)

![Figure 4: Final CAD design using SpaceClaim](image)

A carbon fiber strut bar with the same geometry of the steel strut bar was modeled. Standard material properties of Toray 300 UD with matrix Toray Semi-Toughen 350, °F epoxy resin in Table 1 below, is normalized to 60% fiber volume. Properties are taken from manufacturer’s data sheet and published data [14]. For steel strut bar, a standard material property for steel is used (Table 2).

| Properties                        | Value       |
|-----------------------------------|-------------|
| Ply thickness, t                  | 0.1334 mm   |
| Density, rho                      | 1.76e-09 ton/mm³ |
| Modulus of elasticity in the longitudinal direction, E₁₁ | 130e+03 MPa |
| Modulus of elasticity in the lateral direction, E₂₂ | 8.96e+03 MPa |
| Poisson ratio for uniaxial loading, ν₁₂ | 0.3        |
| In-plane shear modulus G₁₂       | 7.1+03 MPa  |
| Tensile in X-direction, Xₜ        | 1760 MPa    |
| Compressive in X-direction, Xₜ   | 1570 MPa    |
| Tensile in Y-direction, Yₜ        | 80 MPa      |
| Compressive in Y-direction, Yₜ   | 80 MPa      |
| In-plane shear strength, S       | 98 MPa      |
| Inter-Laminar Shear Strength (ILSS) | 108 N/mm² |
| Tensile Strain                   | 1.3 %       |

| Properties                        | Value       |
|-----------------------------------|-------------|
| Thickness, t                      | 2.6 mm      |
| Density, rho                      | 8e-09 ton/mm³ |
Modulus of elasticity, $E$ | $195e+03$ MPa
---|---
Poisson ratio, $\nu$ | 0.29
Shear modulus of elasticity, $G$ | $86e+03$ MPa
Ultimate tensile strength | 505 MPa
Yield strength, $Y_s$ | 215 MPa

2.2 Dynamic analysis and abusive static loading test
The CAD data of benchmarked steel strut bar obtained from reverse engineering process will undergo the normal mode analysis. On top of that, static load evaluation should also be observed to ensure the performance of carbon fiber strut bar has equivalent or better performance than steel strut bar while reducing weight. Static loading tests in this simulation are considered abusive as the load applied is high enough to observe the part deflection under extreme pressure. Loading used is the standard test from the strut bar manufacturer to find relative performance with other aftermarket strut bar hence cannot be considered as the actual operating load applied on the part. Compression test, torsion test, and flexural analysis were conducted to evaluate the performance.

2.2.1 Compression test
A simulation performed to assess the deflection and stress of strut bar when an impact is applied from the lateral direction. Rigid element (RBE2) was applied and fixed all six degrees of freedom (DOF) around each bolt on one side. On the other side, 100 psi or 0.6895 N/mm2 of pressure was applied towards lateral direction (Figure 5).

2.2.2 Torsion test
Torsion test was simulated to identify maximum deflection occurred when a torque is applied from the transverse axis. In this test, 78500 N.mm of torque was applied to simulate the condition 8 kg of mass was applied from a distance of 1 meter on the transverse axis using torsion test jig (Figure 6).
2.2.3 Flexural test
The flexural test was simulated to determine deflection when a torque is applied to the longitudinal axis. Similarly, 78500 N.mm of torque will be applied about Y-axis at bolt mounting on the strut (Figure 7).

![Figure 6: FE model setup for torsion test](image)

![Figure 7: FE model setup for the flexural test](image)

2.3 Carbon fiber optimization

**Phase 1: Free-Size (Topology) Optimization Setup**

The first step in free size optimization is the ply configuration. These plies are initially stacked on each other in a thick laminate with different ply orientation (0°, +30°, +45°, +90°), namely super ply. Then the plies are stacked or glued into a laminate using "smear" option as it neutralized the effect of stacking sequence. Later, boundary condition such as force and support locations are defined. The stacked plies are chosen as the design variables with manufacturing constraints applied, such as beam thickness (MEMBSIZ), pattern repetition type (PTRN) and min / max total composite laminate thickness (LAMTHK). Ply manufacturing constraint (PLYMAN), and balanced ply angles (BALANCE) also can be defined.

Other than that, the typical setup for free-size optimization has been used in this project which has design constraint and objective; i.e., minimize the weighted compliance with volume fraction is less than 80%. When compliance is minimized, stiffness will be maximized. To move to the next process with free-size ply shape given in this phase, FSTOSZ (free-size to size optimization) control card should be selected for automatic generation of plies for sizing optimization. The result of free-size optimization will require designer's interpretation according to manufacturing feasibility. As an example, original ply shapes from free size optimization can be interpreted as a combination of few individual super plies.

**Phase 2: Ply Bundle Sizing Optimization Setup**

There are two steps involved in this phase; continuous size optimization and discrete size optimization. During this phase, optimum shape and thickness for each ply orientation from free-size are separated (interpreted) into several configurations. Continuous size optimization is the fine-tuning design phase to identify the optimum thickness of each ply bundle according to design objective.

Discrete size optimization is a phase when each ply in the ply bundle is "sliced" into few no. of plies according to the user with a manufacturable shape in discrete size optimization stage. Design constraint such as maximum displacement or volume fraction and objective such as minimize mass or compliance still applied according to user preference. Composite behavior such as ply failure is also considered at this phase.

**Phase 3: Shuffling Optimization Setup**

Ply shape and stacking details for the design in phase 2 are not entirely comply with manufacturing requirement or design regulation. For example, maximum no. of successive plies with same ply angle, pairing the +/- degree ply angles and sequence of core and cover (outer layer/ ply) can be set in shuffling optimization on the ply stacking sequence. This phase will optimize the sequence to meet those
manufacturing constraints. Figure 8 and Figure 9 below show the changes occur during each stage.

**Figure 8:** Changes from free size to shuffling optimization.

**Figure 9:** Ply changes during composite optimization.

Shuffling optimization requires the user to change the control card from FSTOSZ to SZTOSH to maintain formulation from bundle ply sizing optimization to this phase. Design variable for size optimization "desvar_size" is renamed to "desvar_shuffle" and can be edited through Analysis > optimization > composite shuffle > parameters to apply manufacturing constraints such as pairing constraint and maximum successive plies.

3. **Result and Discussion**

3.1 *Abusive static loading test of the strut bar*

Static loading test was conducted to find suitable ply orientation for the strut bar design. The results are shown in Figure 10. The thickness of CFRP strut bar is precisely same as steel strut bar.
0°/0°, 30°/-30° gave better resistance towards bending in flexural and compression test. These ply orientations produce a lower displacement compared to others. However, the maximum displacement of CFRP is relatively higher than steel for the same geometry due to the lower modulus of elasticity, E. The elastic modulus of steel is 195 GPa whereas the modulus for CFRP is only 130 GPa (longitudinal) and 8.96 GPa (lateral). The same condition for torsion test, steel strut bar performs better than CFRP strut bar due to its higher shear modulus, G. The shear modulus for steel is 86 GPa while for CFRP is only 7.1 GPa. Therefore, the part made of carbon fiber is thicker than steel is expected. Higher no. of layer leads to significant improvement in term of flexural strength [6]. 45°/-45° plies have a lower frequency in flexural mode but have a higher frequency in torsion mode, in line with Tita et al [15]. However, 45°/-45° plies, 60°/60° and 90°/90° ply orientation will be ruled out in composite strut bar optimization process due to inferior performance as compared to steel in static loading. Although 45°/-45° and 60°/-60° ply orientation show lower displacement in torsion, it is not significant when other ply configuration also achieves a similar result.

Based on static loading test result 0°, 30° and -30° ply orientations are deemed to be the best performing candidates for composite strut bar optimization in improving stiffness and minimize the effect of bending and torsion in all directions.

### 3.2 Design optimization of CFRP strut bar

Below is the pre-optimization result to measure compliance value for each static load case where the thickness of all ply orientation was set to 1 ply (0.1334 mm). The strut bar is consists of three different ply orientations; 0°, 30°, -30°. This process was performed to determine the compliance for each load case. Compliance is the inverse of stiffness and measured in millimeter per Newton [mm/kN].

#### Table 3: Pre-optimization analysis result

| Load case | Complianc $C_{ij}$ [mm/kN] | Weighted compliance, $C_{w}$ |
|-----------|-----------------------------|----------------------------|
| Compression | 6.022749                   | 1.0                        |
| Torsion   | 2.308172                   | 2.6                        |
| Flexural  | 1.322781                   | 4.5                        |

If weighted compliance, $C_{w}$ for all load cases were set to 1.0, the final design would be heavily influenced by flexural load case due to its compliance is the highest. Torsion load case mostly will not be affecting the final design because it is comparatively low than other load cases. Weighting factor had been applied to ensure each load case to influence the final product design equally. Result in Table 3 was determined by the following equation

$$C_{w} = \frac{C_{\text{max}}}{C_{i,n}}$$  \hspace{1cm} (1)

$C_{\text{max}}$ in this design problem is the compliance value of flexural test and $C_{i,n}$ is the compliance for each load case.

**Phase 1: Free size optimization result**
Free size optimization produces an optimum shape by removing unnecessary material outside the load path. The mass of this initial concept is 1.0 kg, which is lower than steel strut bar mass, 1.66 kg. The objective of this optimization is to minimize weighted compliance subjected to maximum 1kg weight and static loadings constraints which were achieved through free size optimization with static displacement as in Figure 11.

**Phase 2: Size optimization result**

In this project, default no. of shape (four shapes) was used. Fig 11 shows one of the effects of free size to continuous size for -30° ply orientation at the mounting.

At this size optimization phase, design objective was changed from minimizing weighted compliance in free-size phase to reducing mass. The constraint was altered from mass (1.0 kg) to static displacement. Here, maximum displacement was allowed up to steel strut bar maximum static displacement value for each load case. Thus, lighter weight with better performance of composite strut bar than steel strut bar can be achieved. CFRP strut bar weight reduces from 1.0 kg to 0.83 kg.

Next, discrete size optimization can be carried out editing the TMANUF entry in each ply control card. When TMANUF is set, the thick ply bundle can be “sliced” into manufacturable ply thickness, which is 0.1334 mm for each ply. At this point, CFRP strut bar mass increases slightly from 0.831 kg to 0.834 kg.

**Phase 3: Shuffle optimization setup**

Shuffle optimization algorithm proposes the optimal stacking sequence could be while preserving the design performance. As current algorithm only supports 45°/-45° ply orientation as a pair and not for 30°/-30° ply, a stacking sequence with a single ply of 30° and -30° to each other is not possible at this moment. The only manufacturing constraint can be applied to the stack is the maximum successive number of plies of the same orientation does not more than four plies in sequence (MSUCC=4).

There are some changes in displacement and the weight increases from 0.834 kg to 0.861 kg. There are plies added in between four successive plies that contributing to the increment in weight.

The result of composite optimization through all phases are shown in Figure 12. There are 48% reduction in mass, 18% improvement in compression, 13% improvement in flexural with 7% increase in torsion. However, a slight increase in torsion is acceptable since the maximum displacement due to torsion only increases by 0.6mm.
Figure 12: Composite optimization result summary

The outcome of composite optimization of automotive strut bar is shown in Figure 13. Surface connecting the mounting and strut bar became slightly thicker to reduce stress concentration in the area.

Figure 13: Shuffle optimization design

Modal analysis of the final product as compared to steel strut bar is shown in Figure 13. The optimized CFRP strut bar only has four modes under 1 kHz. First and second modes are bending towards Z and Y-direction at 217 Hz and 239 Hz respectively. Pure bending Z-direction mode occurred in the third mode at 412 Hz. The fourth mode is a combination of torsion and bending at 698 Hz. The result in Figure 14 shows that natural frequency increased 29% to 40% for each mode.

Figure 14: Modal analysis result

4. Conclusion
Dynamic analysis of carbon fiber proved to be an excellent approach to develop a lightweight yet durable automotive strut bar. Based on dynamic behavior and static loading test result, a combination of 0°, 30° and -30° ply orientations are deemed to be the best performing candidates for composite strut bar optimization in improving stiffness while minimizing the effect of bending and torsion in all direction. Free-size, continuous size, discrete size, and shuffle optimization are the phases involved in composite design optimization. The weight of carbon fiber strut bar can be reduced up to 48% compared to steel strut bar while improving or preserving the static and dynamic performance. Natural frequency also increased
from 29% to 40%. Composite components can also be manufactured according to the manufacturing requirement.

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