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# Predictive Engineering Tools for Injection-Molded Long-Carbon-Thermoplastic Composites: Weight and Cost Analyses

## August 2016

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**Aaron Yocum,** National Energy Technology Laboratory, Morgantown, WV 26507

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## 1. Introduction

This project proposed to integrate, optimize and validate the fiber orientation and length distribution models previously developed and implemented in the Autodesk® Simulation Moldflow® Insight (ASMI) package for injection-molded long-carbon-fiber (LCF) thermoplastic composites into a cohesive prediction capability. The current effort focused on rendering the developed models more robust and efficient for automotive industry part design to enable weight savings and cost reduction. The project goal has been achieved by optimizing the developed models, improving and integrating their implementations in ASMI, and validating them for a complex three-dimensional (3D) LCF thermoplastic automotive part (Figure 1). Both polypropylene (PP) and polyamide-6,6 (PA66) were used as resin matrices. After validating ASMI predictions for fiber orientation and fiber length for this complex part against the corresponding measured data, in collaboration with Toyota Research Institute North America (Toyota) and Magna Exteriors and Interiors Corp. (Magna), PNNL developed a method using the predictive engineering tool to assess the stiffness performance of the LCF/PA66 complex part design. Structural three-point bending analyses of the complex part and similar parts in steel were then performed for this purpose, and the team has demonstrated the use of stiffness-based complex part design assessment to evaluate weight savings relative to the body system target (≥ 35%) set in Table 2 of DE-FOA-0000648 (Area of Interest (AOI) #1) [1]. Starting from the part-to-part analysis, the predictive engineering (PE) tools enabled an estimated weight reduction for the vehicle body system using 50 wt% LCF/PA66 parts relative to the current steel system. This analysis estimated the manufacturing costs, including materials, for making the equivalent part in steel and compared it to the costs for making the LCF/PA66 part to determine the cost per “saved” pound.

**Figure 1.** The 3D complex automotive ribbed part designed with the injection-molded 50 wt% LCF/PA66 material for a replacement of a similar part in steel without ribs.

## 2. Weight Reduction Achieved with 50 wt% LCF/PA66

### *2.1 Weight reduction achieved for a single part*

In the second fiscal year (FY) 2016 quarterly report [2], we reported a weight reduction that could be achieved by replacing a 1-mm thick non-ribbed part in steel with a 2.8-mm thick ribbed part molded from the 50 wt% LCF/PA66 material. The method to estimate weight reduction involves the following steps [2]:

1. Run ASMI analysis of the 30 wt% LCF/PA66 ribbed part and compare predicted fiber orientation and length results to the measured data.
2. Export ASMI nodal fiber orientation and weight-average length result data.

3. Import data into ABAQUS® via EMTA-NLA[1].
4. Perform bending elastic analysis of the 30 wt% LCF/PA66 part using EMTA-NLA/ABAQUS® to obtain load-deflection response.
5. Perform ABAQUS® bending elastic analysis of similar *non-ribbed* parts in steel with different wall thicknesses to obtain load-deflection responses.
6. Determine the wall thickness of the part in steel that produces the same load-deflection response as the 30 wt% LCF/PA66 part.
7. Manufacturing constraint: Parts in steel require thickness ≥ 1 mm.
8. If the 30 wt% LCF/PA66 part does not meet the stiffness performance, increase the fiber loading to 40% or 50%, and then repeat Steps 4, 6, and 8 by replacing 30 wt% with 40 or 50 wt% until achieving the load-deflection response target.
9. Evaluate weight reduction achieved.
10. Estimate manufacturing cost including material cost for making the equivalent part in steel and compare to the costs for making the LCF/PA66 part to determine the cost per "saved" pound.

Table 1 summarizes the part-to-part comparison from the analysis that indicates a *43.2% weight reduction* for the complex part. The 50wt% LCF/PA66 ribbed part has a 2.8-mm wall thickness and 1.25-mm-thick ribs. The equivalent non-ribbed part in steel is 1-mm thick. The weight reduction achieved for the composite part exceeds the system target (≥ 35%) set in Table 2 of DE-FOA-0000648 (AOI #1) [1].

**Table 1.** Part-to-part comparison to evaluate the weight reduction achieved with 50 wt% LCF/PA66 [2].

| | 50wt% LCF/PA66 ribbed part (2.8-mm wall thickness) | Feasible non-ribbed part in Steel (1-mm wall thickness) |
|---|---|---|
| Density ($g/cm^3$) | 1.39 | 7.85 |
| Volume ($cm^3$) | 224.64 | 70 |
| Weight (lb) | 0.688 (43.2% reduction) | 1.211 |

### 2.2 *Weight reduction achieved for a body-in-white*

Knowing the weight reduction that would be achieved for a single part, Toyota conducted a study to determine the components of the body-in-white (Figure 2) that could potentially be replaced with composite material parts using the 50 wt% LCF/PA66. The body-in-white considered by Toyota weighs 225 kg, and the steel components of the body-in-white selected for replacement weigh 115 kg. With an estimated 40% weight reduction achievable with composite materials, the total new weight of the candidate components for replacement would be 69 kg. This would reduce the weight of the body-in-white to 179 kg to achieve 20% weight reduction. Due to performance and other considerations, only certain body system components could be replaced with parts produced using injection molded materials. Practical considerations based on manufacturing insights were included in the weight reduction estimates.

If closures are included in addition to the body-in-white in the weight reduction analysis, Toyota found that a 22.5% weight reduction may be achieved. The current weight reduction estimate is based on weight savings in body-in-white, closures and bumpers. Typically, a lighter weight body-in-white could also result in lighter secondary components (i.e., engine, brakes, suspension, etc.), which would lead to

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[1] EMTA-NLA = Eshelby-Mori-Tanaka Approach to Non-Linear Analysis ABAQUS® user subroutine

further vehicle weight savings. In this work, the components whose main contribution is stiffness (bending) related were considered for replacement to achieve weight reduction. The components that play a significant role in the impact performance were not considered in the scope of this project.

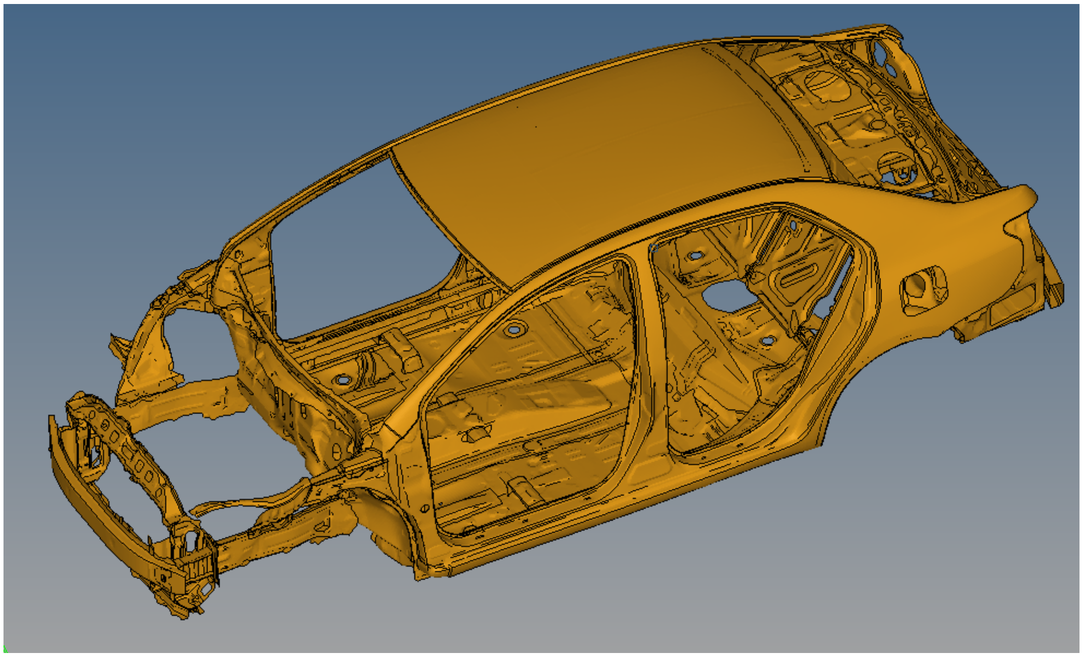

**Figure 2.** It is estimated that a 20% weight reduction is achievable for a body in white using the injection molded LCF/PA66 material.

## 3. Cost Per Saved-Pound Estimates

### *3.1 Cost of saving 1 pound based on the actual cost of carbon fibers*

In discussion with PlastiComp, Inc. (PlastiComp), Magna calculated the estimated cost to make the 50 wt% LCF/PA66 ribbed part based on the annual production rate of 100,000 parts per year. The cost to make a non-ribbed complex part in steel based on the same production rate was obtained from Toyota. Cost comparison indicates that the cost to make the composite part would be 3.2 times that of the part in steel. As a result, the cost to save 1 pound would be approximatively 5 times the target in Table 2 of DE-FOA-0000648 (AOI #1) [1].

### *3.2 Cost of saving 1 pound based on $5 per pound of carbon fibers*

PlastiComp estimated that 42% cost reduction for 50 wt% LCF/PA66 compounds could be achieved if carbon fibers were available at $5 per pound. The cost to make 50 wt% LCF/PA66 compounds (pellets) includes the material cost (for carbon fibers and the PA66 resin) and the compounding cost. Given that the cost of carbon fibers is much higher than that of PA66, the material cost is dominated by the carbon fiber cost. From Magna information regarding the standard cost to make this composite complex part and accounting for the reduced cost for compounds discussed above, molding a 50 wt% LCF/PA66 complex part weighing 0.688 lb would incur a cost approximately 30% lower than the current cost estimates. This would lead to the following conclusions for $5 per pound carbon fiber:

- The cost to make the composite part would be more than twice the cost for the part in steel,
- The cost per saved pound would be about 2.5 times the target.

Table 2 summarizes the analyses considering the current and $5/lb costs of carbon fibers and Table 3 gives an overview of the cost and weight reduction impacts on replacing steel parts with composite parts.

**Table 2.** Estimates for the cost of saving 1 pound.

| | **50wt% CFPA66 part** | **50wt% CFPA66 part (at $5.00/lb)** | **Feasible Part in Steel (1-mm Thick)** |
|---|---|---|---|
| **Weight (lb)** | 0.688 | 0.688 | 1.211 (43.2%) |
| **Cost** | 3.2 times the cost of the part in steel | 2.1 times the cost of the part in steel | --- |
| **Cost per saved pound** | ~5 times the target | ~2.5 times the target | --- |

**Table 3.** Cost and weight reduction impacts on replacing steel parts with composite parts.

| **Vehicle system** | **System definition** | **Weigh reduction** | **Cost per lb saved** | **Additional requirements** |
|---|---|---|---|---|
| Targets | Body in white, closures, fenders, bumpers | ≥35% | < $3.18/lb | Safety = OK<br>Structure = OK |
| Results | Body in white + Closures | 22.5 % | ~ 5 times Target | Safety = NA<br>Structure = OK |
| (if $5/lb carbon fibers) | Body in white + Closures | Same | 2.5 times Target | Same |

## 4. References

[1] U. S. Department of Energy, National Energy Technology Laboratory, Funding Opportunity Number: DE-FOA-0000648. “Predictive Modeling for Automotive Lightweighting Applications and Advanced Alloy Development for Automotive and Heavy-Duty Engines”. Announcement Type: 003. CFDA Number: 81.086 Conservation Research and Development, Issue Date: 05/04/2012.

[2] Nguyen BN, Fifield LS, Wang J, Franco C, Lambert L, Baird DG, Gandhi UN, Mori S, Tucker III CL, Wollan EJ (2016). Predictive Engineering Tools for Injection-Molded Long-Carbon-Fiber Thermoplastic Composites – FY 2016 Second Quarterly Report; PNNL-25372; Pacific Northwest National Laboratory, Richland, WA.

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