Using Computer Aided Engineering to Design Better Thermoset Composite Parts

Bruce Davis, Paul Gramann, Antoine Rios
The Madison Group: Polymer Processing Research Corporation
505 S. Rosa Rd., Ste. 124, Madison, WI 53719

Abstract

This paper focuses on the effects of fiber orientation anisotropies on the structural performance of thermoset composite parts. The most important factors to consider when predicting fiber orientation are gate or initial charge location, as well as, part geometry. The structural performance of the part is greatly affected by the amount of fiber orientation. Taking an automotive headlamp housing and a truck front bumper as examples, this paper presents the structural effect that gate and charge location, as well as, choice of injection and/or compression molding have on performance of the final part. First, a mold filling computer simulation is performed for each case. Then fiber orientation is computed and used to model the structural performance of the part under load. Results are compared to structural performance modeled without taking into consideration fiber orientation. The results show up to 100% difference on the final stress when fiber orientation is taken into account. These results demonstrate the importance of considering fiber orientation when modeling structural performance to design better composite parts.

Introduction

The increase use of composites in the automotive, electrical, aerospace, marine and household goods industries is predicted to increase for many years to come. This is mainly due to the excellent strength-to-weight ratios, damping characteristics, corrosion resistance and design freedom for sleek looking parts that composites have to offer.

Composite parts typically contain fibers that are made out of glass, carbon, and wood, among many others, which act as a reinforcement and increase mechanical properties. There is some freedom when choosing the polymeric-based matrix. Common thermoset matrices are phenolic, epoxies, polyesters or vinylesters.

Fiber reinforcement is generally used to improve mechanical properties of the final part. However designing and molding composite parts offer some challenges and disadvantages. These disadvantages, when known and controlled, in fact can be beneficial. When molding composite parts fibers will tend to orient in different directions. This orientation improves mechanical properties in the fiber direction while diminishing it in the transverse direction. If fiber orientation can be predicted, and thus controlled, the designer can optimize the geometry and process to produce a lighter weight and lower cost product. At the very least, the engineer will know the true maximum amount of stress the part can handle.

Current technologies permit fiber orientation to be predicted with molding simulation software [1-2]. This same software can be used for optimizing molding conditions to improve fiber orientation to strengthen the part. Combining the results of mold filling and fiber orientation with structural analysis the molding process can be modified to adapt fiber orientation to strengthen the part in critical structural areas. Furthermore, location of ribs and thicker sections can be optimized to reduce weight, cost and improve performance of the part.

Background

Process Overview

The compression molding process is widely used in the automotive, aerospace, sporting goods, and electronics industries to produce parts that are large, thin, lightweight, strong and stiff. Compression molded parts as shown in Fig. 1 are formed by squeezing a glass fiber reinforced polyester charge, known as sheet molding compound (SMC), between two heated cavity surfaces. The usually 25 mm long reinforcing fibers are randomly oriented in the plane of the sheet and make up for approximately 25% of the molding compound's volume fraction. Generally, the mold is charged with 1 to 4 layers of SMC, each layer about 3 mm thick.

An alternate process is injection-compression molding. As shown in Fig. 2, injection-compression is a hybrid molding process that incorporates both the features of injection and compression molding. In this case a bulk molding compound (BMC) is injected into the mold and then compressed. BMC materials typically have shorter glass fibers than SMC and accordingly exhibit lower structural properties. The main benefits of injection-compression molding are automation and shorter cycle times.

Mold filling

Mold filling analysis is used to study the advancement of material inside the mold cavity starting with the initial charge shape or injection point and finishing with the full mold. This information is used to predict cycle times, compute pressure balance, ensure complete filling of the mold, predict knitlines and detect air entrapment. Before the mold design is finalized the engineer can avoid future operating problems by simulating mold filling for varying molding conditions, mold thickness and for a series of charge configurations or injection gates.

Knitlines and trapped air are important in predicting the structural integrity of the final part. These anomalies can cause weak points and surface finish problems that can lead to cracks and failure of the final part. A knitline occurs when distinct flow fronts meet each other and fibers fail to bridge between the two fronts. Air entrapment occurs when two flow fronts meet around an unfilled area leaving a void on the final part.

To model the mold filling of thermoset materials the Barone & Caulk flow model is used [3]. This model is more accurate for thermosets than the Hele-Shaw model used for thermoplastic materials. The Barone & Caulk model assumes that the material deforms uniformly through the thickness with slip occurring at the mold surface. The flow phenomenon of thermoset materials has been well documented by Osswald [4]. The resulting Barone & Caulk's based mold filling algorithm has been extensively tested with a host of experimental studies and practical applications [2, 4-6]. Osswald, *et al* [5], compared a mold filling simulation based on this algorithm with a short-shot experiment for the hood of a Corvette showing an excellent comparison between the mold filling simulation and experiments.

Fiber orientation

As depicted in Fig. 3, material flow and deformation in the mold causes the reinforcing fibers to rotate and orient to create a part with anisotropic properties. This fiber orientation greatly affects stiffness and strength of the final part, and is the major cause for warpage after the part is cooled and removed from the mold. High degrees of fiber orientation become a problem in places where peak stresses are encountered such as around hinge or fastener attachments.

The most widely used model for fiber orientation in compression molding is the Folgar-Tucker model [7]. This model considers the material's velocity gradients, strain rates, and fiber-fiber interaction. Using a fiber orientation algorithm based on the Folgar-Tucker model, Osswald, *et. al.*, [1] were able to successfully describe the anisotropic mechanical properties of an oriented composite.

Anisotropic Properties and Structural Analysis

An important trait that all composites parts have in common is the effect fiber orientation has on the final properties of the part. As the fiber orientation in the part becomes less random the properties change from isotropic to anisotropic (properties throughout the part are not the same.) This is directly related to how the part is produced [8-9]. In the case of injection and compression molding, the fiber orientation is dictated by the way the material flows in the mold.

The properties of the part in the direction of fiber orientation and transverse to it are significantly different. The stress-strain graph shown on Fig. 4 demonstrates this effect [10]. The elastic modulus is much higher when a stress is applied in the direction of fiber orientation (top curve) than when the stress is applied transverse to it (bottom curve). If the stress is applied to a sample with a random fiber orientation, the elastic modulus will be somewhere in between these two (middle curve). As explained earlier, mold filling will create a non-random fiber orientation field that is different throughout the part. This phenomenon will directly affect the stress and displacement field in the part and must be accounted for when performing a structural analysis.

A structural analysis, or commonly called FEA analysis, simulates the mechanical performance and durability of the part during real operating conditions and loads. Due to the anisotropic mechanical properties throughout the part it is imperative to perform the structural analysis including the effects of fiber orientation. Using a random fiber (isotropic) assumption when performing a structural analysis to determine stresses and deformation can give results that are dramatically different than reality.

Cost Savings Benefits of CAE

The CAE analysis cycle of thermoset composite parts is shown in Fig. 5. An analysis starts with the creation of a computer solid model and a finite element mesh of the mold cavity. After the processing conditions are specified, mold filling, fiber orientation, curing and thermal history, and shrinkage and warpage can be simulated. The anisotropic material properties calculated by the simulation can be used to model the structural behavior of the part. After the analysis is finished an optimized part can be produced with reduced knitlines, optimized strength, controlled temperatures and curing, and minimized shrinkage and warpage.

CAE analysis offers the possibility of testing various processing conditions and part geometries on the computer before the mold is manufactured and the final part is processed. The designer or engineer is capable to quickly review the effect of changing initial charge location, gating scenarios, geometric features, material and different molding conditions on the structural performance of the final part. To exploit the cost benefits of CAE, the material supplier, designer, molder and manufacturer should apply these tools concurrently early in the design cycle.

Figure 6 shows a qualitative expense comparison associated with part design changes [11]. It is clearly seen that when design changes are done at an early stage on the computer the cost associated is on the order of 10,000 times lower than if the part is in production. Cost savings arise from avoiding mold modifications such as gate location and part thickness changes, production delays, scrap parts and machine set-up trial-and-errors.

At early design stages engineers and molders typically finalize part design based on their previous experience with similar parts. As parts become more complex it is harder to predict processing and part performance without the use of CAE tools. Even in the case of simpler parts the effects of processing, such as fiber orientation, can seriously change the structural capability of the product. The new trend is to use CAE tools to prevent the late and expensive problems that can arise during and after processing.

Case Studies

Automotive Headlamp Housing

The following case study exemplifies the importance in considering fiber orientation when analyzing structural performance. The part is a typical automotive headlamp housing whose computer finite element model is shown in Fig. 7. This part was molded under four different molding cases, (i) compression molding, (ii) injection/compression molding, (iii) one-gate injection molding and (iv) two-gate injection molding. The compression molding housing is made out of SMC with 100 L/D glass fiber reinforcement. The compression/injection and injection molding housings are made out of BMC with 25 L/D glass fiber reinforcement. Both SMC and BMC are reinforced with 21% fibers by volume. The fiber length and the fiber/matrix volume ratio are assumed to be constant throughout the part.

The mold filing, fiber orientation and structural performance was computed for each case [12-13]. A snapshot of mold filling for the one-gate injection molding case is shown in Fig. 8. A structural load was placed on each end of the lamp resembling the loading encountered during installation. The structural performance for each molding case was compared to a part where the properties are assumed isotropic with random fiber orientation throughout. Figure 9 shows the resulting stress contours from the structural analysis for the isotropic case. The maximum stress occurs on the middle of the housing.

The maximum stress encountered in each molding case is shown in the following table:

	Maximum Stress	Change from isotropic
Isotropic	427	-
Compression Molding	510	19%
Injection/Compression	817	91%
Injection (one gate)	879	106%
Injection (two gates)	829	94%

Here, the change with respect to the isotropic case reflects the inaccuracy that will be incurred if fiber orientation was neglected. As expected, the greatest difference in stress is found in the injection molding process. With the injection molding process the fiber orientation is generally greater than with compression molding. The fiber orientation for the headlamp housing is depicted on Fig. 10. Here a vector on each element represents the fiber orientation. The direction of the vector represents the main orientation of the fibers and the scale is the magnitude of this orientation. The “one-gate” injection molding case shown in Figure 10b shows higher orientation than the compression molding case in Fig. 10a. This occurs because in injection molding the material flow is radial whereas in compression molding the material flow is equibiaxial (equal in both plane directions). Furthermore, before reaching the gate the material flows through the runner system and nozzle, which in turn, induces a high fiber orientation.

Truck Front Bumper

To illustrate the effect of changing initial charge on structural performance a truck front bumper is analyzed. Figure 11 shows the finite element model of the truck bumper. The bumper is made out of SMC 21% by volume reinforced with 100 L/D glass fibers.

Two initial charge locations shown in Figure 12 are simulated. Figure 12a shows a small area coverage charge location, whereas, Fig. 12b shows a large coverage charge. These two cases are expected to yield different fiber orientation, therefore, showing distinct structural performance.

For each case, mold filling, fiber orientation and structural analysis were performed [12-13]. Mold filling for both initial charge cases is shown in Fig. 13, and corresponding fiber orientation in Fig. 14. As shown in the mold filling simulation (Fig. 13), when the large charge is used the material has a lower flow length towards the end of the bumper compared to the case with the small charge. This difference yields a larger fiber orientation for the small coverage case, as depicted in Fig. 14.

The structural analysis is completed by assuming a load of 300 lbs on the end of the bumper. This load is equivalent to a person standing on that end of the bumper. The stress contour plot is shown in Fig. 15 for the smaller initial charge case. The maximum stress occurs around the support at the loaded end of the bumper.

The results for the structural analysis at the point of maximum stress is shown in the following table:

	Maximum Stress [MPA]	Change from isotropic
Isotropic	56	-
Small initial charge coverage	59	3.7%
Large initial charge coverage	72	27%

Here the results for the two differently charged cases are compared to the maximum stress on the isotropic case. There is little difference between the isotropic case and the smaller initial charge. However, when a larger charge is used the difference is more important. The difference on the maximum stress by changing the charge location from small to large initial mold coverage is 22%. As seen in Fig. 13, mold filling for each case is substantially different. Therefore, as shown in Fig. 14, fiber orientation varies, which yields a considerably different structural response.

Conclusions

Fiber orientation is a crucial piece of information that must be taken into account to analyze structural performance of composite molded parts, but it is commonly neglected. As shown in the case studies, the molding process, and the location of gates and charges have an important effect on the final structural performance of the part. In these case studies differences of up to 100% can be found in the stress level of the parts during load. This can be the difference between a successful application and a catastrophic one. Mold filling analysis is important to ensure proper part filling and avoid knitlines, but also to compute fiber orientation to perform anisotropic structural analysis. It is the combination of these CAE analyses that will lead to optimization of the process and geometry to achieve a part with the optimal structural integrity, lower weight and lower cost.

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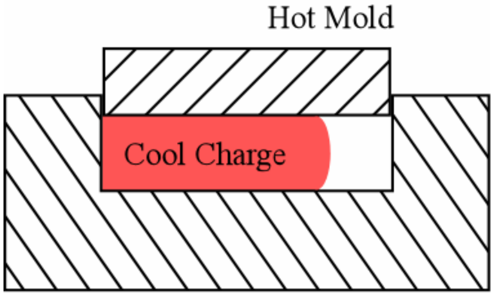


Figure 1. Compression molding process

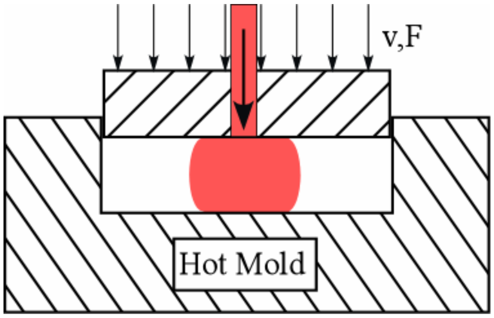


Figure 2. Injection-compression molding process

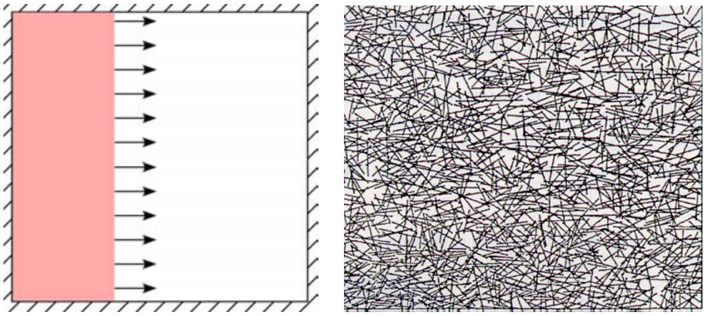


Figure 3. Fiber orientation induced by the material flow in the mold.

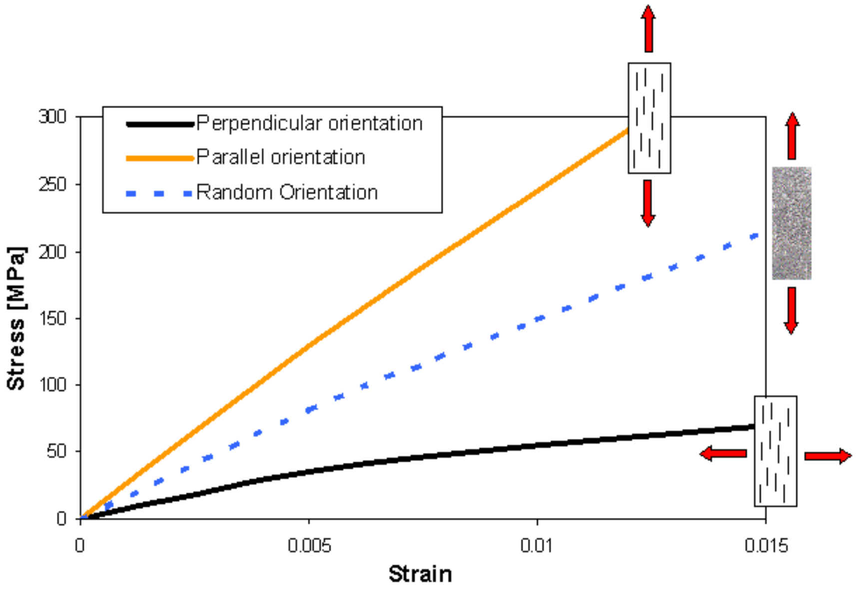


Figure 4. Stress-strain graph with fibers oriented in the direction of strain, random oriented and fibers oriented transversal to strain [4]

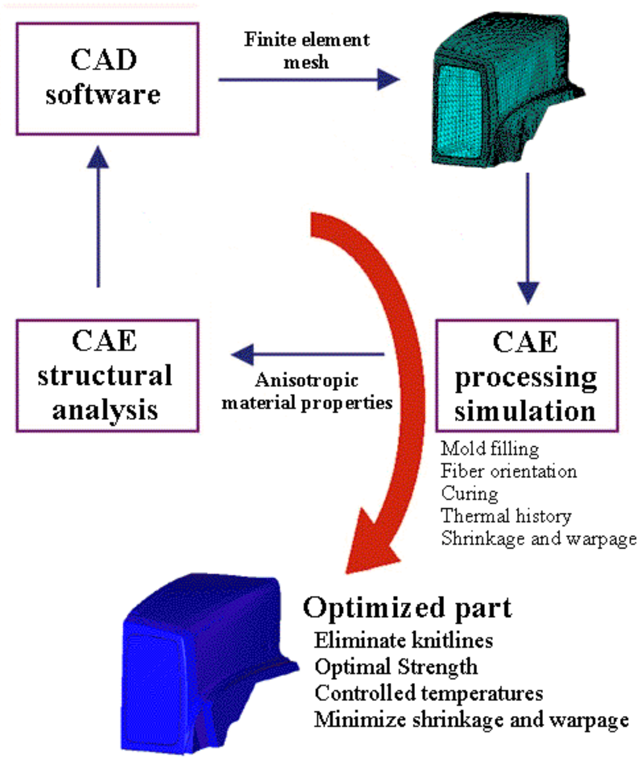


Figure 5. The CAE analysis of compression molded parts

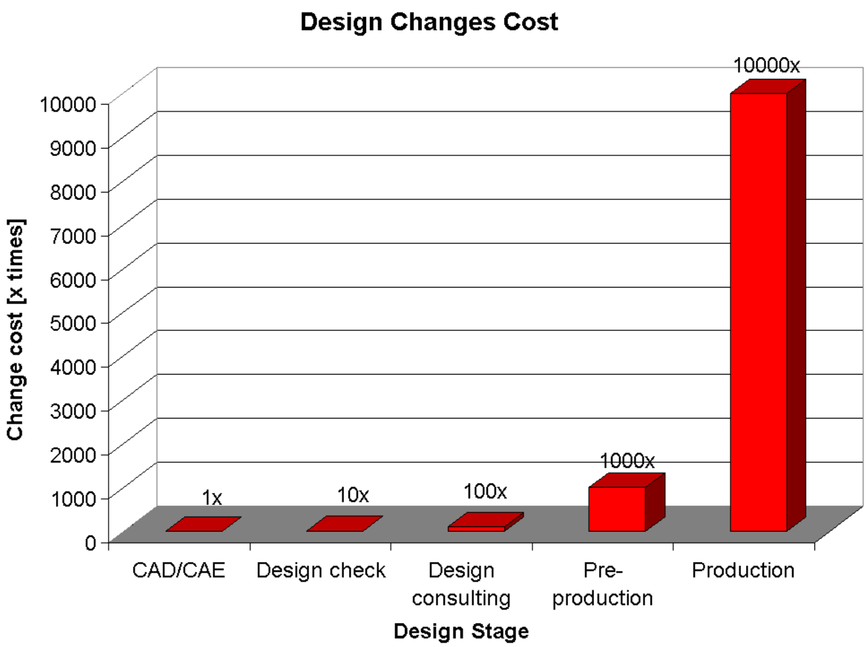


Figure 6. Qualitative cost of design changes during part design and manufacturing

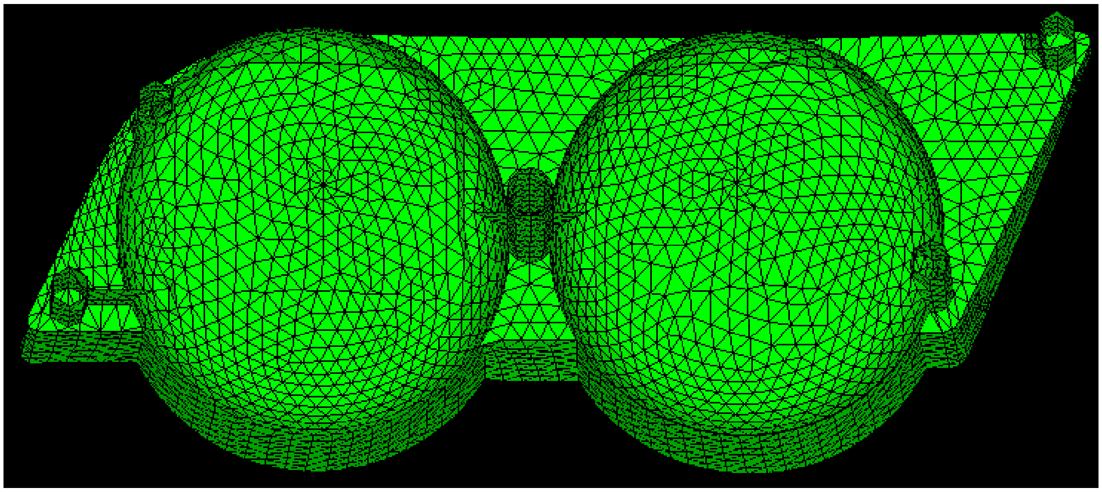


Figure 7. Finite element model of automotive headlamp housing

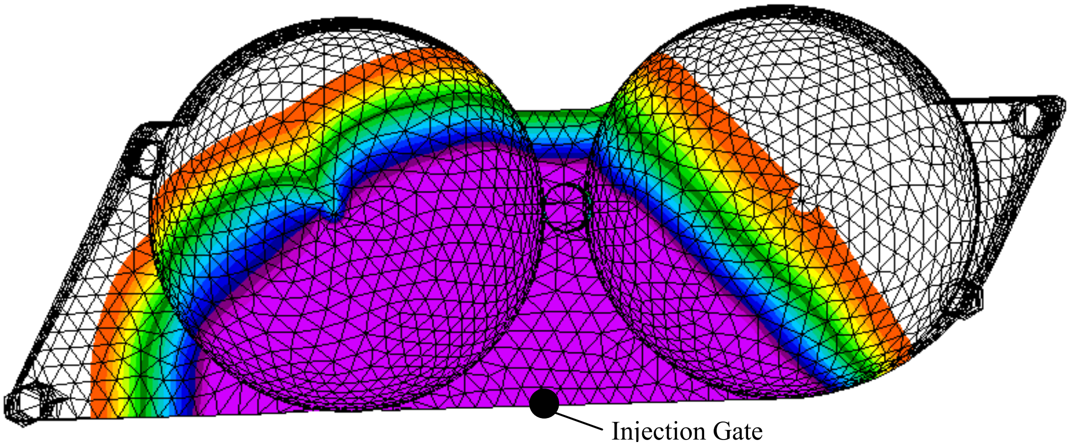


Figure 8. Mold filling of automotive headlamp housing for one-gate injection molding case

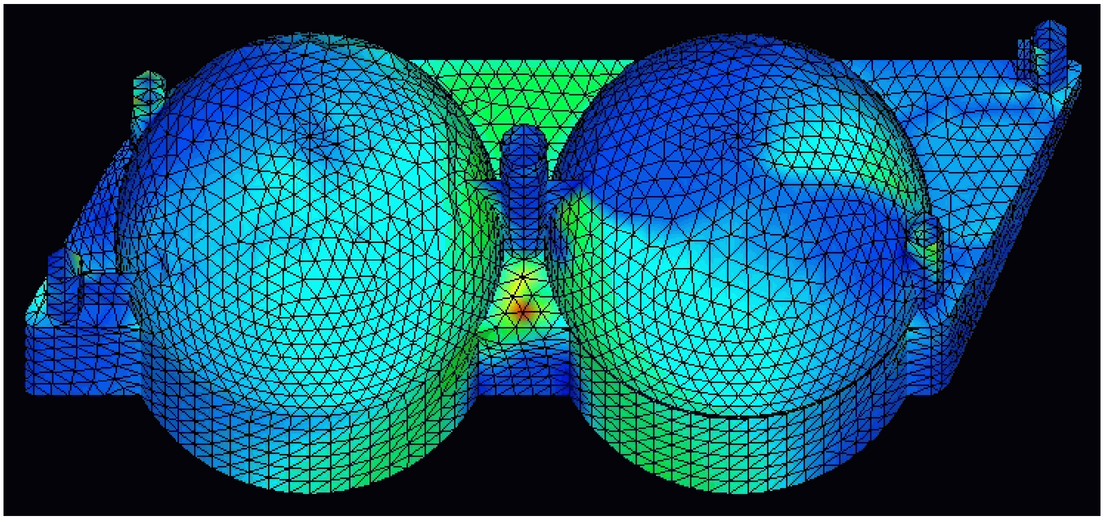
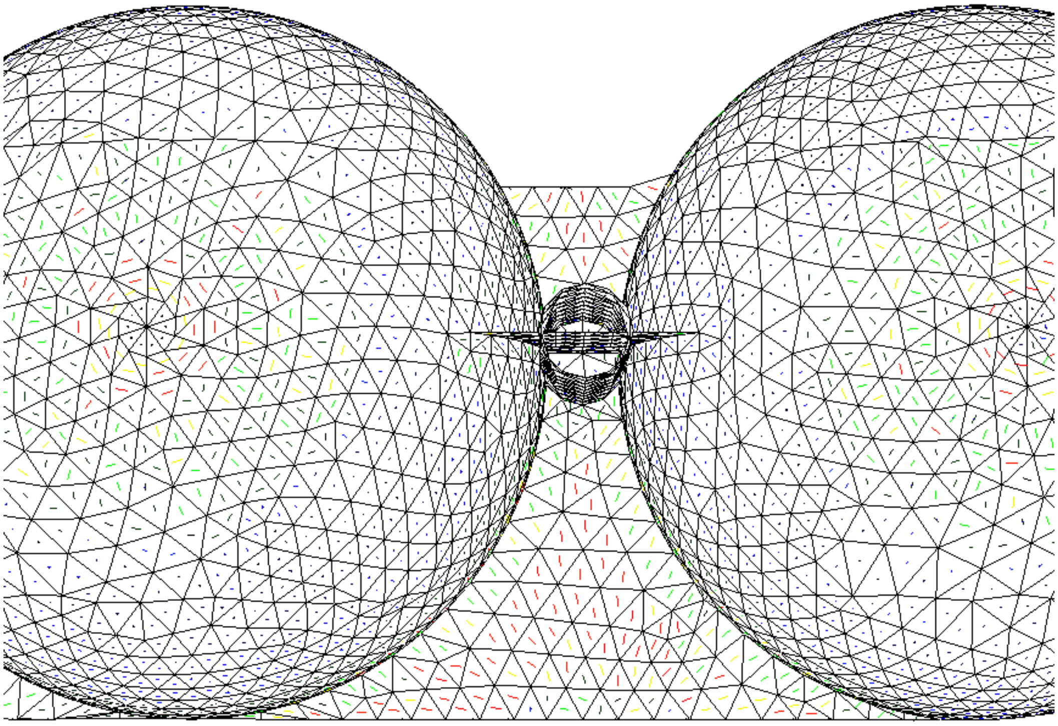
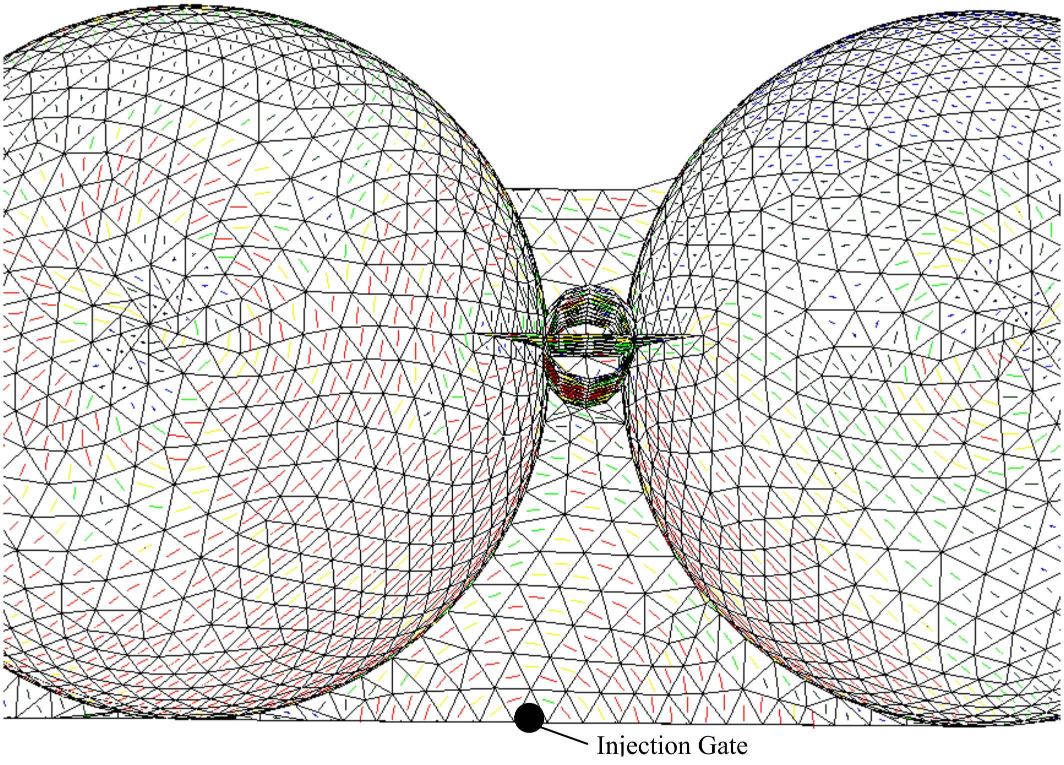


Figure 9. Stress contours of automotive headlamp housing for isotropic case



(a)



(b)

Figure 10. Fiber orientation of automotive headlamp housing for(a) compression molding and (b) one-gate injection molding cases

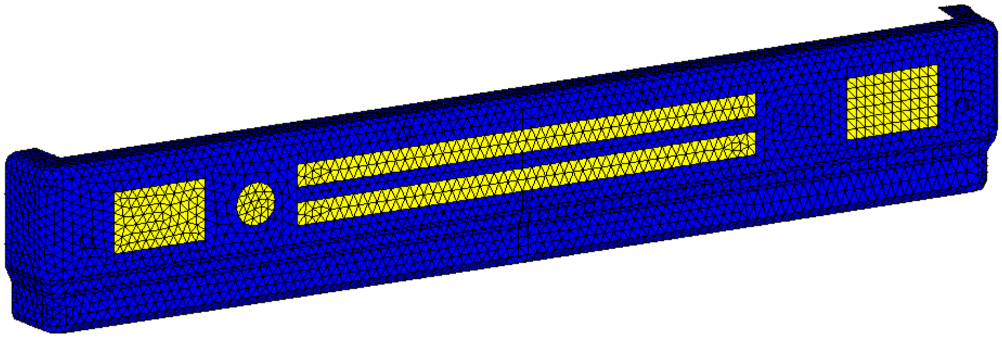
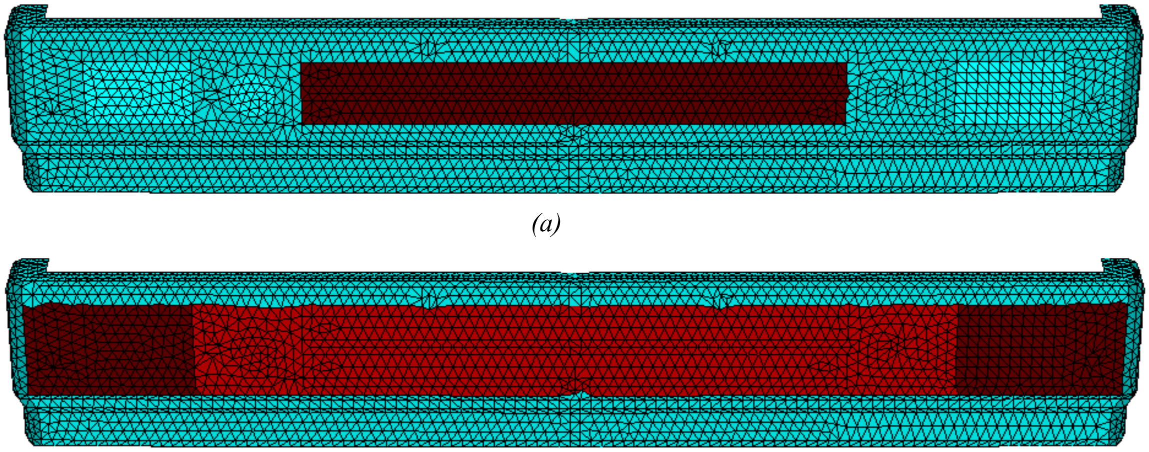


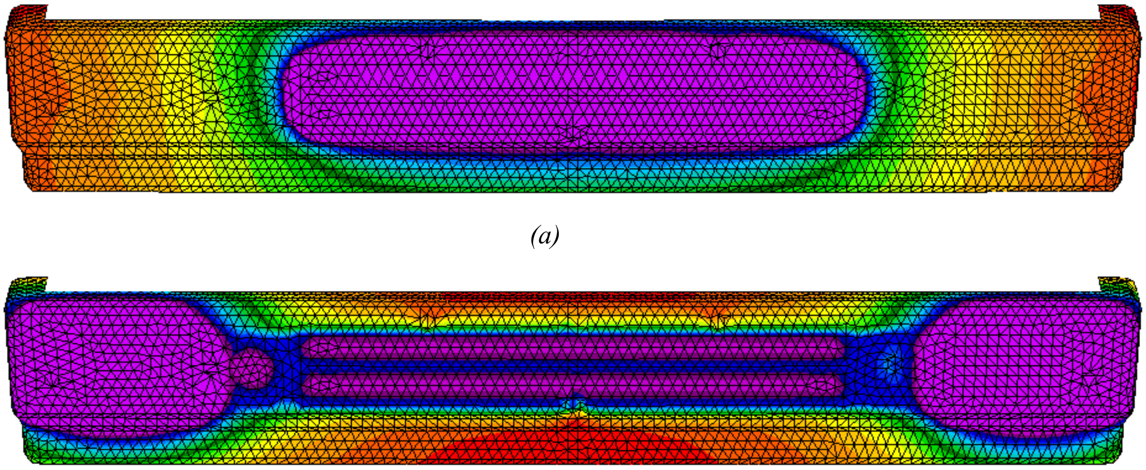
Figure 11. Finite element model of front truck bumber



(a)

(b)

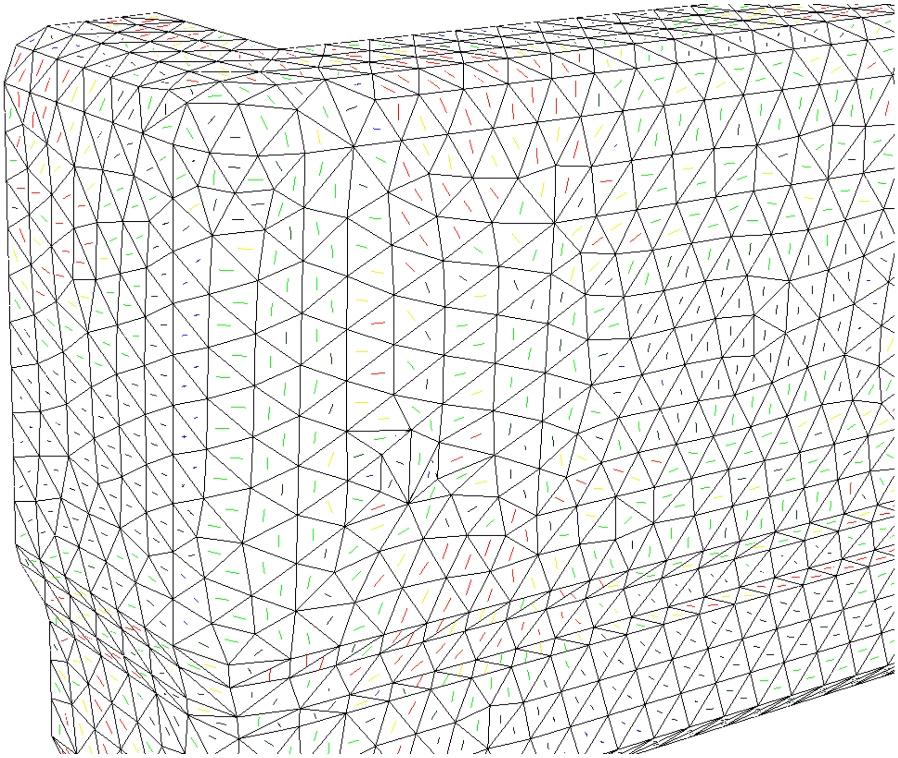
Figure 12. Initial charge location of compression molded bumper. (a) small charge coverage, (b) large charge coverage



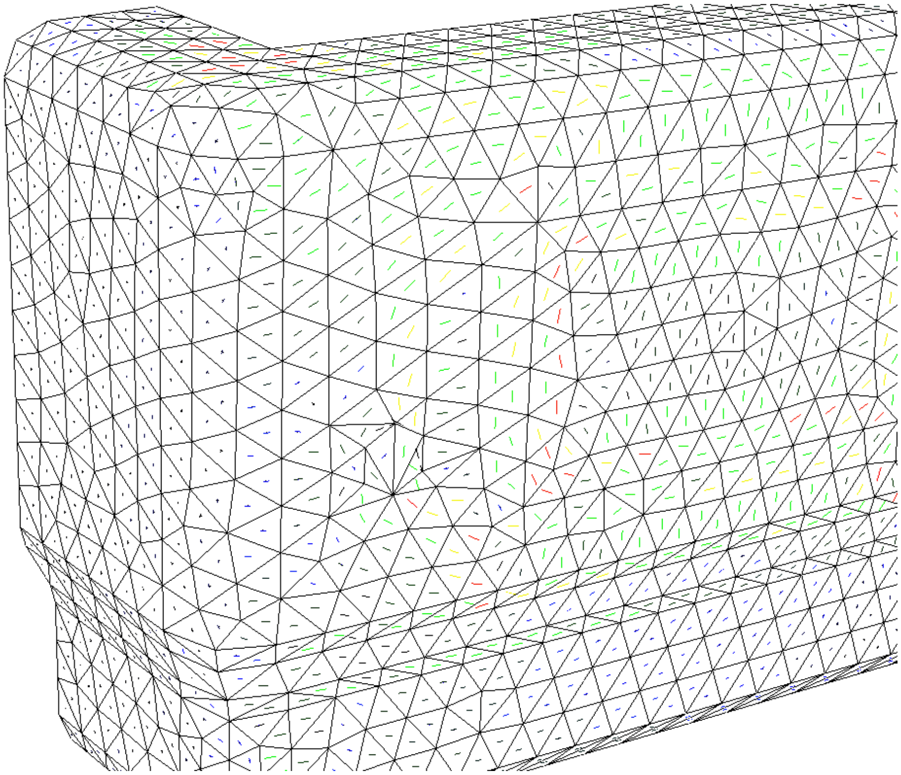
(a)

(b)

Figure 13. Mold filling for compression molded bumper with (a) small charge coverage, and (b) large charge coverage



(a)



(b)

Figure 14. Fiber orientation of compression molded bumper with (a) small charge coverage, and (b) large charge coverage

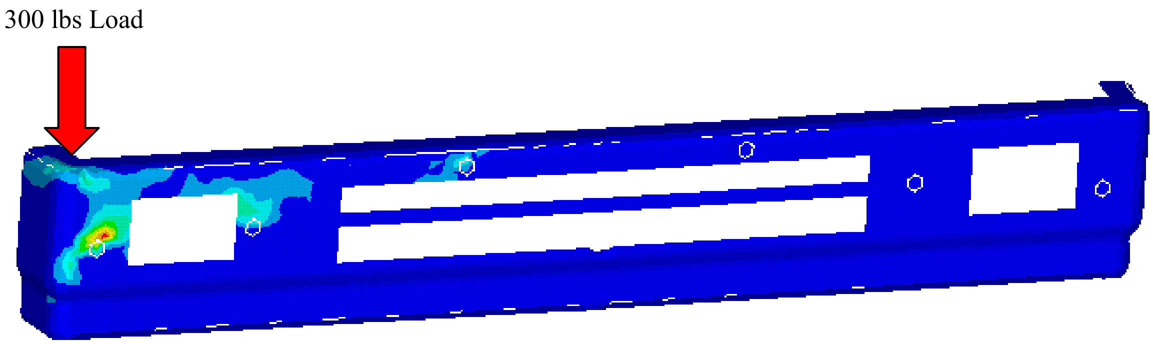


Figure 15. Stress contours for loaded compression molded bumper