SIZE AND SHAPE OPTIMIZATION OF OVERMOLDED CONTINUOUS GLASS FIBER LAMINATE WITH SHORT GLASS FIBER REINFORCED POLYAMIDE FOR MAXIMUM IMPACT RESISTANCE USING ANSA, LS-OPT, AND LS-DYNA COUPLED WITH ULTRASIM®.

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ABSTRACT – The drive to increase performance while reducing mass, in modern automotive engineering, make high demands on the materials used. This, coupled with the need to reduce cost by reducing the number of prototypes, makes rapid and accurate predictions and design optimization in Computer Aided Engineering (CAE) very critical.

This paper studies size and shape optimization of plastic composites using ANSA for morphing the initial orientation of the continuous fiber laminate, height of over-molded ribs, and the shape of the mold. A draping simulation is first run to obtain the fiber orientation of the formed woven laminate. ULTRASIM® is used to map the fiber orientation and BASF material law to the structural mesh, and the model is then run through an impact simulation in LS-DYNA. The energy to failure is extracted from the simulation using µETA and returned to LS-OPT to maximise the energy absorption of the plaque. Such shape optimization is of utmost interest for automotive powertrain components such as oil pans which are subject to stone impact requirements.

BASF ULTRASIM® generates an advanced numerical material description that integrates the manufacturing process into the structural simulation, creating a unique material definition for every finite element of the structural model based on the fiber orientation and strain-rate effects. This description takes into account the typical characteristics of plastics in an integrated simulation with the manufacturing process and leads to an ideally designed component.

1. INTRODUCTION

Purpose of optimizing a plaque for normal impact simulation

Injection molded plastic composites are increasingly used in engine oil pan applications due to mass and cost reductions. One of the most difficult requirements to be met for this under-body application is from stone impacts to the oil pan. The crucial parameter that needs to be optimized is the energy absorbed by the oil pan prior to material failure. To maximise this parameter, the oil pan needs to be stiff while simultaneously being able to significantly deform plastically prior to failure.

Simply choosing a highly ductile composite with a high stiffness is not sufficient when compared to the ductility and stiffness that can be achieved with many metals. A different design strategy is required.

In selecting materials for the test, the BASF Ultralaminate®, a woven continuous glass fiber laminate, was used as the base material. This offers increased stiffness and strength over traditional short glass reinforced plastics and so potentially provides a lower mass alternative. Continuous fiber laminates are getting increasingly common in the automotive industry with increasing demand for these superior properties. Investigating the performance of continuous fiber laminates in various loading scenarios would be of help in finding the best applications for these products. This study aims to investigate how woven laminates could potentially be used in an oil-pan application.

The woven material is supplied as sheets of fixed dimensions, and is formed into the desired shape in a process called draping. The organosheet is first cut down to the desired flat shape. This is then heated and compression molded into the desired form. This process can be simulated in CAE by a draping simulation which allows for the prediction of any wrinkling of the organosheet during the draping process. It also predicts fiber orientations of the organosheet around complex geometry features.

The formed woven part is then over-molded with short glass reinforced thermoplastic ribs. The BASF Ultramid® B3ZG7 OSI was chosen for the over-molding material as it was specifically formulated for stone impact resistance, containing a 35% by weight of glass for high stiffness and an impact modified polyamide 6 matrix to increase ductility of the material (1). These are used to form cross-hatch ribs on the surface of the woven material to increase the stiffness of the part, as well as to act as sacrificial ribs to absorb energy prior to the failure of the base.

ANSA and μETA

Implementing these design changes would have required an unfeasible amount of effort if each design change had to be manually created. The morphing capabilities of ANSA and the strong coupling with LS-OPT make ANSA an extremely capable pre-processor for this study (2, 3). The morphing tool in ANSA has proven to be very powerful in modifying the mesh, and maintaining the mesh quality despite significant geometry changes. The Task Manager in ANSA and the dedicated interface to ANSA in LS-OPT made it extremely straightforward to parameterize the control of the morphing boxes and to drive these parameters from LS-OPT.

Use of morphing with ULTRASIM® is complicated by the fact that the structural mesh used in the impact simulation must be in the same location as the draped organosheet. Even small deviations in this positioning will result in ULTRASIM® not being able to capture the fiber orientation. Therefore, morphing the doming angle, which applies to the mold surfaces in the draping simulation and the structural mesh in the impact simulation, must be perfectly coordinated such that ULTRASIM® can map across the two meshes.

μETA was used for extracting the energy to failure value and return it to LS-OPT as a response (4). The morphing of the plaque meant that impact and failure did not initiate at the same time across all runs. Therefore, extracting energy to failure was a more complex request than what LS-OPT could handle on its own. A more powerful post-processor that could programmatically find out the failure time, calculate the failure energy up to the failure point and return this value to LS-OPT was required. μETA proved capable of meeting these requirements without requiring significant user setup.

ULTRASIM®

Fiber reinforced thermoplastics are highly anisotropic, and structural properties can vary significantly based on the fiber orientations in the matrix. ULTRASIM® is a BASF proprietary software that generates a custom material model for each element in a part based on the fiber orientation in that region. It takes into account fiber orientation, differences between tension and compression loading, strain-rate effects, temperature, moisture, and has an improved strain-energy based failure model that includes material damage prior to element erosion (5).

In this analysis, ULTRASIM® is used to map the material properties based on the draping simulation fiber orientation to the structural mesh of the woven material used in the impact simulation. This will allow for more accurate simulation of the fiber orientations near the corners and sharp geometry transitions.

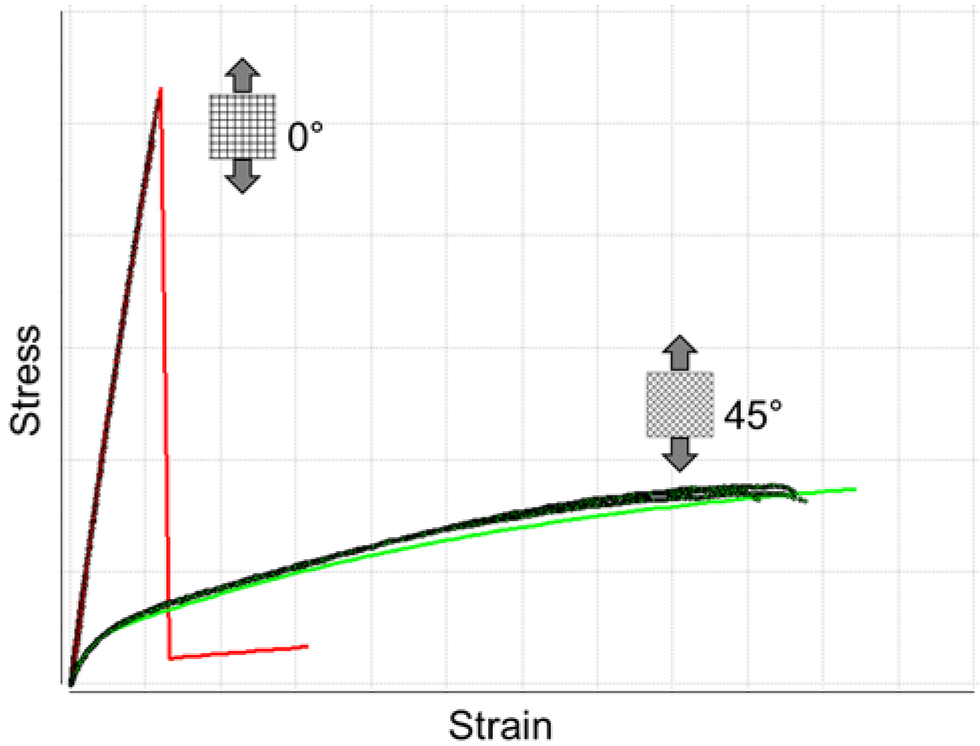

Figure 1 – Effect of woven laminate fiber orientation on stress-strain curve. (5)

Figure 1 shows how much of an impact, fiber orientation can have on the behaviour of the laminate. In the 0 and 90 degree directions, the material is essentially purely elastic, with a highly brittle failure. In the 45 degree direction, however, the material has a lot more ductility prior to failure.

Simply changing the draping angle could drastically alter the performance of the impact plaque.

2. LITERARY REVIEW

ULTRASIM® has been available for many years as a software package for mapping material properties, based on injection molding simulations, onto a structural mesh. Multi-disciplinary optimization using ULTRASIM® and ANSA for morphing of these composites has been performed in the past using diverse optimization methodologies in TOSCA and LS-OPT (6, 7). Further, ULTRASIM® has correlated well against tested impact performance of a short glass reinforced polyamide-6 oil pan, showing the capabilities of the technology and the improvements in predictive ability gained by using ULTRASIM® (8).

For continuous fiber laminates, there are standard LS-DYNA orthotropic material models that are capable of taking into account strain rate dependency with advanced damage and failure models, such as MAT162 (9). However, these are still unable to account for any deformation of the glass fiber directions arising from the manufacturing process. This paper investigates the newly developed support for continuous fiber laminates in ULTRASIM®, with the capability to capture local fiber orientations from a draping simulation.

The morphing capability of ANSA has been used in many design studies. However, the uniqueness of the multi-disciplinary approach requires that the mesh used for the processing simulation be similarly morphed to the structural simulation. Where a mold filling simulation is used as the processing simulation, a single morphing task can be defined in LS-OPT, with the same mesh being used for both the mold filling and structural simulations (7). In this study, however, the mold surfaces for the draping simulation and the plaque for the impact simulation have to be morphed in separate ANSA tasks in LS-OPT.

3. ANALYSIS SETUP

Three design variables were chosen for this conceptual study to investigate the capabilities of morphing and ULTRASIM® in a parametric optimization set-up. The choices of design variables were narrowed based on prior experience and new manufacturing variables that arose with the draping simulation.

(a) Effect of draping direction of woven materials: The orientation of the glass fibers significantly changes the properties of the material. The organosheet is rotated between -45 to +45 degrees about the global z-axis, as shown in Figure 2.

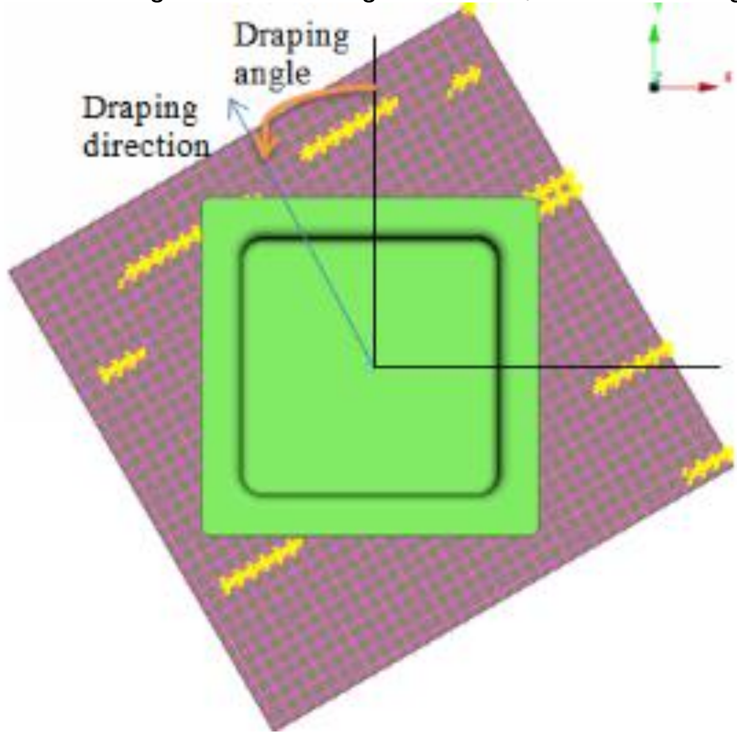

Figure 2 – Draping Angle Definition

(b) Effect of doming the impact surface: Doming a surface, even with a small curvature, is known to increase stiffness (10). The top face of the plaque in the impact simulation is morphed such that the center node can move ± 10mm vertically, as shown in figure 3 below. The mold surfaces in the draping simulation are also morphed using the same parameter to ensure that the draped organosheet and the structural woven mesh are in the same locations to enable fiber orientation mapping in ULTRASIM®.

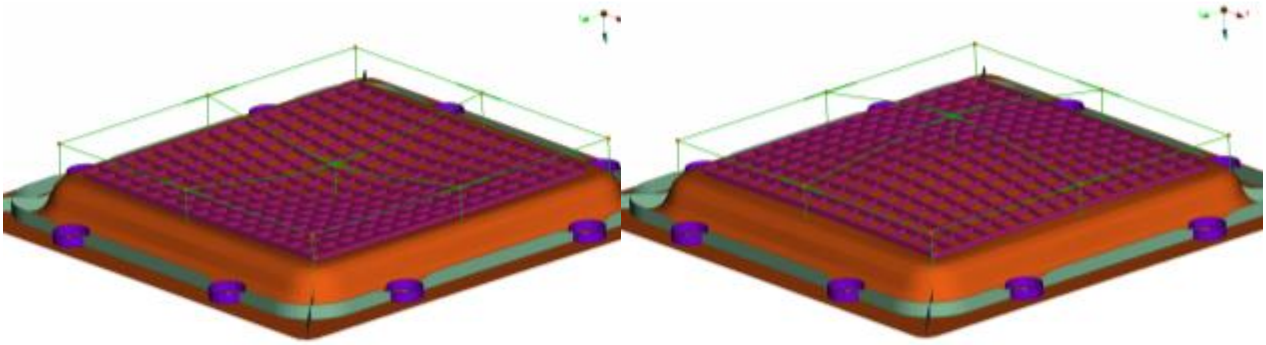

Figure 3 – Doming of Impact Surface

(c) Rib height: 5 parameters were used to vary the cross-hatch rib height at different radial distances from the impact location. The rib heights were allowed to vary from 2.5mm to 7.5mm at these control points. The morphing boxes used to morph the ribs are shown in figure 4. These would serve as sacrificial ribs that will fail prior to the woven wall failure, increasing the energy absorbed.

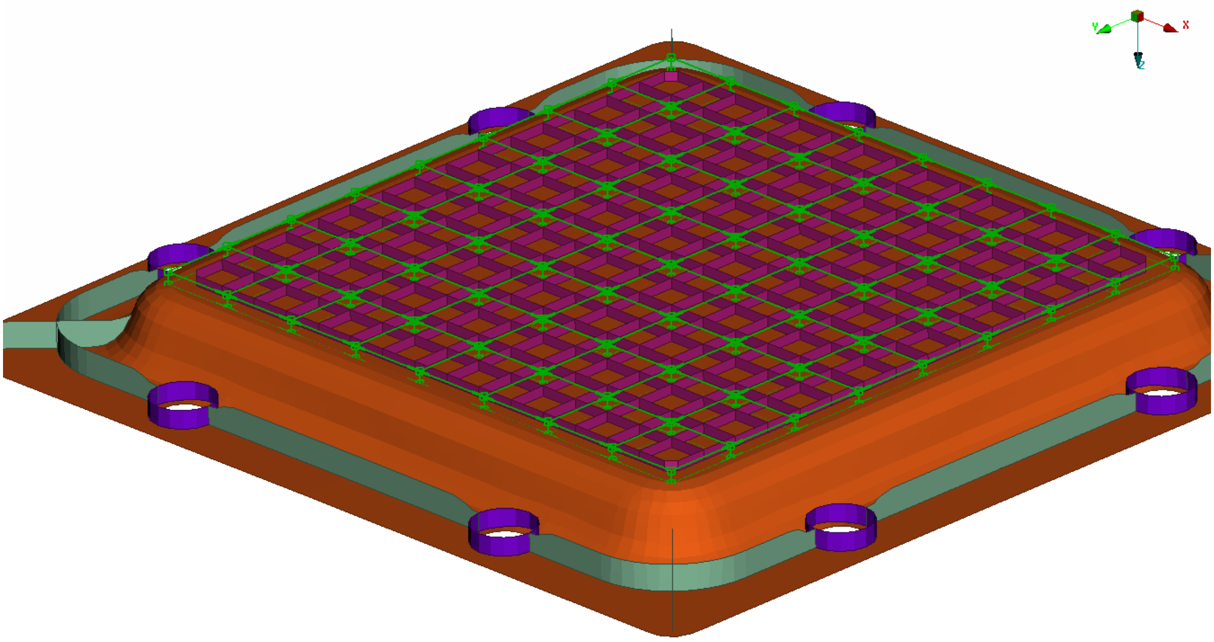

Figure 4 – Rib Height Morphing Boxes

The LS-OPT loop set-up is detailed in figure 5. A sequential domain reduction optimization using a radial basis function based meta-model was chosen. The parameters defined above were modified in the ANSA_Draping and ANSA_Impact stages.

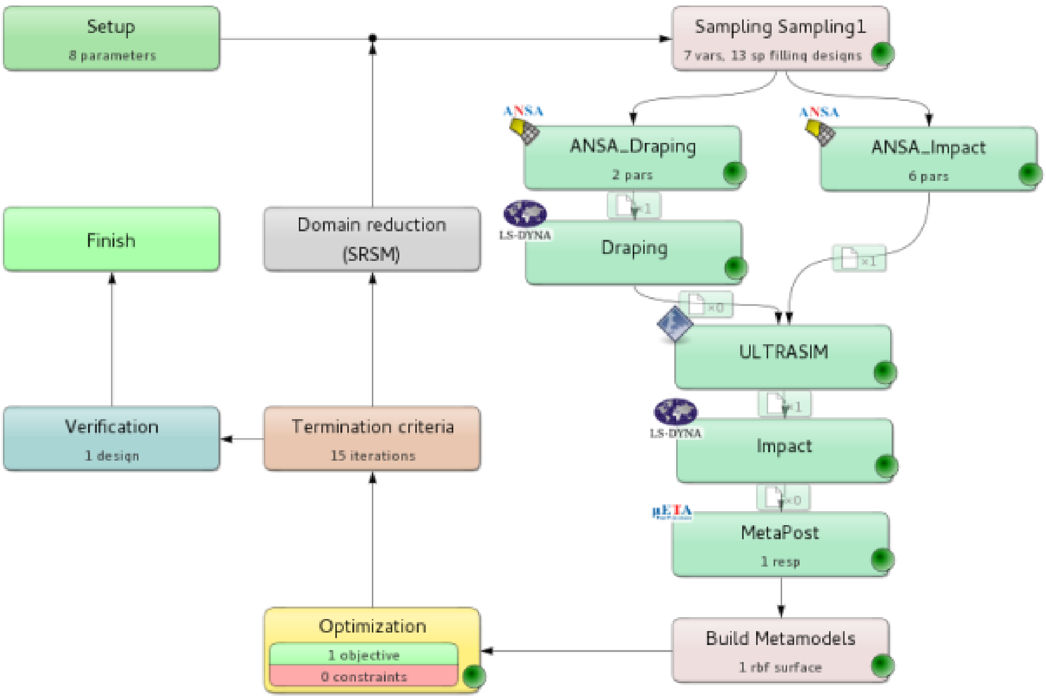

Figure 5 – LSOPT Set-up

ULTRASIM® then mapped the material properties onto the impact mesh based on the draping simulation results. The impact simulation was carried out with a rigid 34kg (75lb) impactor of 25.4mm (1in) diameter with a 3.4 mm ms^{-1} initial velocity striking the center of the plaque while the bolt bosses around the perimeter were fixed rigidly, as in figure 6 below. The velocity was chosen to ensure the impactor would have sufficient energy to cause failure of the plaque even at the most optimum plaque design.

μETA was called to read the resultant binout file, plotting the impactor reaction force against the impactor displacement, and then calculating the area under the force-deflection curve up to the peak force (which was assumed to be at failure initiation.) This energy to failure was then reported back to LS-OPT to be used as the parameter for maximization.

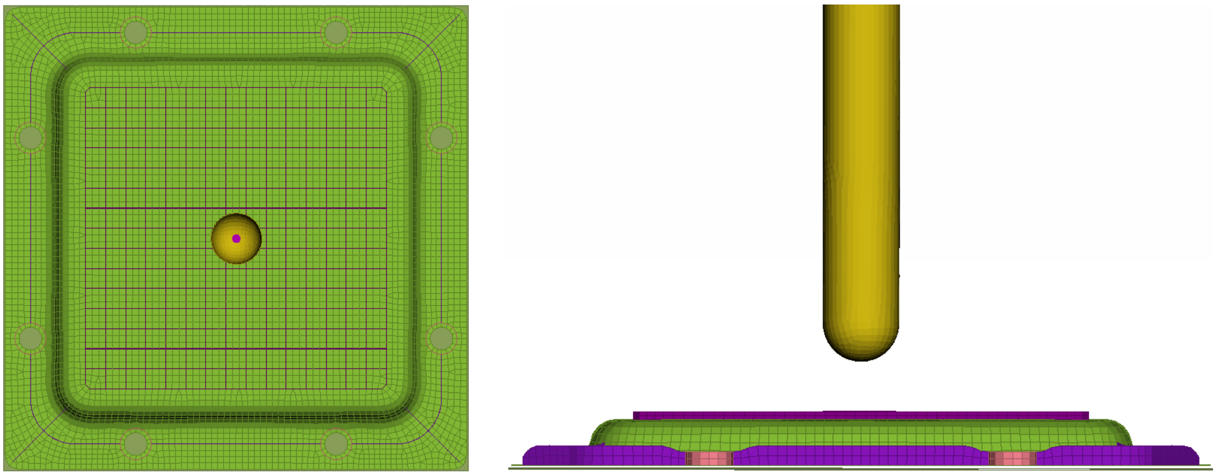

Figure 6 – Impactor set-up

4. RESULTS

Effect of fiber draping direction in impact simulation

Given that the properties of the woven sheet are so dependent on fiber orientation, and given that all the plies were oriented along the same draping angle, it was expected that changes in the draping angle would drastically change the energy to failure.

Figure 7 shows the effect of altering the draping angle when all the other parameters were held fixed at their optimum values. The graph shows a bell-curve distribution, with the optimum draping angle being close to 0º. The asymmetry of the bell-curve, and the slight offset from a 0º optimum are likely artefacts of the meta-model based optimization methodology used by LS-OPT.

The corners of the part are made stiffer by the curvature of the woven sheet in those regions. As the draping angles approach 0º, the glass fibers tie the impact region with the more compliant edges of the plaque, increasing the amount of deformation the part can withstand before it fails. As the fibers align more towards the stiffer corners of the part, the compliance of the structure decreases, as does the energy to failure.

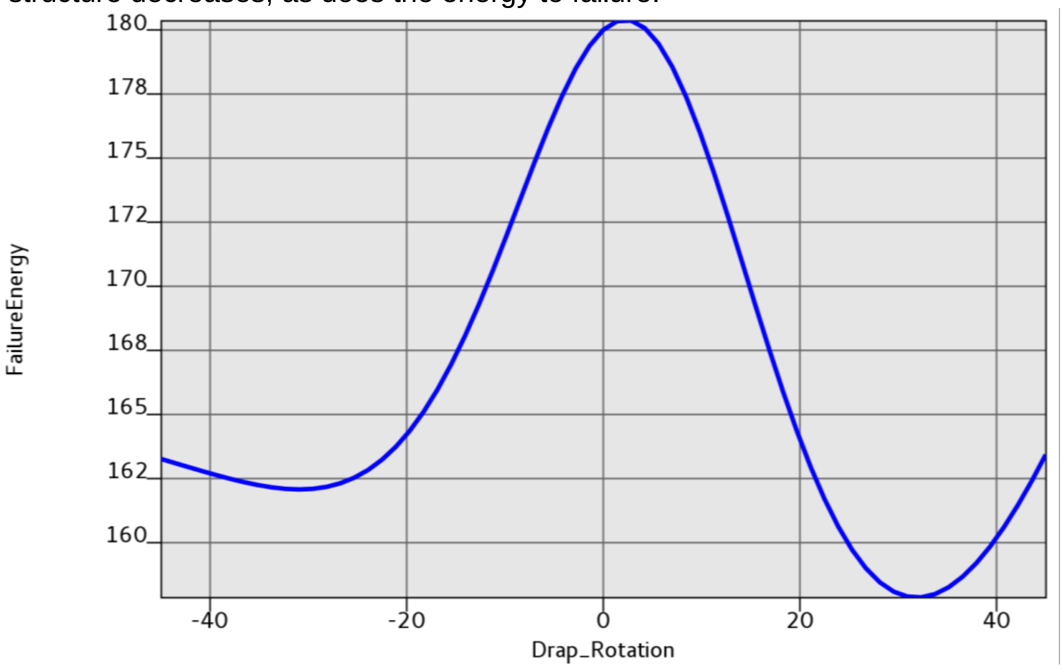

Figure 7 – Effect of Draping Angle on Energy to Failure.

Doming to reduce stiffness

Doming a surface is known to increase the stiffness of that surface, allowing the surface to better handle loads normal to the surface. Initial thoughts would suggest that either doming upwards or downwards would increase the stiffness of the part equally and thus allow more energy to be absorbed. However, figure 8 shows that a negative doming value is significantly better than a positive value.

In fact, a small positive doming adversely affects the energy absorption capabilities of the plaque. More than 5mm of positive doming is required before the energy absorption characteristics start to improve. However, even a small negative doming significantly improves the situation.

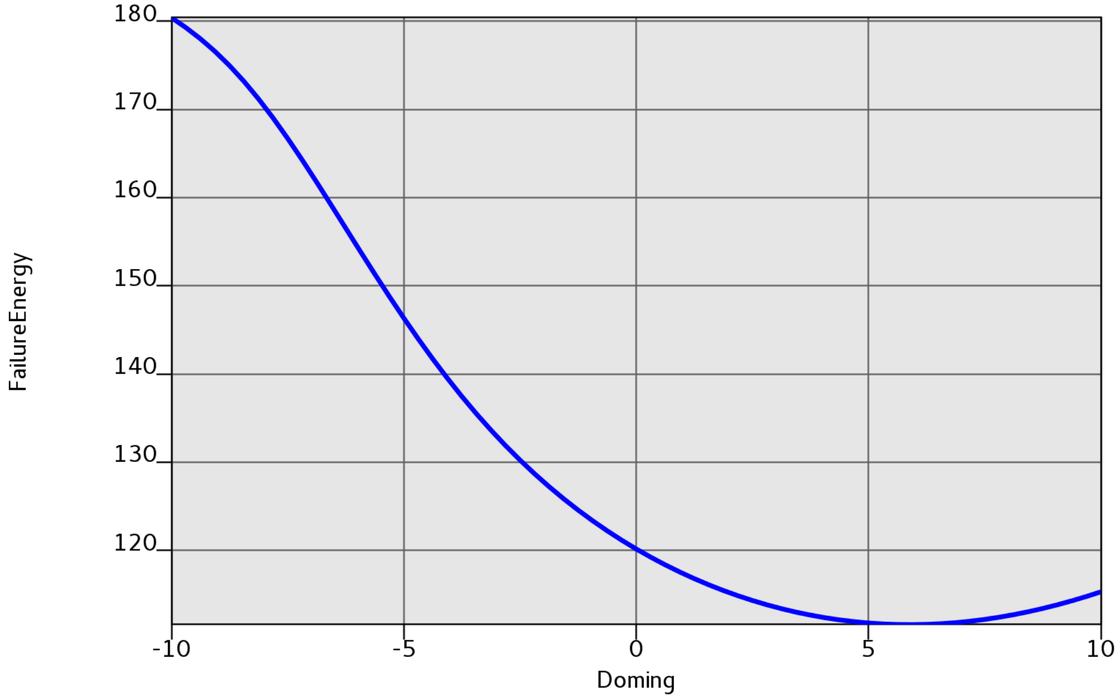

Figure 8 – Effect of Doming on Energy to Failure

Figure 9 shows a cross-section how the model would look like at a -10mm doming value. The ‘hump’ that is created near the edges acts as a buffer that allows the area under the impactor to deform more, increasing energy absorption. This is the reason that a negative doming is far more effective. Allowing the part to flex under load significantly improves performance.

A much greater positive doming is required to increase the compliance of the design. At small positive doming values, it only serves to increase the stiffness and the brittleness of the design.
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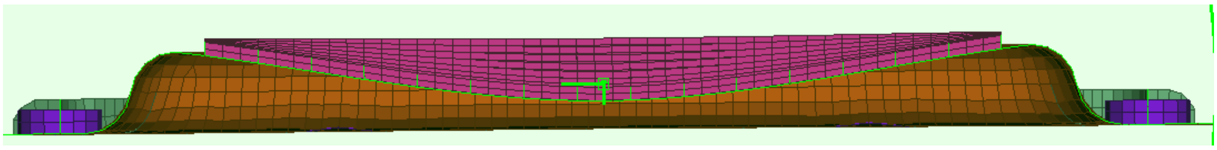

Figure 9 – How negative doming angle can decrease stiffness

Recommendations on rib height

5 parameters were chosen at different radial distances from the impactor. RingVar_1 controlled the rib height at the furthest distance from the impactor, while RingVar_5 affected the rib height directly under the impactor. Figure 10 shows the how each of these rib height

variables affects the energy to failure of the part under the assumption that all the other parameters are held at their optimum values.

The ribs at the furthest distances from the impactor (RingVar_1 to RingVar_3) seem to require a shorter rib height, despite the lack of any mass constraints. The only reasonable explanation is that a lower rib height in this region decreases the stiffness around the perimeter of the ribs, allowing more flexure of the part under the impact loading, allowing more energy to be absorbed. However, their impact on the stiffness is fairly small, and this shows in the minimal decrease in the failure energy as these values approach 5.5.

The ribs under the impactor (RingVar_4 and RingVar_5) favour taller ribs in order to maximize the amount of material directly under the impactor to help distribute the loads and allow more energy absorption by the failure of the ribs before the woven sheet fails.

RingVar_5 affects the control point directly under the roller, and its impact on how much the ribs actually morph by is limited, and although a tall rib is slightly favoured, there is not a significant decrease in failure energy by having a short rib structure.

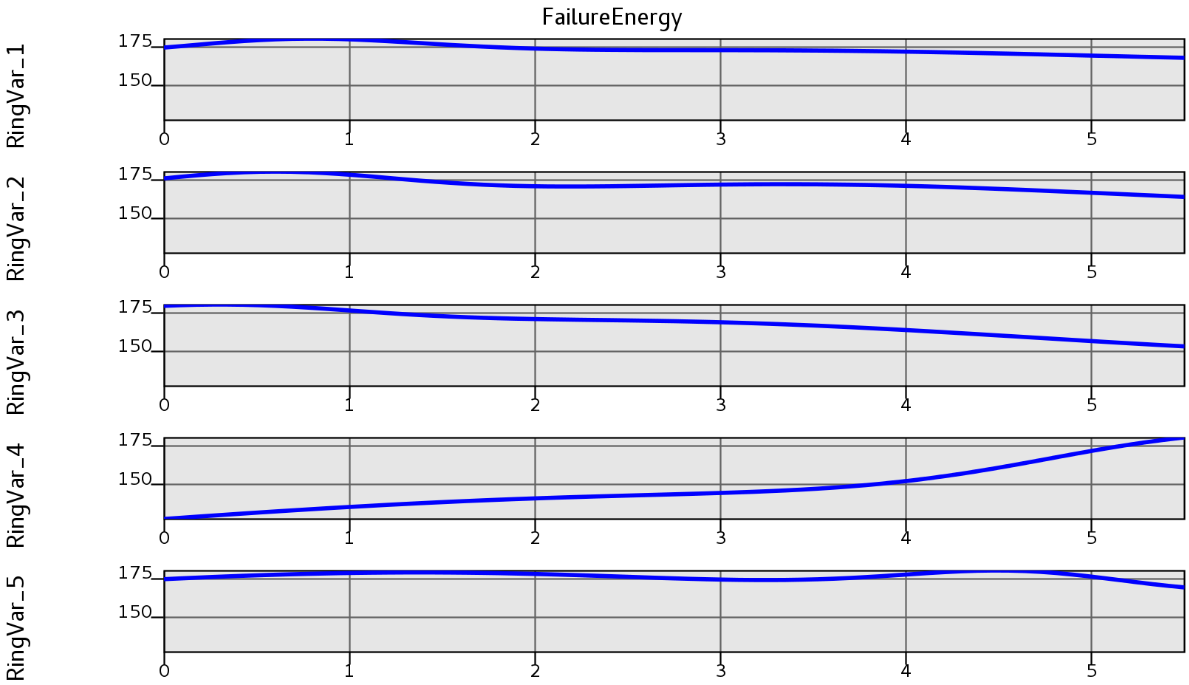

Figure 10 – Rib Height Optimized Values

5. CONCLUSION

This study provides insights into the design of a ribbed structure to withstand stone impacts. Stiffness is found to be very critical in the impact region to better distribute the load as widely as possible, as was expected. However, the compliance of the part became increasingly important further away from the impact location to allow the part to flex and absorb the energy.

In an actual part application, it can be difficult to determine exactly where an impact might occur, and therefore modifying rib height in local regions may not be appropriate. But allowing the side walls to flex more by either reducing their thickness, especially at corners, or by removing ribs that stiffen up the side walls can help the oil pan better withstand stone impacts.

In general, simply adding material to a part may not always be the best way to improve the part. Especially in impact and crash problems, where energy absorption is critical, allowing part flexure may actually improve the situation.

Regarding the software, the morphing capability of ANSA and its ease of set-up and compatibility with LS-OPT drastically simplified setting up the optimization problem. ANSA was more than capable of handling the complex morphing requirements and was able to perfectly morph two separate models in sync such that ULTRASIM® could still map between the two meshes. Setting up the response in μETA proved straightforward in defining a relatively complex response from the analysis programmatically.

6. ACKNOWLEDGEMENTS

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