SIMULATIONS ENABLING MULTIMATERIAL AUTOMOTIVE ASSEMBLIES

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Abstract

Adhesive bonding of multimaterial substrates will often cause dimensional issues due to differences in thermal expansion. This can require designing bonding conditions that mitigate dimensional change as much as possible. The state of the art for adhesive modeling is effective but computationally expensive, limiting the size and complexity that can be modeled. In order to make modeling of large, complex adhesive bonded multimaterial structures possible, a combined shell and solid element finite element model has been developed which captures most of the results that can be obtained using a solid element model only but which allows for great flexibility in size and complexity.

Introduction

As new materials, such as fiber reinforced polymer composites, become more prevalent in automotive structures, multimaterial bonding will be necessary. This can create dimensional issues due to the large differences in coefficients thermal expansion (CTEs) between different materials. Finite element models can help guide the bonding process to design a bonding process that mitigates the effects of CTE mismatch between the substrate materials. COMPRO, a simulation tool made by Convergent Technologies, can solve the physics involved in an adhesive bonding process. However, its restriction to only solid elements means that COMPRO cannot feasibly be used on complex geometries (like most automotive geometries are) because they are so difficult to mesh and computationally expensive to run. Therefore, it would be advantageous for the automotive industry to have an analog to COMPRO that allows for shell elements (COMPRO restricts its software to solid elements for a reason that will be discussed subsequently).

Material Properties

The goal is to create a joining model that will be able to estimate residual deformation and stress so it can be used to guide decisions in the bonding process to mitigate final part warpage. The physics involved in this process that must be included are adhesive cure kinetics and modulus development as well as a standard thermal and mechanical characterization of adhesive and substrates. In this paper a bonding between a Dow carbon fiber SMC material and aluminum will be modeled. Since the carbon fiber SMC has a very low CTE and aluminum has a high CTE, bonding these materials can create severe warping issues. A Dow 2K adhesive will be used to bond the substrates together.

Cure Kinetics

Estimating the cure kinetic behavior of the adhesive is critical since the modulus of the adhesive is dependent on it degree of cure and the temperature at which the adhesive modulus is developed determines to a large part the amount that the assembly will warp when it cools down. Cure curves are generated using a differential scanning calorimeter (DSC) by measuring the heat which is generated during cure. The heat curves are then integrated with respect to time and divided by the total heat of reaction to generate degree of cure curves. Figure 1 shows the heat flow curves of the 2K adhesive at several different temperature conditions. Figure 2 shows the degree of curves for the same data.

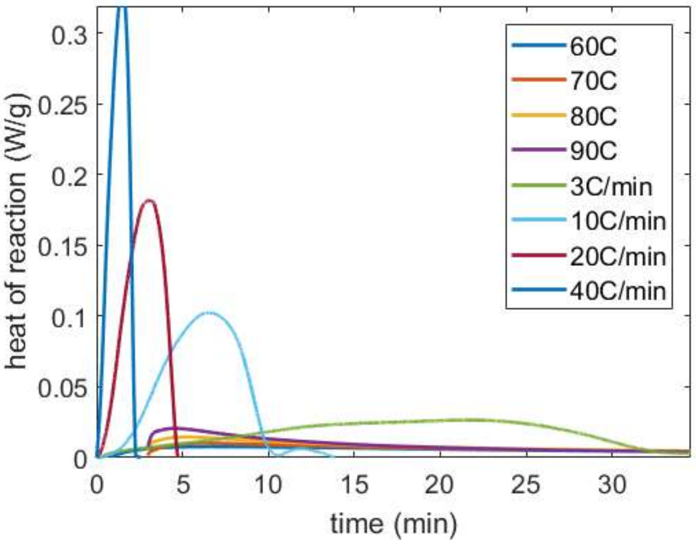

Figure 1: Heat flow curves for a Dow 2K adhesive.

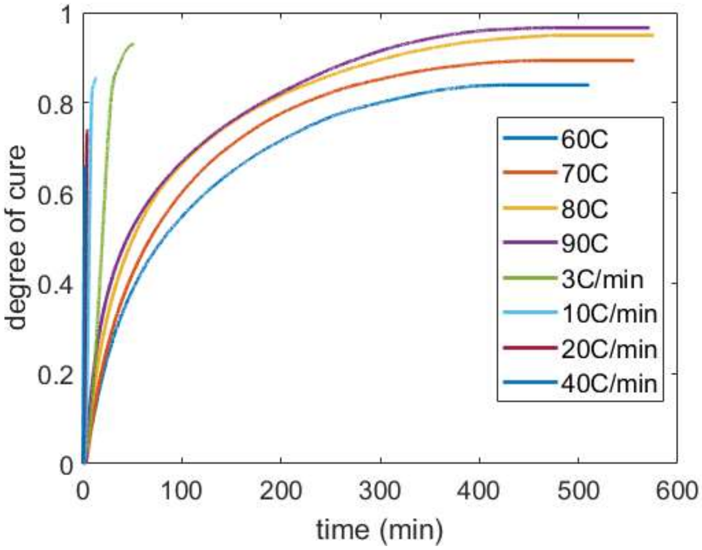

Figure 2: Degree of cure curves for a Dow 2K adhesive.

This data is used to fit a surface of the cure rate as a function of temperature and degree of cure. Figure 3 shows an image of the fitted cure rate surface with the data. This method works very well as long as the model will be estimating the cure rate within the region that the data has been taken. For all models shown in this paper this will be the case.

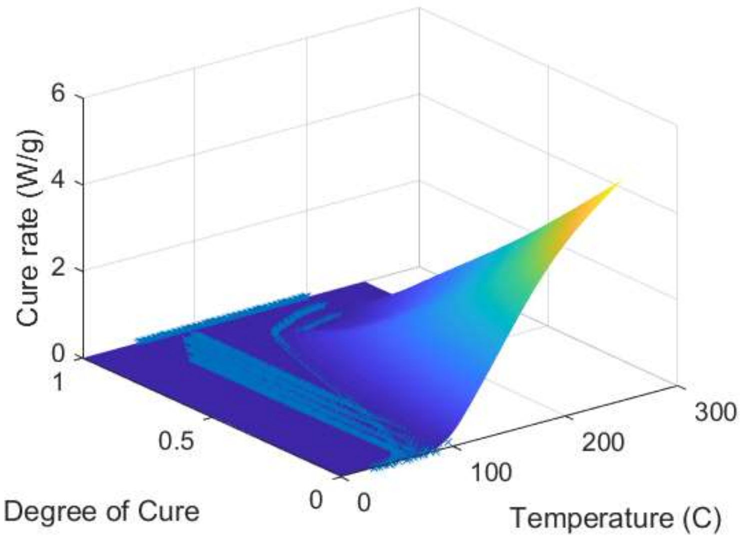

Figure 3: Cure rate surface.

Modulus Development

Adhesive modulus is typically treated as a function of degree of cure and temperature relative to the glass transition temperature. For this work, the adhesive was fit to a modulus model developed by Khoun[1], with the glass transition temperature being fit to the Dibenedetto equation[2]. Figure 4 shows the temperature dependent modulus of the cured adhesive as measured on a dynamic mechanical analyzer (DMA) compared to the model.

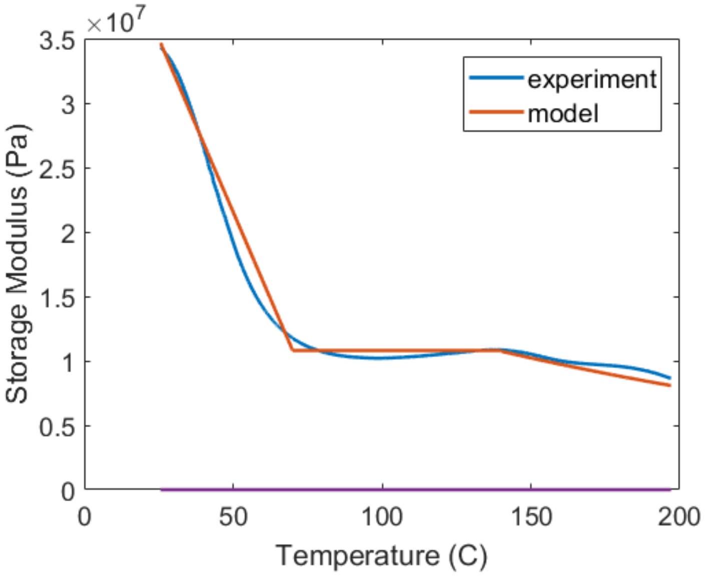

Figure 4: Modulus of the cured adhesive as a function of temperature.

Thermal Properties

Because a heat transfer analysis is a part of the adhesive bonding model, thermal properties must be measured for the substrates and adhesive. Table 1 shows the thermal properties for all materials used in the model.

Table 1: Thermal properties of all materials.

	Aluminum	CF-SMC	Adhesive
Specific Heat (J/kgC)	896	1450	1640
Thermal Conductivity (W/mK)	167	2.1	0.148
CTE (με/°C)	23.6	5	4

Mechanical Properties

The mechanical properties of the substrates are also needed for the model. The properties for the aluminum substrate were taken from publicly available data for aluminum 6061 and the CF-SMC properties were measured and are shown in table 2.

Table 2: CF-SMC mechanical properties.

Property	Value
E_1 (GPa)	141
E_2/E_3 (GPa)	7.5
ν_{12}	0.32
G_{12} (GPa)	5.7

Model Verification

A model was developed in ABAQUS using user subroutines which sequentially couples a heat transfer analysis to a stress/deformation analysis with user subroutines calculating the cure kinetics of the adhesive and the properties of the adhesive being estimated using the temperature and degree of cure of the adhesive. When only solid elements are used, this model calculates the same things that can be done using COMPRO. Therefore, COMPRO was used to verify that the model was programmed correctly. A simple hem flange geometry was used to compare results. A picture of the meshed geometry is shown in figure 5. Outer surfaces of the geometry were given a heat transfer coefficient of 10 W/m^{2}K and the ambient temperature was ramped from 20 C to 200 C and then ramped back down to 20 C. The model was running with identical material properties and boundary conditions using 1) COMPRO; 2) an ABAQUS user subroutine model using only solid elements, which will be referred to as the “UMAT” model; 3) an ABAQUS user subroutine model using solid elements for the adhesive layer and shell elements for the substrate layers, which will be referred to as the “UMAT SHELL” model. The temperature, degree of cure, displacement, and stress for each model was compared at a point in the middle of the adhesive layer at one of the ends. Figures 6 through 9 show the comparison between these models.

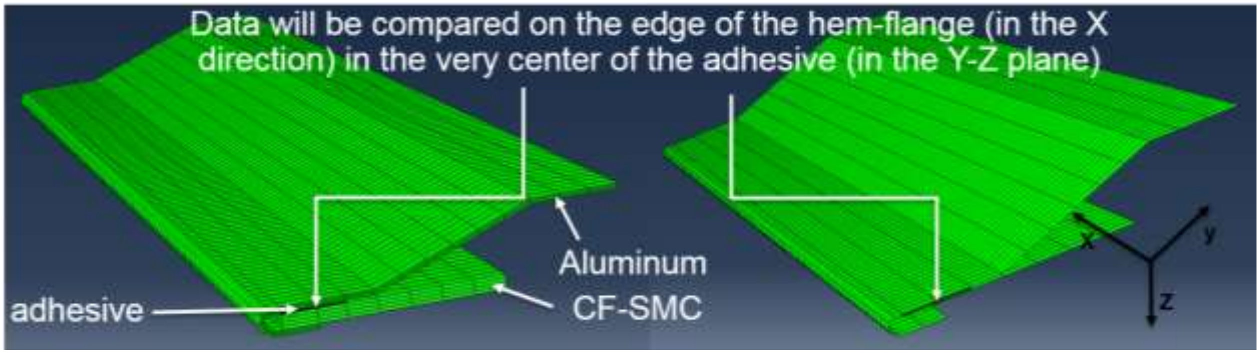

Figure 5: Bi-material strip geometry.

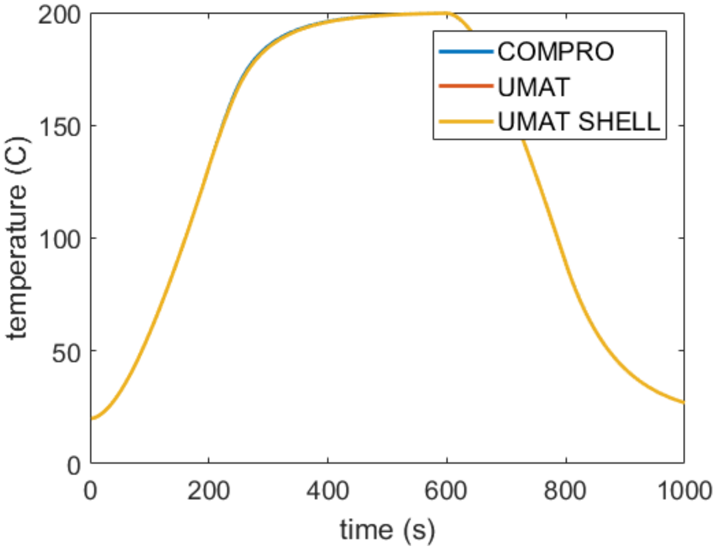

Figure 6: Temperature comparison.

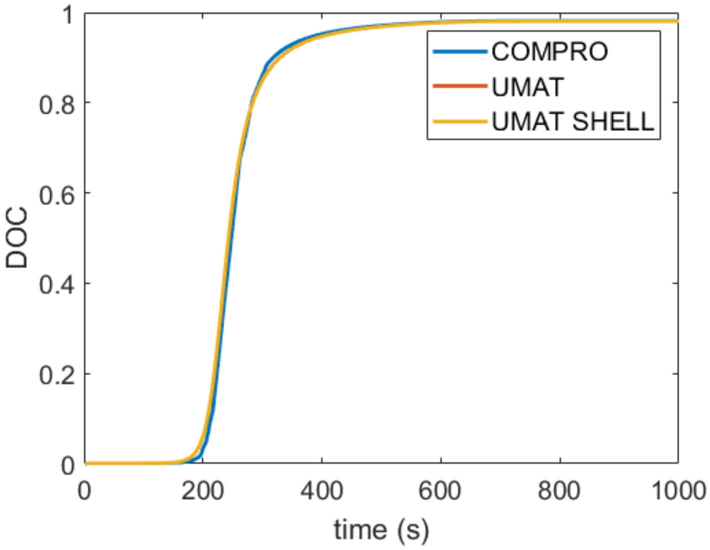

Figure 7: Degree of cure comparison.

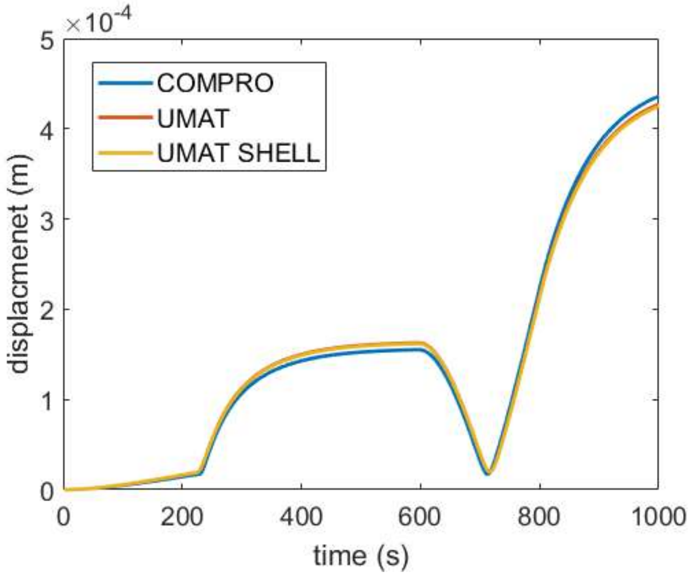

Figure 8: Displacement comparison.

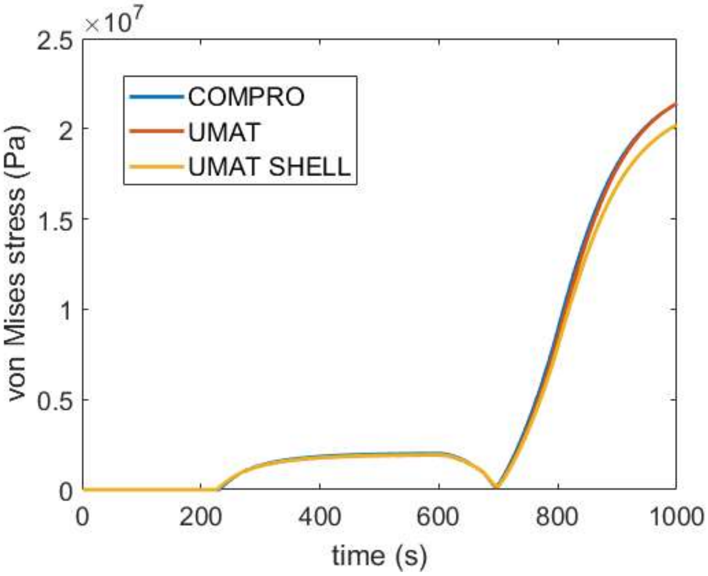

Figure 9: Stress comparison.

As figure 6 shows, the temperatures are essentially identical for all three models. In figure 7, the COMPRO model shows a slightly different degree of cure profile than the two UMAT models. All three models were given the same cure kinetics data and the temperature inputs were the same for all the models, so most likely this difference is due to a difference in either the numerical method used to estimate the cure rate at each time step or the algorithm used to determine what the time step should be. The UMAT models utilized a 4th order Runga-Kutta method with a time step algorithm which limits the amount the temperature or degree of cure can change in one time step. It is unknown what is used inside COMPRO. Likely because of the slight difference in the cure kinetics curves, the displacement curves also show a slight difference (maximum difference of about 2%) between the COMPRO and UMAT models. The stress results show close agreement between the COMPRO and UMAT models with the UMAT SHELL model showing a maximum difference of about 5%. The reason for this is that the shell elements are not able to generate a stress gradient through the thickness of the substrate while the solid element models are. Figure 10 shows the comparison between the stress fields in the UMAT and UMAT SHELL models and shows that the results are similar but not identical because of the inability of the shell model to vary through the thickness. This is the reason that COMPRO restricts its code to only using solid elements and it is a drawback to using the UMAT SHELL model; the stress results are not captured accurately. However, for complex geometries in which meshing and running a model using only solid elements is not possible, this is an acceptable tradeoff to be able to get good estimates of the displacement of the part, which is often the result of main interest anyway.

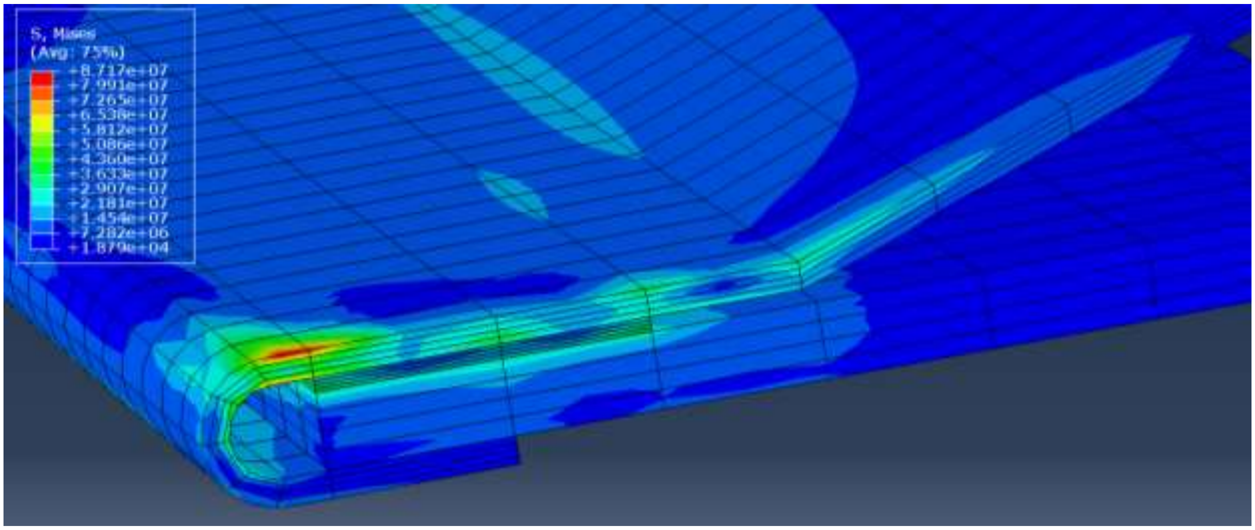

Figure 10: Stress distribution at the final time step for the UMAT model.

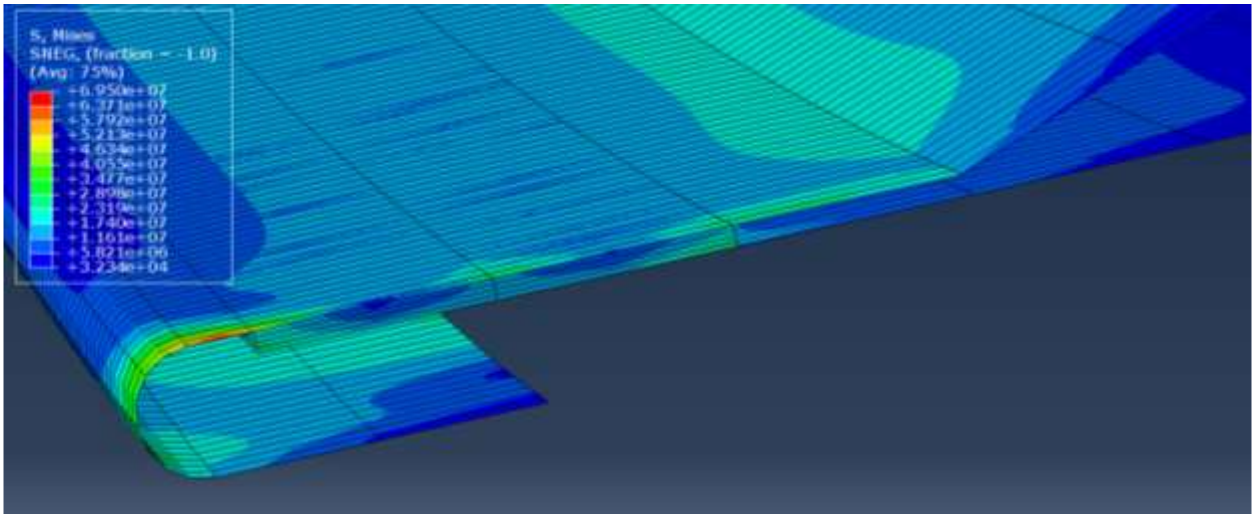

Figure 11: Stress distribution at the final time step for the UMAT SHELL model.

Figures 12-14 show meshed geometry images of a Ford prototype decklid which is an example of a geometry for which it would not be feasible to mesh or run using only solid elements. The shell element model can be meshed and run without any issues, however. Even with some error in the stress state of the part, this model can be extremely useful for designing bonding processes which mitigate thermal CTE mismatch issues as much as possible. Table 3 shows that the UMAT SHELL model runs about 20 times faster than the COMPRO model. For complex geometries the difference would likely be even greater because of the difficult which arises in trying to mesh a complex geometry using solid elements.

Table 3: Run times for COMPRO and UMAT SHELL models.

	Run time (seconds)	
Model	COMPRO	UMAT SHELL
Heat Transfer	1241	156
Stress	5307	158
Total	6548 (109 minutes)	314 (5 minutes)

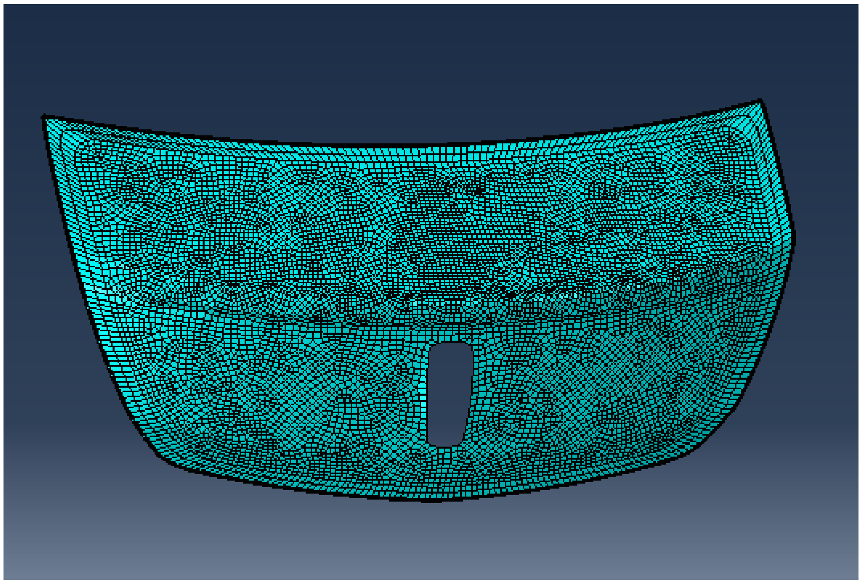

Figure 12: Ford prototype decklid aluminum outer surface.

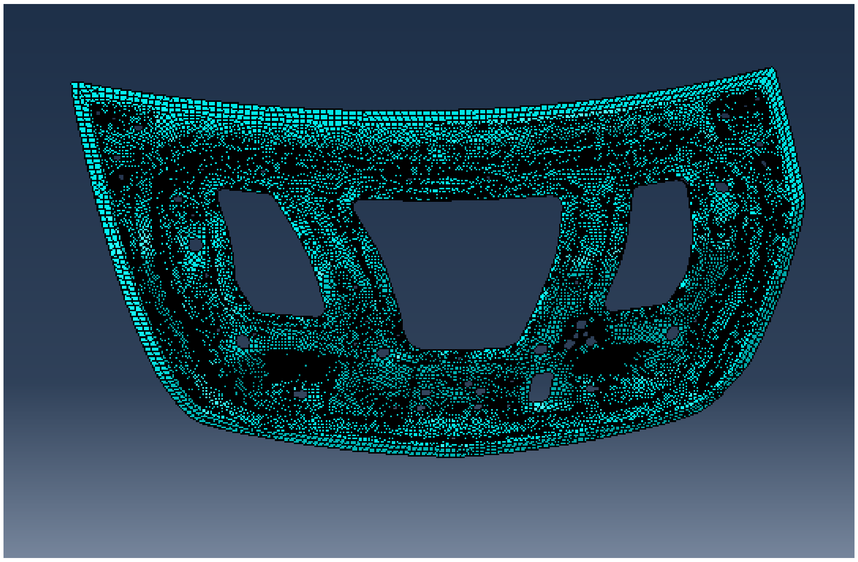

Figure 13: Ford prototype decklid CF-SMC inner surface.

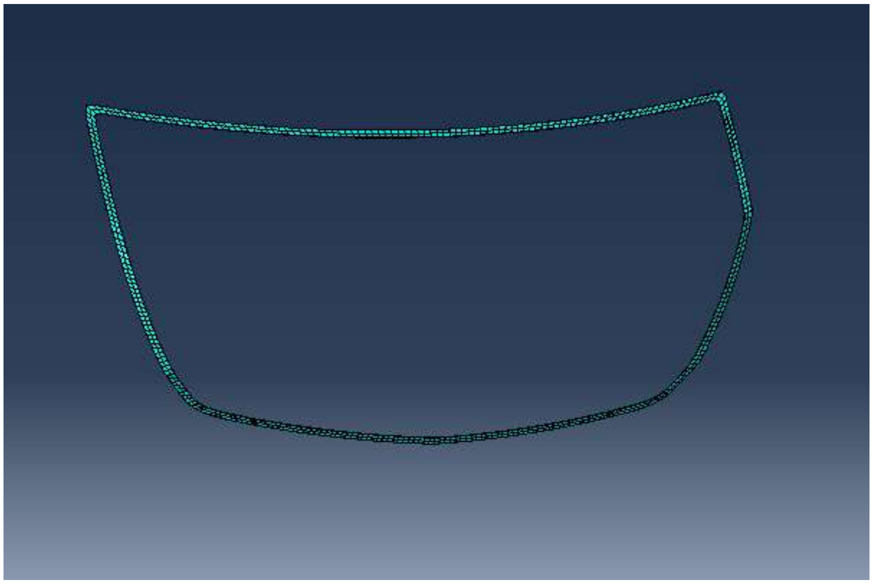

Figure 14: Ford prototype decklid adhesive bond.

Conclusion

Multimaterial bonding is an increasingly important process in the automotive world that often creates technical difficulties. Being able to simulate the bonding, even of very complex geometries, can help when exploring feasibility or can help guide the design of the bonding process. A new model which utilizes shell elements has been developed and verified

Acknowledgements

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2. DiBenedetto, A. T. "Prediction of the glass transition temperature of polymers: a model based on the principle of corresponding states." *Journal of Polymer Science Part B: Polymer Physics* 25.9 (1987): 1949-1969.Hangs, B., C. Esch, M. Reif, T. Huber, & F. Henning, “Integration of Features into Parts Made from Thermoplastic, Unidirectional Tape — Overview and Case Study,” SPE ACCE, Sept. 2011, Troy (Detroit), MI, http://speautomotive.com/SPEA_CD/SPEA2011/pdf/RNF/RNF2.pdf .