Material Model Development for Impact Strength Validation of a Composite Truck Bed Design

Emily Nutwell
Honda R&D Americas
Currently with Altair Engineering

Dylan Thomas
Honda R&D Americas

Abstract

A recently developed pick-up truck has a unique bed structure which includes an under bed storage system. This truck bed and storage system design is made of sheet molded composite (SMC) material. SMC is a composite material where chopped glass fiber is laid on a poly(vinyl)ester sheet and run through a compaction process. SMC sheets are then loaded into a press to mold the desired part. During the molding process, certain design features such as molded-in ribs can cause the random orientation of the glass fibers to become directional, causing non-homogeneous material properties in the final product.

A finite element material model of the SMC material was developed using material tests performed on flat SMC specimens and SMC specimens with molded-in ribs. This paper presents the details of the SMC material model development and application of the model to static and impact strength simulations on the truck bed design. The truck bed design did not include molded-in ribs, as simulations showed these ribs would crack during impact requirement tests. Furthermore, simulation was able to validate the final design prior to test without having to re-work the tooling.

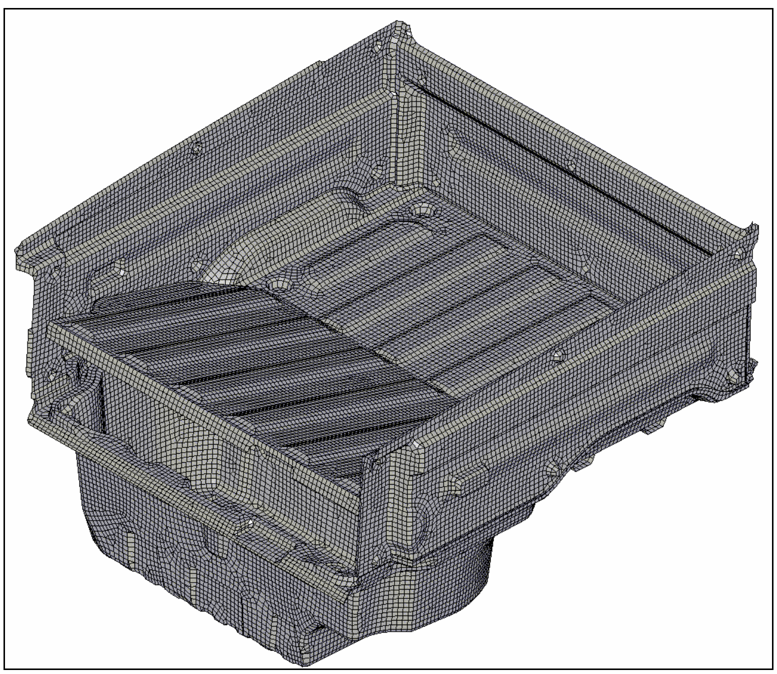

Figure 1: This figure shows a finite element model of the final truck bed design. This model was used to simulate impact and static strength requirements prior to the creation of mass production tooling.

Introduction

A new pick-up truck on the market is built using a ladder frame structure integrated into the unibody, rather than the typical body-on-frame structure. This vehicle also has a four-wheel, fully independent suspension system. This underbody layout allows for the design space to include a unique under-bed storage system. For this design, steel was not considered an option, due to cost, weight and manufacturability. An alternate material was needed that could accommodate the more complex truck bed design. This new material needed to be dent and corrosion resistant, as well as meet the manufacturer's impact and static strength requirements for a truck bed.

Sheet Molding Composite (SMC) is a sheet material that consists of randomly oriented glass fibers imbedded within a heat curable resin. SMC was selected as the material for the truck bed since it was lightweight and could be molded into the desired shape. Use of SMC also allowed the impact and strength requirements of the truck bed to be achieved. The LS-DYNA [1] "*MAT_PLASTICITY_WITH_DAMAGE" (MAT81) material model was chosen to represent the SMC during finite element simulations as this material model allows for damage to be considered as well as failure based on plastic strain.

SMC is essentially isotropic in the plane of the sheet due to the random orientation of the glass fibers. Certain design features, such as molded-in ribs can cause directional orientation of the glass fibers. In these highly detailed features, the fibers align themselves during the manufacturing process. The LS-DYNA MAT81 material model was also used to represent these features; however, different material properties were applied in order to account for the variation expected due to the directionality of the fibers. The properties for the LS-DYNA material models were developed by testing small specimens and then correlating LS-DYNA simulations models to match the test results.

Impact and strength requirements were validated by building small test parts which represented certain areas of the final design intent for the truck bed. Impact and static strength tests were performed on these parts in tandem with LS-DYNA simulations of the same test. This process allowed for a damage scale to be defined that related plastic strain values present in the LS-DYNA models to the visual damage observed in the actual test parts.

The result of this effort drove the design away from features such as molded in ribs, and any other highly detailed molded-in feature, to a structure which included bonded steel ribs that also serve as the mounting structure for the truck bed to the body. This final design was then tested when prototypes of the truck bed were available, and no major problems were found relating to the impact strength of the truck bed.

Material Model Development

Flexural testing of flat SMC specimens was performed in order to develop the material model. Figure 2 shows the test setup schematically, while Figure 3 shows typical test results.

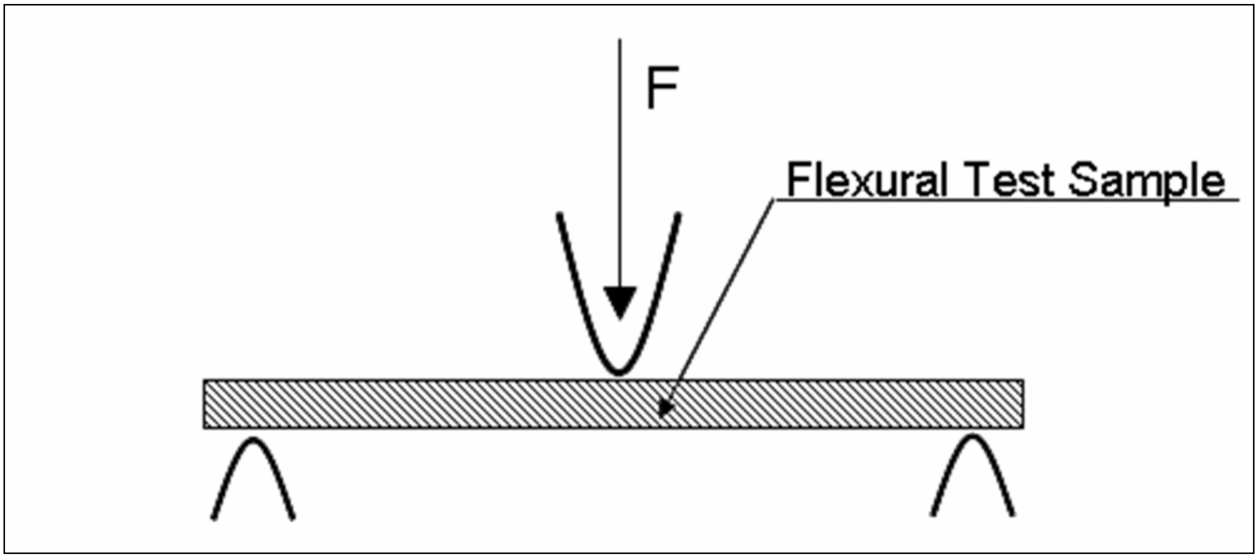

Figure 2: This figure shows a schematic diagram of the flexural test setup that was used to determine the base material yield properties of SMC.

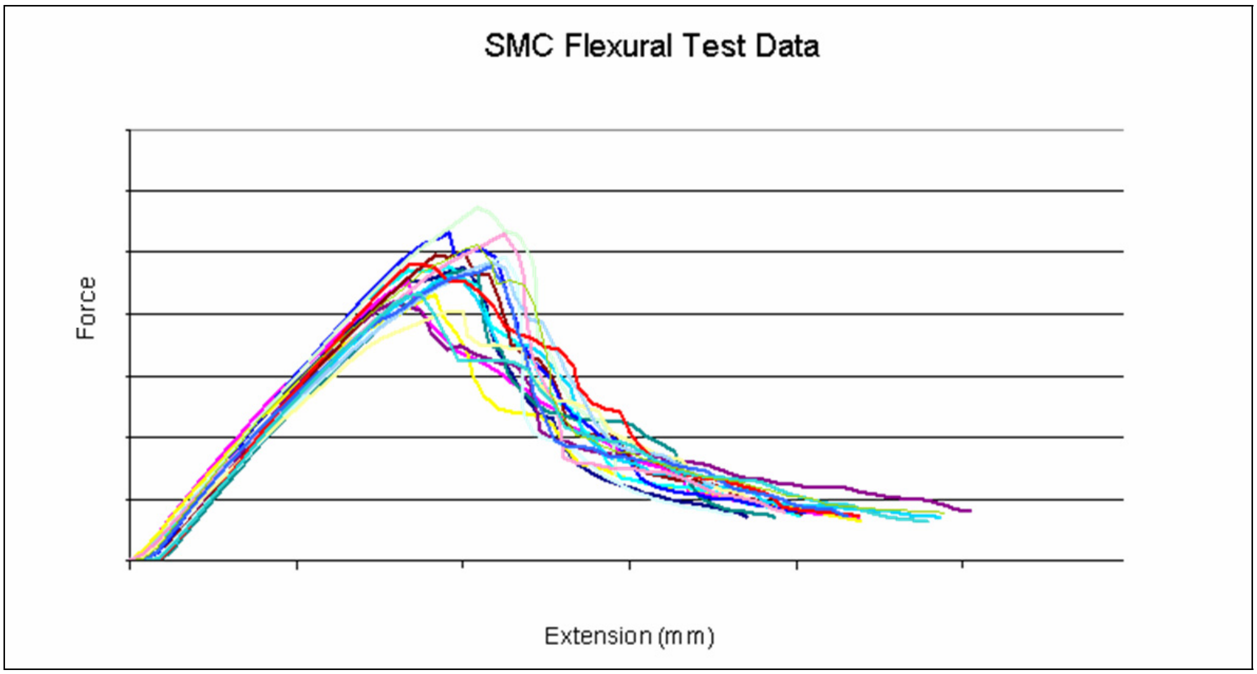

Figure 3: This figure shows test data from a typical flexural test series.

As shown in Figure 3, there was a significant amount of variability in the flexural test data. The intent was to model the part as a homogenous material so the test data was averaged to obtain a reference curve that could be used to determine the material properties for the simulation model.

Once the flexural test curve was averaged to best represent the material of the final test part, a simulation of the same test was performed. The simulation model was correlated to the test by adjusting the MAT81 material properties of the Young's modulus (E), the tangent modulus (ETAN), the plastic strain at which the material begins to soften (EPPF) and the plastic strain at failure (EPPFR). Figure 4 shows the results of this correlation with the reference test curve.

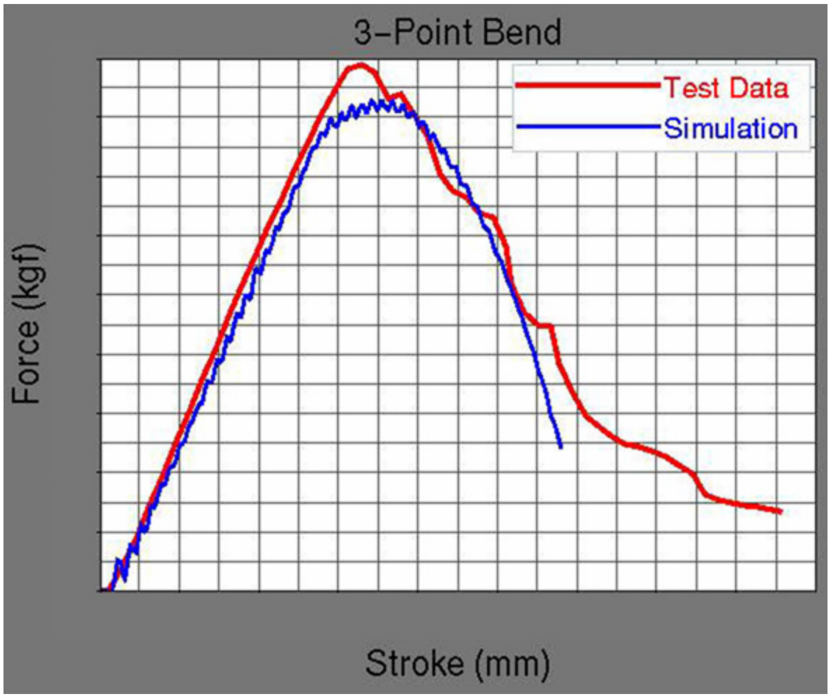

Figure 4: This figure shows the correlation of the final simulation model to the averaged flexural test data.

Effect of Design Features

One of the advantages of SMC is that small design features can be molded into the part. In particular, reinforcing ribs can be molded from the flat sheet during the compaction process. A simple tool was manufactured so that test specimens with different rib designs could be evaluated. Flexural testing was performed on these specimens with molded-in ribs and new LS-DYNA simulations were performed. Figure 5 shows one of these simulations.

It was found that if the material properties that were derived from tests on the flat specimens were also used for the rib in the new simulation models, the simulation models did not correlate well, as shown in Figure 6. Thus, the material properties for the ribs had to be created separately so that the simulations would correlate. For this particular case, the Young's modulus and the yield strength for the rib material was reduced by approximately 50%.

In order to understand why the rib was so weak compared to the base material, the resin was burned off of the test piece, and the glass structure was examined. Figure 7 shows one of the test specimens before and after the resin was burned off. When the resin was burned off, it became apparent why the molded in rib was considerably weaker than the base SMC. During molding, as the glass fibers get extruded into the rib, they become oriented vertically along the rib. Figure 8 shows the same test specimen from different angles. Also shown in Figure 8 is the presence of a resin-rich area at the root of the rib. This resin-rich area would further reduce the strength of the product that was designed to use molded-in ribs.

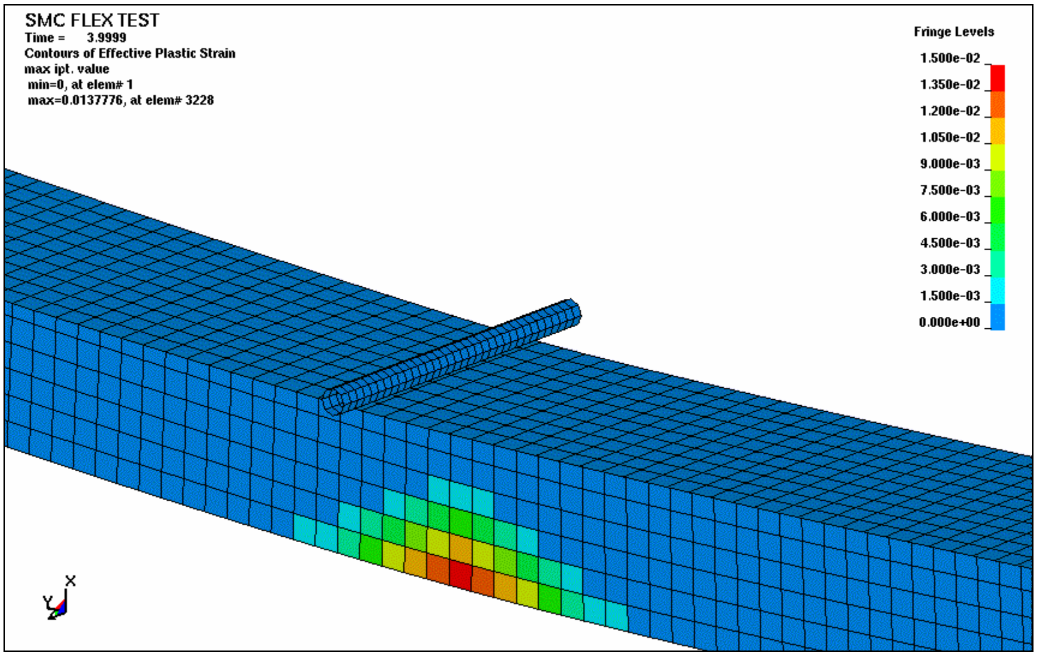

Figure 5: This figure shows the simulation of the flexural test of SMC with a molded in rib. As expected, the maximum effective plastic strain is at the bottom of the rib. The rib also has much weaker properties than the base SMC material.

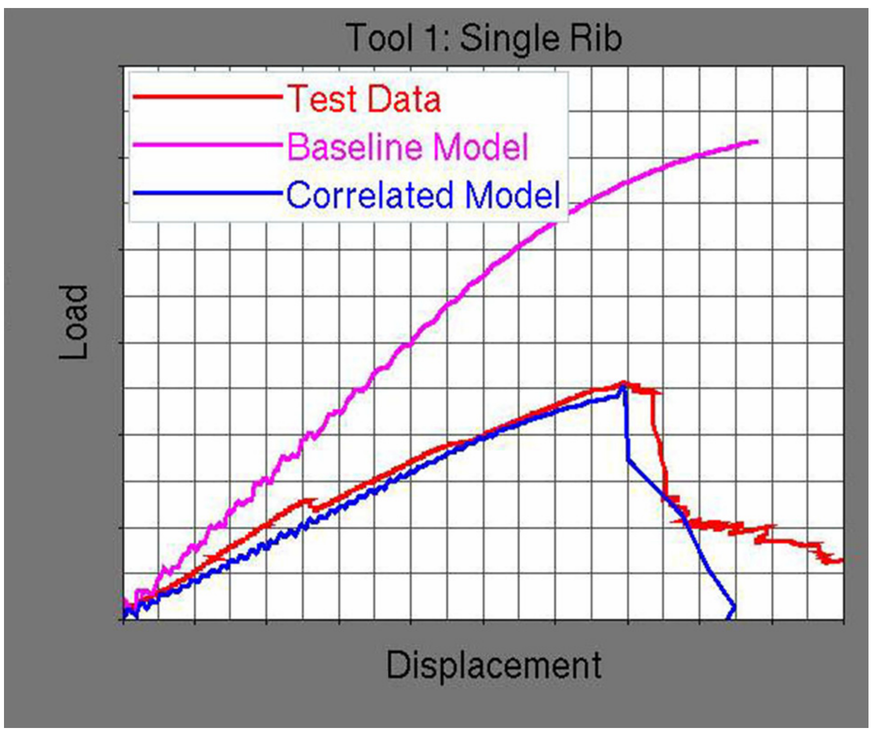

Figure 6: This figure shows the force-stroke correlation of the simulation model of molded in rib flexural test. The baseline model used the same material properties for the top and the molded rib, while the correlated model used updated material properties for the rib.

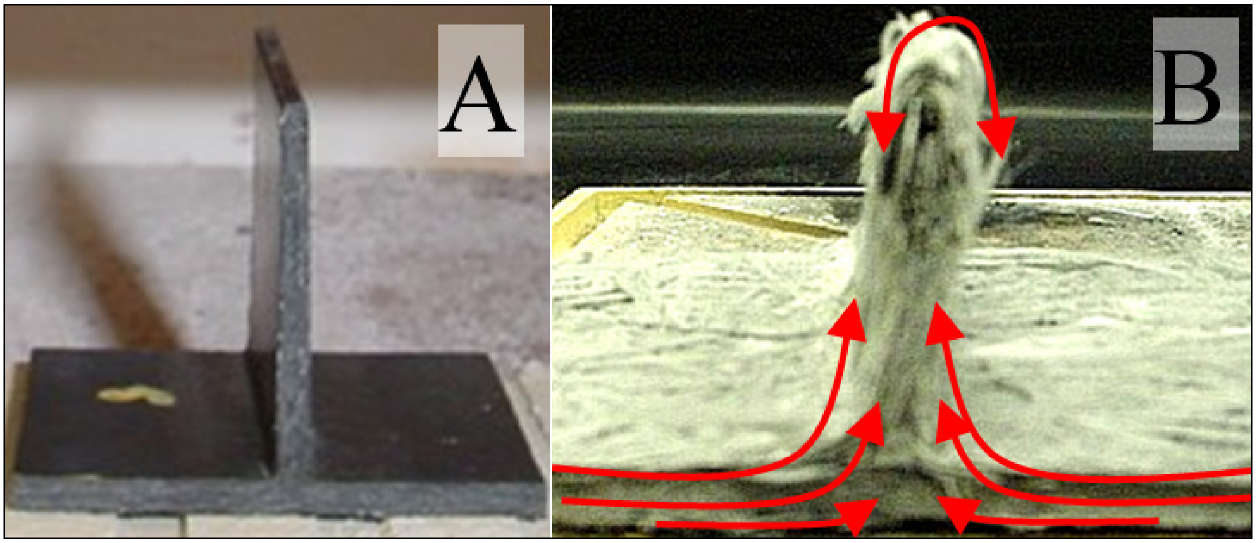

Figure 7: This figure shows the molded in rib before (A) and after (B) burn-off of the resin. Note how the glass fibers get folded into the rib during the molding process.

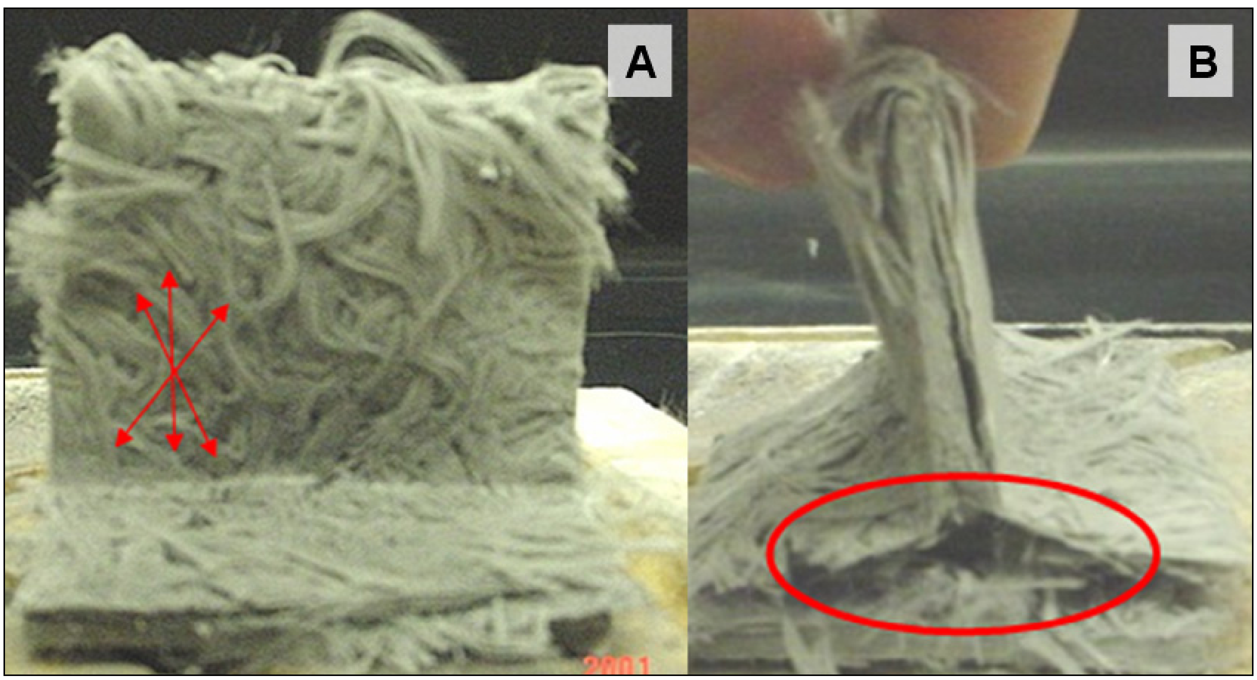

Figure 8: This figure shows how the glass fibers tended to align vertically during the molding process (A). This reduces the strength of the rib in the horizontal direction. Also shown is how a void at the base of the rib is created during molding, further reducing the strength of the product around the root of the rib. (B)

After burning off the resin, it became evident that different material model properties were necessary for the rib and the base SMC material. It was also found that different rib designs required different material properties since the flow of the glass fibers into the rib was dependent on the geometry of the rib. As shown in Figure 6, using the same material properties that were developed for the flat SMC sample in the rib portion of the design would significantly over-predict the strength and impact performance of the design.

One final concern for the molded-in ribs was the resin rich portion at the bottom of the rib that occurs because the glass fibers get folded into the rib during molding. Without glass fibers to reinforce this area, the impact toughness of the rib would be reduced at the bottom of the rib, which is where the maximum stress occurs during loading. Once a crack was initiated at the bottom of the rib, it lost its effectiveness in stiffness, impact, and strength. Since the truck bed was required to withstand impact loading, molded in ribs were not included in the final design.

Impact Testing and Simulation

The actual impact test criteria for the truck bed are qualitative in nature, and are based on the visual appearance of the truck bed after drop testing was performed. Impact damage such as cracking, blistering and fiber tearing in the SMC would determine whether the test was successful. Determining the presence of such failures through the use of simulation was problematic, so a method that related the effective plastic strain in a simulation to SMC damage in a component level test was derived. The component test piece was manufactured to represent the design intent of the floor of the in-bed storage system. This test piece matched the final design in material thickness, overall dimensions and other basic design features. Figure 9 shows the component level test and the simulation model of the same test.

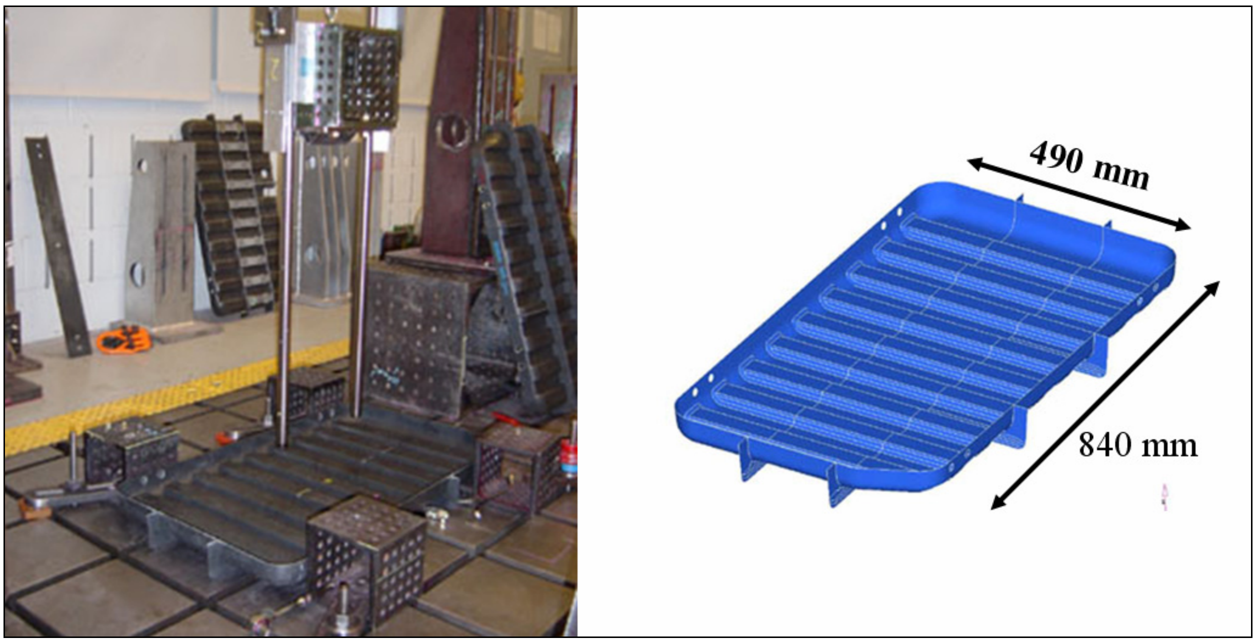

Figure 9: This figure shows the component level drop test that was used in conjunction with simulation to determine the safe levels of effective plastic strain that could be present in the final part, for a successful test.

In order to quantify the visual judgment criteria established early on during testing, a rigid test fixture was dropped from various heights to establish damage levels that were acceptable, marginal, and unacceptable. Based on the results of these drop tests, the damage present when the rigid fixture was dropped from 500 mm was determined to be acceptable, while the damage present at a drop of 575 mm was unacceptably severe. The LS-DYNA simulation model shown in Figure 9 was used to perform the same drop tests from heights of 500 mm and 575 mm. The effective plastic strain values at the top and bottom surface of the SMC was used to define a damage scale that could be used to judge the final truck bed design at critical locations. Figure

10 graphically shows the judgment criteria that were developed using the component level tests and simulations. These same criteria were used within simulations that directed the final truck bed design during development, prior to the production of tooling. Figure 11 shows one of the drop test simulations being performed on one of the potential designs for the underbody storage system in the truck bed.

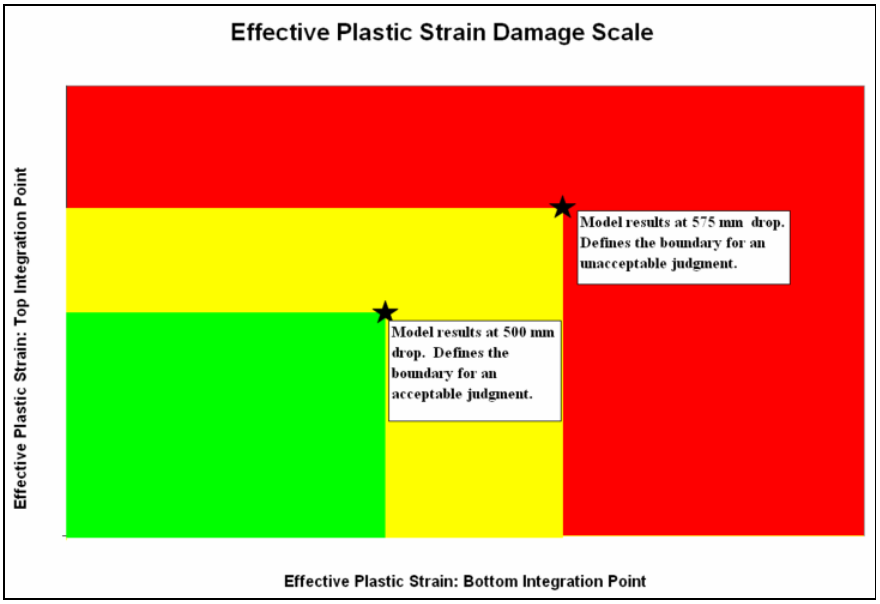

Figure 10: This figure shows the damage scale that was created based on observed effective plastic strain at the upper and lower surface integration points of drop-test simulations.

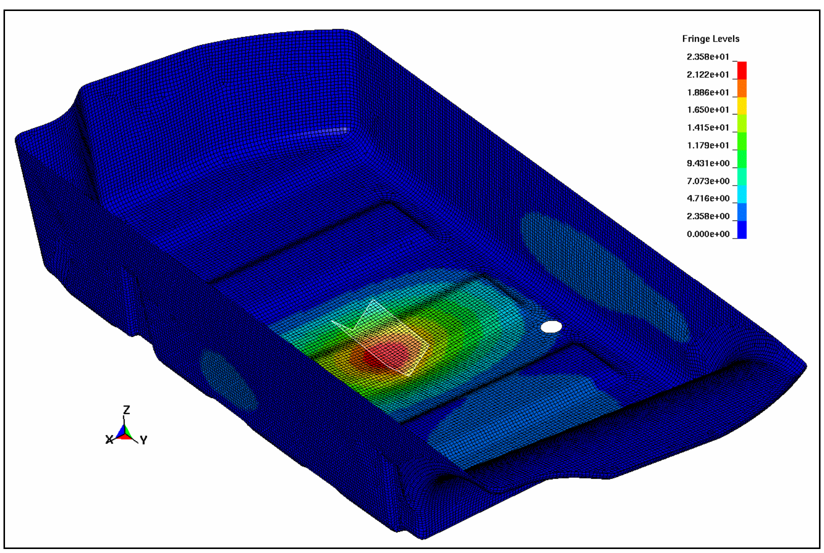

Figure 11: This figure shows an impact simulation being performed on one of the potential designs for the under body storage system for the truck bed.

Quasi-Static Strength Analysis

Another consideration for the truck bed design was to protect against damage when large objects with small footprints, such as appliances, were loaded onto the truck bed. These requirements range from a no yielding requirement, to no functional loss, to a severe usage requirement which protects against sudden failures. Figure 12 shows the test specimen that was used for this analysis. The specimen was similar to that used for the impact analysis; however, steel cross members were bonded to this test piece in order to represent the construction of the floor of the truck bed. The test specimen was loaded through a 30 mm diameter rigid tool. A simulation of the static strength test was created and compared to the test results. The yield point was found to correlate well between the simulation and the test. The failure load from the test was noted and the effective plastic strain in the simulation at the same load was used as a judgment criterion for other static strength simulations that were performed on the complete truck bed model. Using the same plastic strain values obtained from the small scale tests, the final design of the truck bed construction was validated using simulation, prior to the creation of mass production tooling.

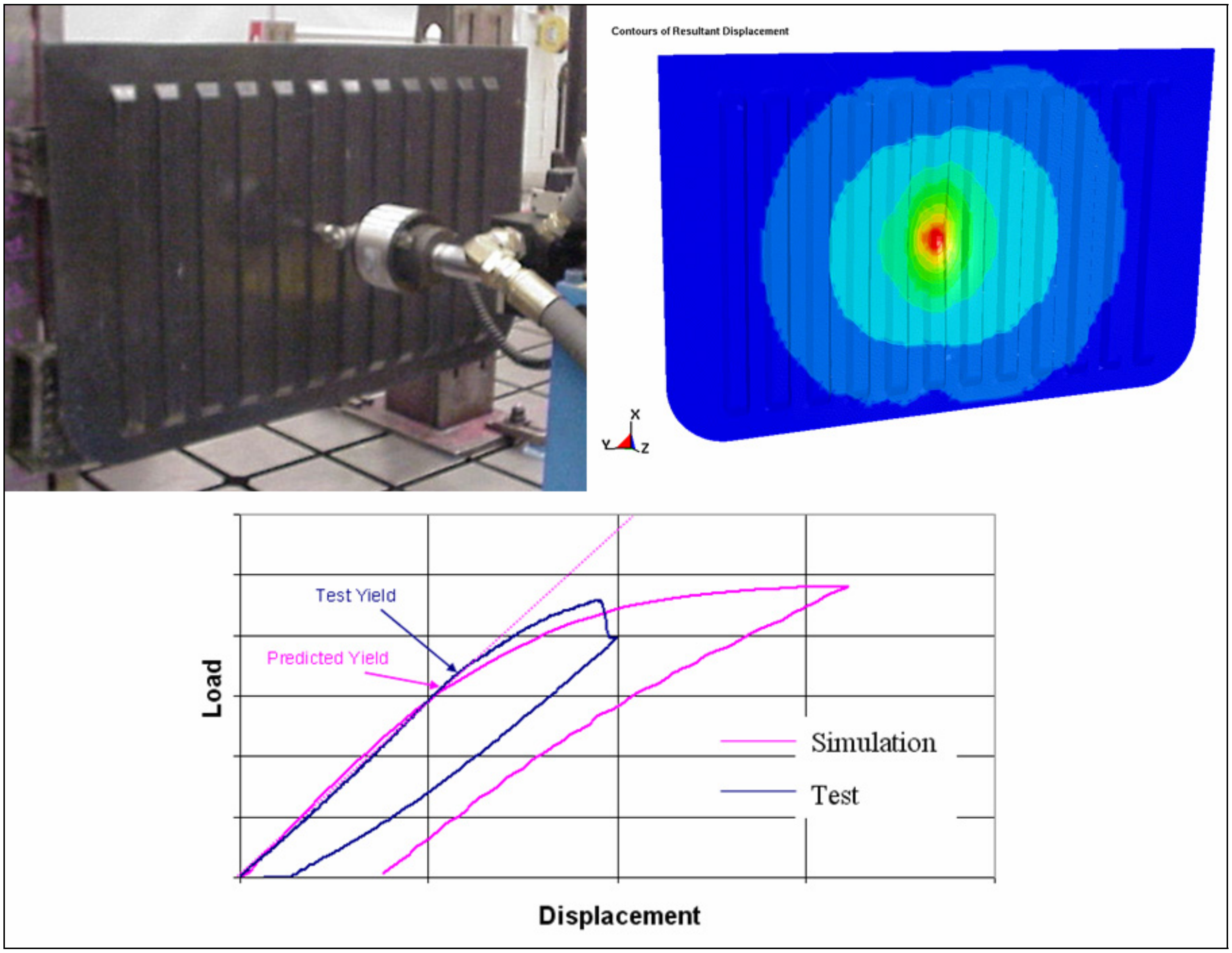

Figure 12: This figure shows the quasi-static component level tests that were performed on the lid of the truck bed, and the truck bed floor. Contours of displacement are shown for the simulation, along with the load-versus displacement curves from the test and simulation.

Conclusions

In this paper, a methodology was presented to develop a material model that would adequately validate the design of a truck bed constructed from SMC. Because the impact and strength performance of SMC is highly dependent on the design, the judgment criteria used for the simulation model were developed by using small test pieces that represented critical components of this final design. It was relatively inexpensive to construct these test pieces, and they were the link relating the test performance to the simulation model. The judgment criteria were then used during simulations that evaluated the truck bed design as a whole. This allowed the simulations to shape the final design so that no major problems were found relating to the impact strength of the truck bed.

Acknowledgments

Thanks to Dennis Chung, Alex Hutter, Robb Augustine, Jim Ryan, and other members of the research team for supporting this work.

References

[1] Livermore Software Technology Corporation (LSTC), LS-DYNA Keyword User's Manual, Version 970, (2003)