DESIGN AND VALIDATION OF A THERMOPLASTIC COMPOSITE LIFTGATE

Peter H. Foss
Charles C. Mentzer
Douglas W. Franklin

General Motors Research and Development Center, Materials and Processes Lab
General Motors Structure and Safety Integration

Abstract

A thermoplastic composite version of a typical SUV liftgate was designed and built to investigate mass reduction over the production steel design. This paper documents the comparison of experimental stiffness of the liftgate with predictions using several finite element models of increasing detail. One of the most time consuming aspects of modeling the stiffness of composite structures is modeling panels stiffened with ribs. Creating and meshing each individual rib represents a significant time investment. By using isogrid ribbed panels to evaluate the structural stiffness of panels stiffened in specific areas, many different rib heights, thicknesses, spacing, etc. can be modeled in a very short time. However, care must be taken that the isogrid ribbed areas are feasible within geometric constraints imposed on the future detailed design. We will show that when properly applied, the concept of modeling ribbed areas of panels with the isogrid simplification gives excellent accuracy.

Introduction

A composite version of a typical SUV liftgate was designed and built to investigate mass reduction over a typical production steel design. Rather than starting with a totally new liftgate, the program imposed several constraints on the design. First and foremost was the assumption that the composite liftgate must directly replace an existing steel liftgate. This included using the same internal hardware and fitting the existing body opening and seal locations. For the program, mass was the major driver with a goal of reducing the liftgate-in-white mass by at least 30%.

The pieces that make up the typical production liftgate are shown in Figure 1. This liftgate shows the typical method of construction for steel liftgates. The liftgate-in-white consists of an inner and outer panel with a separate latchbox. In addition, the hinge and beltline areas are reinforced with separate reinforcements for a total structural part count of 7. On this particular hinged glass design, the upper half of the outer panel is covered by three appliqués surrounding the glass on the top and sides. Only the lower half of the outer panel is a Class A cosmetic surface. Also note that due to steel formability constraints, almost 30% of the area of the lower cosmetic panel must be covered by a separate injection molded license plate appliqué.

Finite element analysis on modified versions of the steel liftgate finite element model was used to drive the design of the liftgate panels. In those analyses, a mathematical approximation known as isogrids was used to model the stiffness enhancement resulting from using ribs to locally stiffen the panels. Given the design clues provided by the original series of finite element analyses, a Unigraphics CAD model was built and a detailed finite element model created for further analysis. In this paper, we discuss the results of comparing the stiffness predictions from the original model and the detailed model.

As shown in Figure 2, the composite liftgate consists of three pieces. The inner panel and the upper portion of the outer panel were extrusion-compression molded from long glass filled polypropylene. The hinge and beltline reinforcements included in the steel design were replaced with ribbed reinforcement areas of the inner panel. The upper outer panel was a uniform thickness shell. Finally, the lower portion of the liftgate was covered with an injection molded TPO panel with the license plate pocket integrated into the panel.

This design was a significant departure from commercially available thermoplastic composite liftgates that commonly have a thermoplastic composite structural inner panel with an injection molded cosmetic outer panel and fixed glass. Both the outer panel and the fixed glass are bonded in place with a nonstructural urethane adhesive. The flip glass of the baseline steel liftgate design necessitates the added complication of a two-piece structural system with structural bonding of the glass-reinforced polypropylene. While common in SMC liftgates [1], a structural bond between two glass reinforced polypropylene panels had not been attempted at GM.

Finite Element Modeling

Finite element analysis was used to help convert the steel liftgate design shown in Figure 1 into the composite design shown in Figure 2. In the simplified models, ribbed areas of the panels are replaced with equivalent shell elements known as isogrids. This allowed the analysis of many different rib panel configurations without building detailed finite element models of each configuration.

Dimensional parameters for an isogrid ribbed structure are shown in Figure 3. Given the thicknesses of the facesheet (t) and ribs (b), the rib spacing (h) and the rib depth (d), an EXCEL spreadsheet from NASA [2,3] was used to calculate the required NASTRAN parameters for the equivalent shell elements to approximate the properties of the ribbed areas. The flange thickness (c) and width (w) were always zero, since the panels were to be compression molded.

Dozens of different isogrid shells were used in the optimization of the composite liftgate inner panel. Two of these are shown in Table I for illustration. The baseline sheet was a flat plate that was 2 mm thick. In ribbed plate 1, the sheet thickness was increased to 2.5 mm while 2.5 mm thick and 15 mm high ribs were added to the plate every 50 mm. This results in a plate that is 2.38 times heaver than the flat plate while only 1.63 times as stiff in tension. However, the bending stiffness increased by a factor 20.8. As another example, ribbed plate 2, with a few tall thin ribs is almost twice as heavy as the flat sheet while only 8% stiffer. However, the bending stiffness increased by 57.3 times. Ribs are not effective in increasing tensile stiffness but they have a huge effect on bending stiffness.

The use of these isogrid shell element parameters rather than modeling the details of the individual ribs is a tremendous time saver at the conceptual design phase. In this paper, we will compare the predictions for these approximate and detailed finite element models.

Materials

Several materials were used in the investigation of composite liftgates. Important material properties are tabulated below in Table II. The steel sheet is typical automotive stamping grade. The basic starting point for the PP Chop material was yarn consisting of a commingled mixture of glass and polypropylene fibers. Glass and polypropylene fiber were spun separately and then commingled before being rolled onto spools. PP chop is a 50% by weight mixture of polypropylene and 40mm long glass fibers. It is received as 40mm long pellets at 70% glass content. These pellets are mixed with more polypropylene in a low shear extruder and then compression molded. The PP fabric material is a balanced fabric woven from the commingled yarn. Upon heating, the polypropylene fibers melt to form the matrix of a continuous glass fabric reinforced PP composite. The TPO used was a paintable class A grade of nano-composite clay filled TPO [4]. The liftgate assemblies were bonded using an acrylic adhesive designed for low surface energy materials.

Loadcases

The stiffness loadcases used to optimize the design of the liftgate are shown in Figures 4-6. The four torsion loadcases are shown schematically in Figure 4. In all four cases, the hinges were pinned to allow no XYZ motion but free rotation around the hinge pin. The liftgate was twisted by pushing on either the left or right side. For one pair of loadcases (left and right force), the gas strut attachment locations were both pinned. For the other pair of loadcases, the gas strut attachment point on the side where the force was applied was unpinned. The bending loadcases are shown in Figure 5. For these two loadcases, the hinges and gas strut locations were pinned as before and a force was applied either up or down on the liftgate near the latch. Finally, the loadcases for the closed liftgate are shown in Figure 6. For those three loadcases, the hinges were pinned as before. The latch area was also pinned to simulate a closed and latched condition. For the beltline rigidity loadcases a force was applied to either side of the liftgate in a rearward direction. For the strutload case, a force was applied to the strut attachment points to simulate the effect of the gas struts when the gate was closed. Loads and displacements for the steel liftgate are shown in Table III.

Finite Element Models

As stated above, three different finite element models of the composite liftgate were used in this work. The first model, part of which is shown in Figure 7, was the "*Original model with isogrid ribs*". In this early concept model, the nominal material thickness was 1.8 mm. The yellow hinge reinforcement area shown in Figure 7 was 2.5 mm thick with 15 mm high ribs and was modeled using the isogrid approximation. In addition, the bonding flanges were modeled as a single 3.6 mm thick flange to simulate the bonding of the two 1.8 mm thick parts.

The "*Detailed model with explicit ribs*" model was built based on the CAD data and included all details of the panels. The inner and outer panels were bonded together using rigid links between the flanges on the individual parts. Because of the differences between the predictions of these two models, a corrected isogrid based model was built to verify the isogrid concept. This model, shown in Figure 9, is a much more accurate representation of the ribbed areas in the detailed model than was used in Figure 7. As will be shown below, this model much more accurately simulates the behavior of the detailed model while retaining the advantages of the isogrid method.

Results

Stiffness results for the steel and various different composite designs are shown in Table IV. The steel deflections are shown in millimeters while the composite deflections are shown as a percentage of the steel deflections for each loadcase. The "*Original model with isogrid ribs*" at 10.5 kg showed equivalent stiffness (within $\pm$25%) to the steel model which weighed 20.4 kg. This model was unrealistically stiff compared to the "*Detailed model with explicit ribs*" even when the panel masses were increased to a total design weight of 12.0 kg. Clearly there was either a problem with the isogrid concept or our implementation. Given NASA's experience with isogrid ribs and our own testing of simple flat and isogridded plate models, we determined that the error was in our implementation.

One large error was the assumption that the upper outer panel could be ribbed in addition to the inner panel. In the detailed models, the upper outer was always a uniform (3 mm) thickness panel, while in the original model the entire part, except for the bond flanges, was covered with 15 mm high ribs. In developing the CAD models of the panels, it became apparent that the outer panel could not be ribbed due to interference with the ribs on the inner panel.

The second error was a gross overestimation of the extent of ribbing we could introduce into the inner panel. Since we were constrained by the original 360 steel liftgate packaging, ribbing in the upper section of the liftgate was quite reduced. Compare the ribbed areas in the original model shown in yellow and green in Figure 7 with the actual ribs shown in magenta (2 mm thickness) on Figure 8. The loss of bending stiffness in the hinge attachment point, which could not be ribbed, was particularly important. Small deformations in the hinge area translate into large motions at the bottom of the gate due to pivoting around rigid strut attachment point.

In order to verify the accuracy of the isogrid concept, a corrected isogrid version of the detailed model was built. Hinge and corner detail are shown in Figures 9. In this version, only the red and gray regions were isoribbed, a much closer approximation to the actual geometry shown in Figure 8. As shown in Table IV, the *"Detailed Model With Explicit Ribs"* and *"Detailed Model With Corrected Isogrid Ribs"* agree within 6%. Clearly, if applied carefully, the isogrid concept can be used to simulate the stiffness of ribbed structures early in the design process before detailed CAD/CAE models exist.

In order to meet mass targets of 30% mass savings, the composite structure could not be as stiff as the steel structure. The composite structure was expected to be about 1/3 less stiff than the steel gate, which was confirmed experimentally. Three prototype composite liftgates were used for validation of the room temperature stiffness performance relative to the steel gate. The molding and assembly of the prototype liftgates will be the subject of a future paper.

All tests were done at the GM Warren Body Structure Lab. The loadcases used to design the liftgate were also used to compare the experimental results with the predictions. For example, in the *"Left Torsion 1 Strut"* test shown in Figure 10, the hinge pin locations were fixed in space but allowed to rotate. The left gas strut location was fixed fore-aft. A force on the lower right corner of the liftgate was ramped from 0 to 117 N to 0 and displacement of the liftgate corner was recorded. For the experiment, the liftgate was mounted in the "closed in car" position and the force was applied forward in car direction. In this position, the effect of gravity is negligible. In the simulations, since gravity was turned off, the liftgate orientation was immaterial. As shown in Figure 10, the steel gate was predicted to be about 33% stiffer than composite gate. Experimentally, the steel gate was about 35% stiffer while both gates were not quite as stiff as the simulations. The lower stiffness of the simulations is not surprising since the effect of the displacement of the test fixture was not modeled in the simulations.

Future Work

There are several barriers to expansion of the use of composites in exterior automotive applications. One currently facing the composites industry is compatibility with the high temperature powder prime process being installed in most automotive assembly plants. While offline painted applications will continue to exist in special situations, true high volume application of composites requires the ability to easily paint in the assembly plant.

At the quality levels required in the automotive industry, it is very difficult to save significant mass over steel with cost effective composites. Surface appearance and bondline readout remain challenges with thin mass efficient exterior panels. Competition from other light materials such as aluminum and magnesium will keep the pressure on composites to save mass in a cost effective manner.

Future use of composites especially in liftgates may be affected by the new rear moving barrier test described in the revised FMVSS 301 Fuel System Integrity test [5]. In the new test shown in Figure 11, the tested vehicle will be impacted from the rear with a 1368 kg deformable barrier at more than 80 kph. In this test, the incident sled is aligned with the target vehicle but offset so 70% of the rear of the target vehicle is impacted. This impact can cause very significant deformation of the rear structure of the vehicle which can result in large relative motion between rear body components.

The liftgate structure is designed to be stiff at low strains in the region of normal use. In severe crashes, system ductility becomes important to absorb the displacements imposed on the structure. The load-displacement (stress-strain) response for most composite materials is essentially linear. Current research to improve the ductility of composite structures is ongoing at GM with a goal to reach a load-displacement response similar to Figure 12.

References

1. Ustick, N. A., et. al, SAE Transactions Section 5 v. 102, SAE-930466.
2. Isogrid Design Handbook, NASA CR-124075, February 1973.
3. http://analyst.gsfc.nasa.gov/FEMCI/Isogrid/ISOGRID.xls
4. Ottaviani, R. A., Rodgers, W. R. and Fasulo, P. D., "TPO Nanocomposite Development at GM / Montell," SPE Automotive TPOs Conference, September 20-22,1999.
5. http://www.nhtsa.dot.gov/cars/rules/rulings/301NPRM/Index.html

Table I Properties of Flat and Ribbed Plates

	Flat Plate	Ribbed Plate #1	Ribbed Plate #2
Cell spacing, h		50	100
Facesheet thickness, t	2.0	2.5	1.8
Rib thickness, b	0.0	2.5	1.8
Rib height, d	0.0	15	20
Relative mass	1.0	2.4	1.9
Relative tensile stiffness	1.0	1.6	1.1
Relative bending stiffness	1.0	20.8	57.3

Table II Liftgate Materials

Material Name	Description	Modulus, GPa	Density, g/cc
Steel	Rolled steel sheet	200.	7.84
PP Chop	50% glass filled polypropylene (40mm glass)	8.75	1.35
PP Fabric	60% glass fabric filled polypropylene	13.0	1.50
TPO	Cladding grade nanocomposite filled TPO	1.4	0.91

Table III Applied Forces and Resultant Deflections for the Steel Liftgate Model

Loadcase	Force, N	Deflection, mm
Bending	117	15.2
Checkload	400	52.5
Left Beltline Rigidity	600	6.5
Left Torsion 1 Strut	117	54.5
Left Torsion 2 Struts	117	16.5
Right Beltline Rigidity	600	5.7
Right Torsion 1 Strut	117	51.5
Right Torsion 2 Struts	117	16.4
Strutload	1250	1.7

Table IV Predicted steel and composite liftgate displacements

	Mass (kg)	Mass Saved	Left Torsion 1 Strut	Left Torsion 2 Struts	Checkload	Strutload	Left Beltline Rigidity	Bending	Right Torsion 1 Strut	Right Torsion 2 Struts	Right Beltline Rigidity
Steel	20.4	0%	54.5	16.5	52.5	1.7	6.5	15.2	51.5	16.4	5.7
Original model with isogrid ribs	10.5	48%	102%	119%	124%	76%	83%	84%	110%	119%	88%
Detailed model with explicit ribs	12.0	41%	128%	133%	120%	94%	111%	110%	133%	138%	119%
Detailed model with isogrid ribs	11.8	42%	126%	132%	115%	88%	106%	107%	131%	134%	114%

Steel displacements in mm while composite displacements are relative to the steel performance.

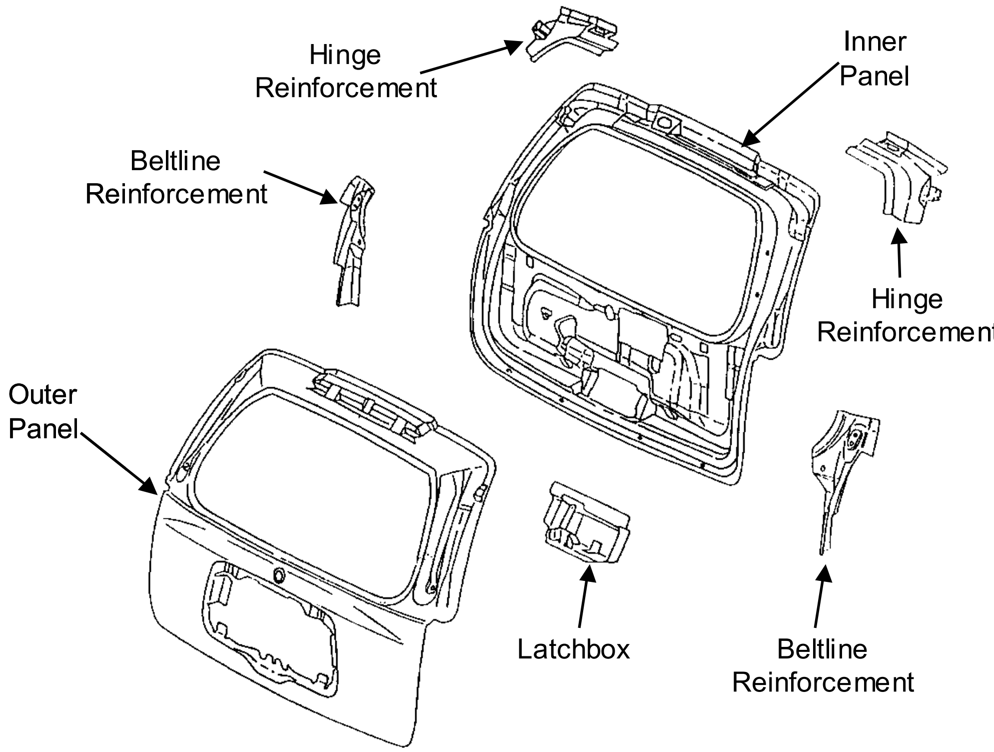

Figure 1. Typical steel liftgate in white parts.

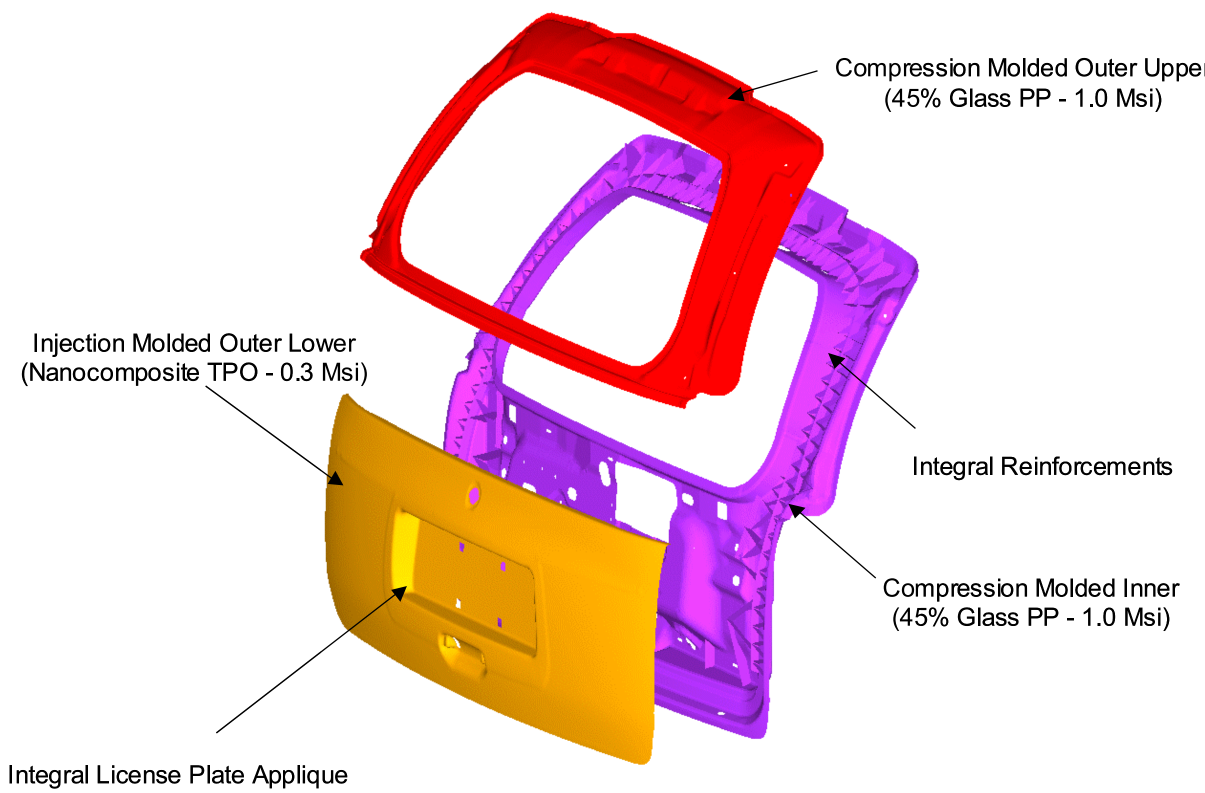

Figure 2. Revised design composite liftgate panels.

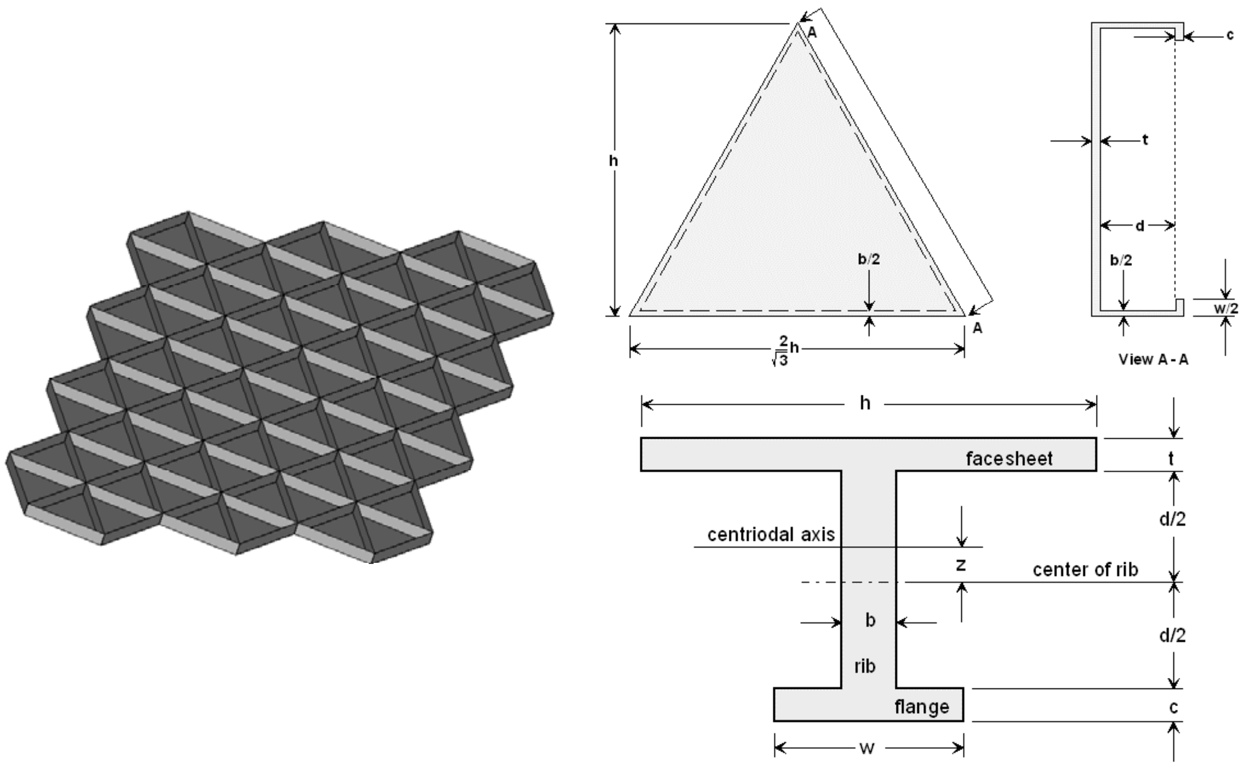

Figure 3. Parametric description of a typical isogrid ribbed stiffened panel.

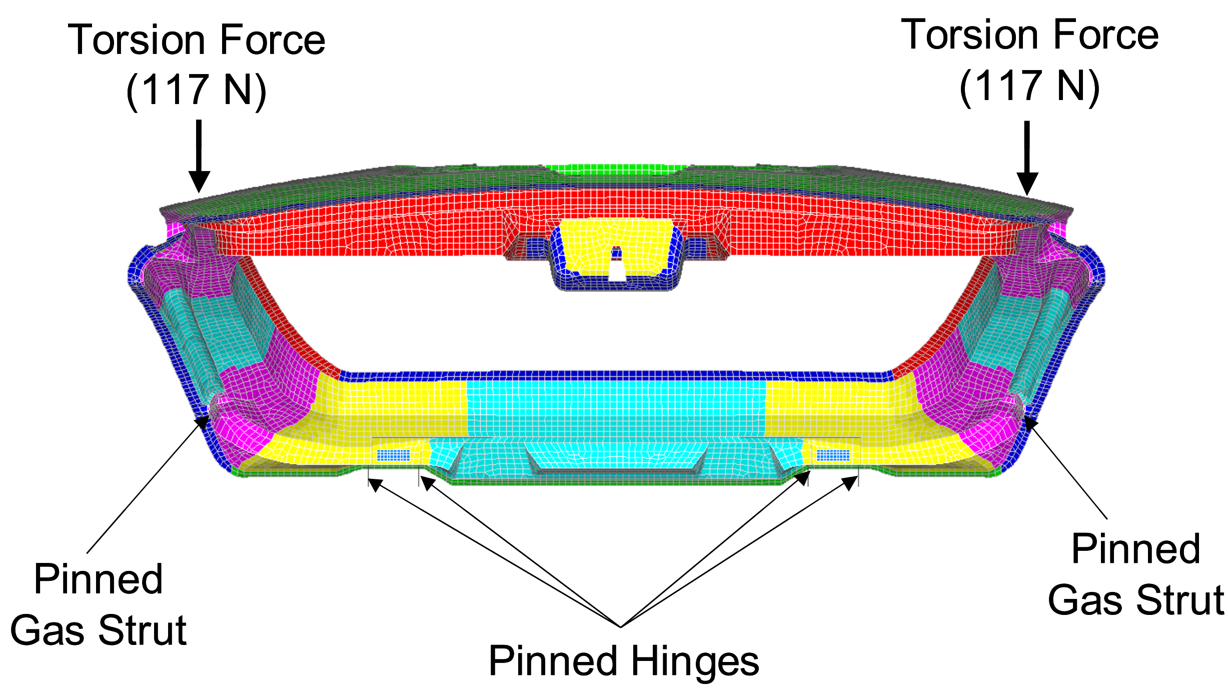

Figure 4. Torsion loadcases schematic.

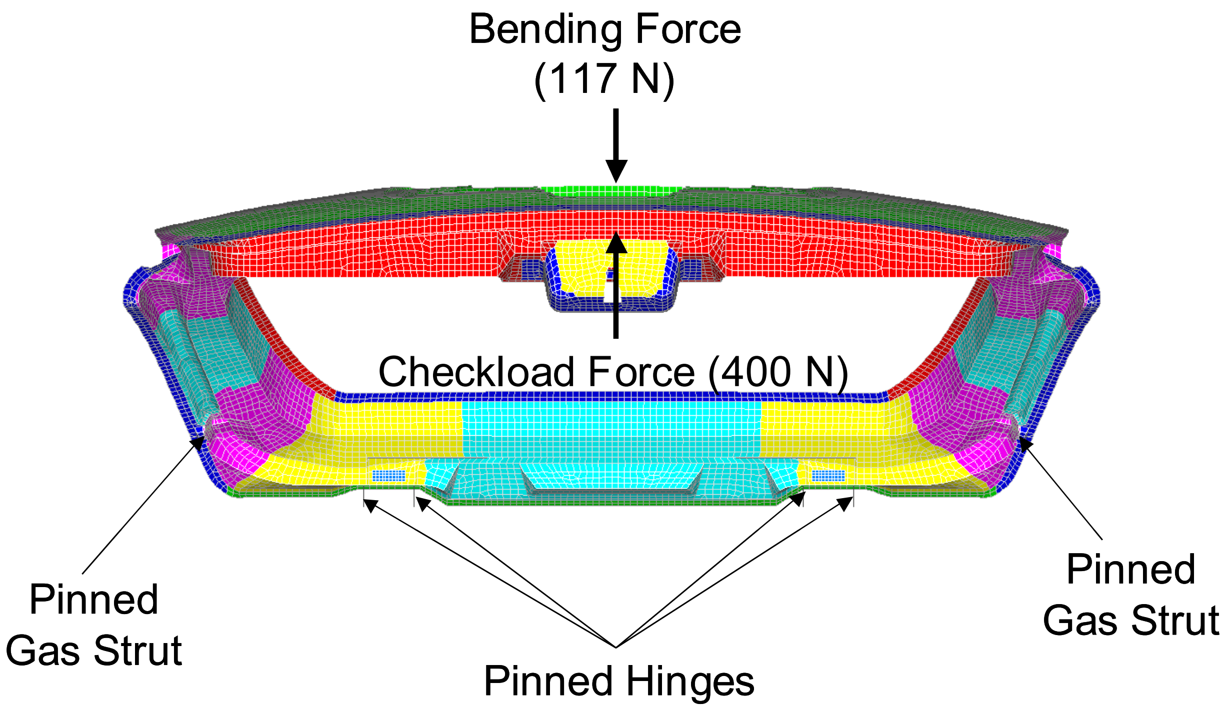

Figure 5. Bending loadcases schematic.

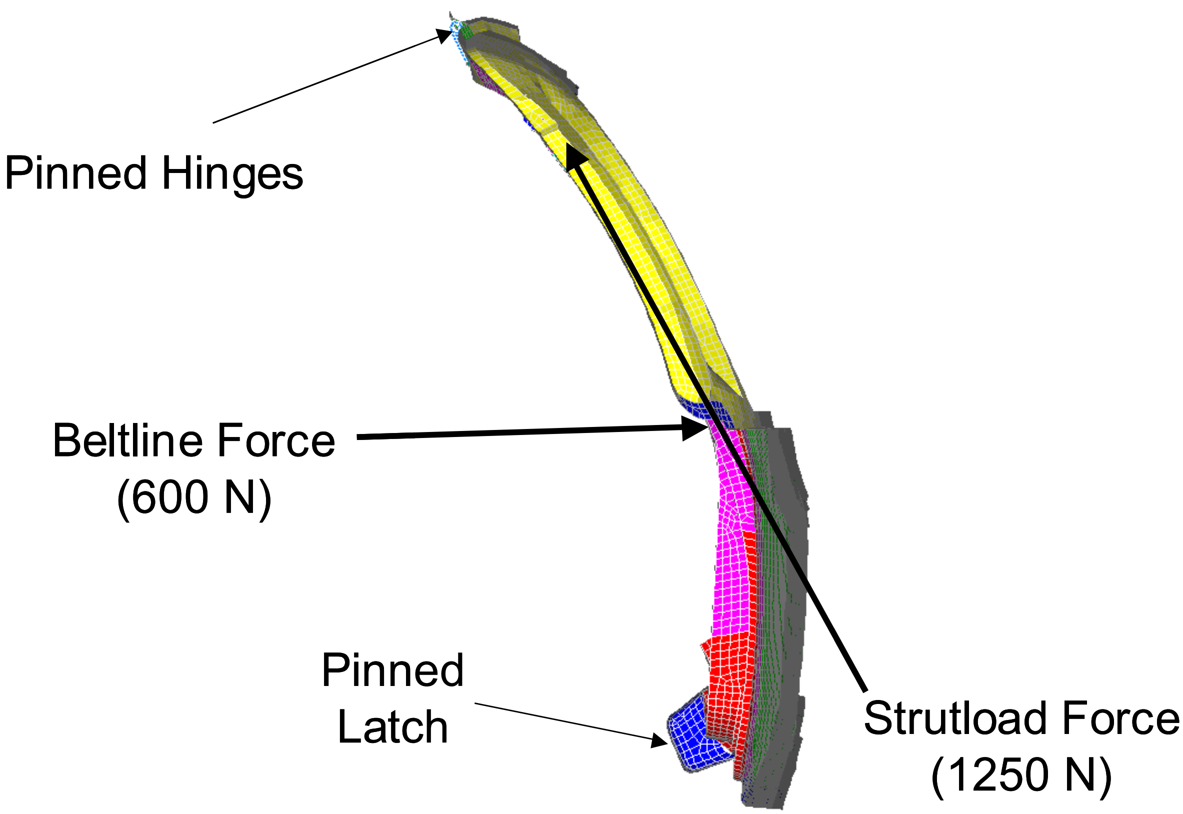

Figure 6. Closed loadcases schematic.

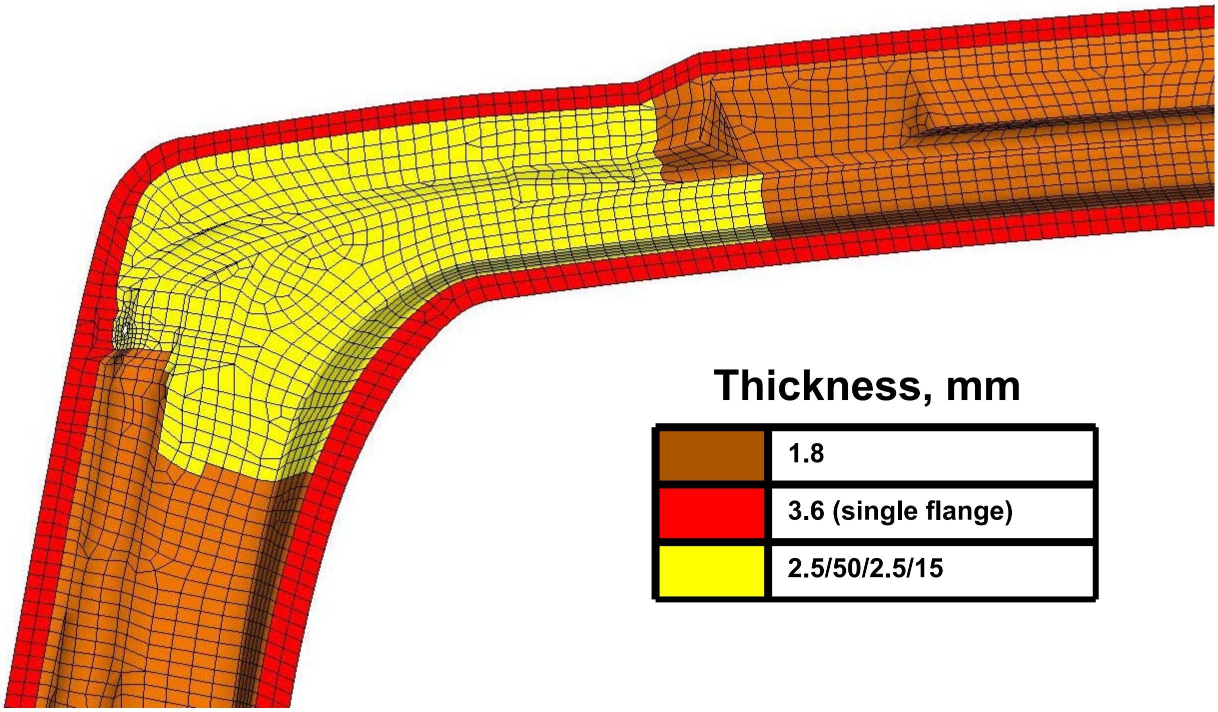

Figure 7.Hinge and corner detail of original inner panel finite element model with isogrid approximation for ribbed areas. For the isogrid regions the parameters given in the legend are facesheet thickness, rib spacing, rib thickness and rib height.

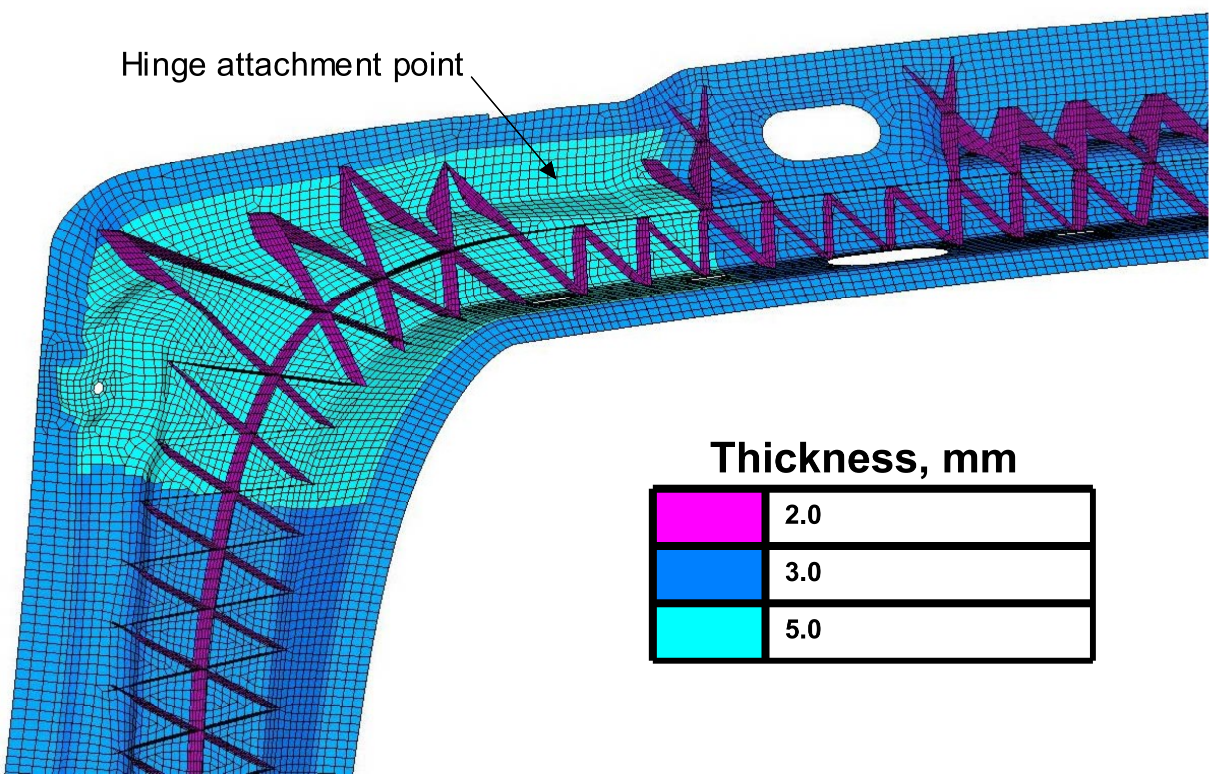

Figure 8.Hinge and corner detail of detailed finite element model with explicitly modeled ribs.

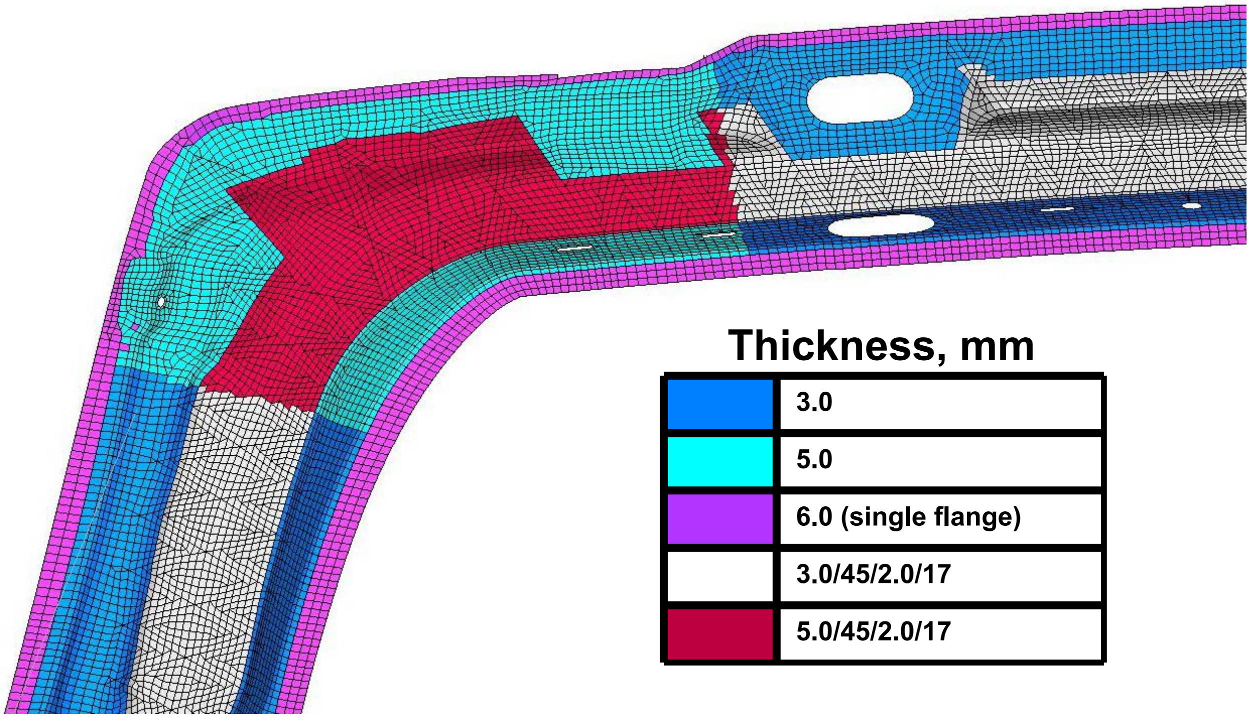

Figure 9.Hinge and corner detail of detailed inner panel finite element model with isogrid approximation for ribbed areas where appropriate. For the isogrid regions the parameters given in the legend are facesheet thickness, rib spacing, rib thickness and rib height.

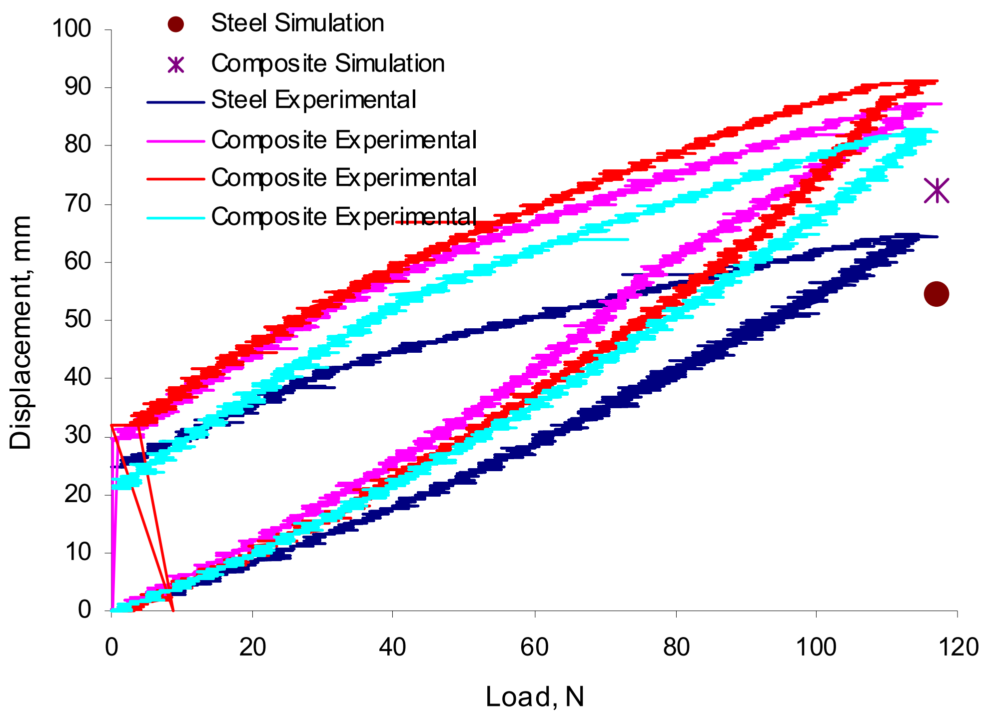

Figure 10.Comparison of predicted and experimental displacements vs load for the single strut torsion loadcase for one steel and three composite liftgates

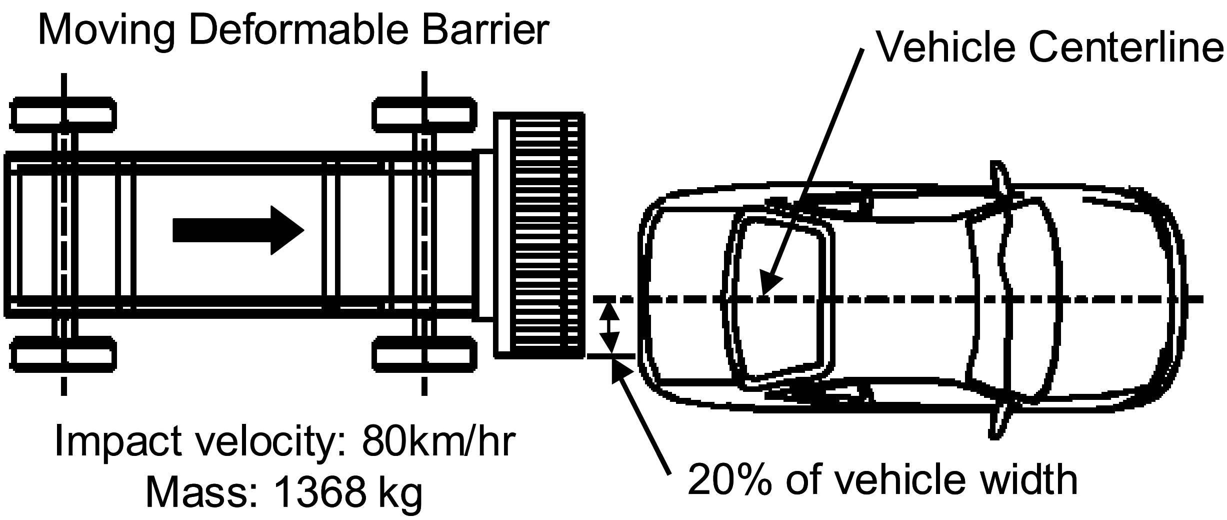

Figure 11. FMVSS 301 offset deformable barrier test configuration.

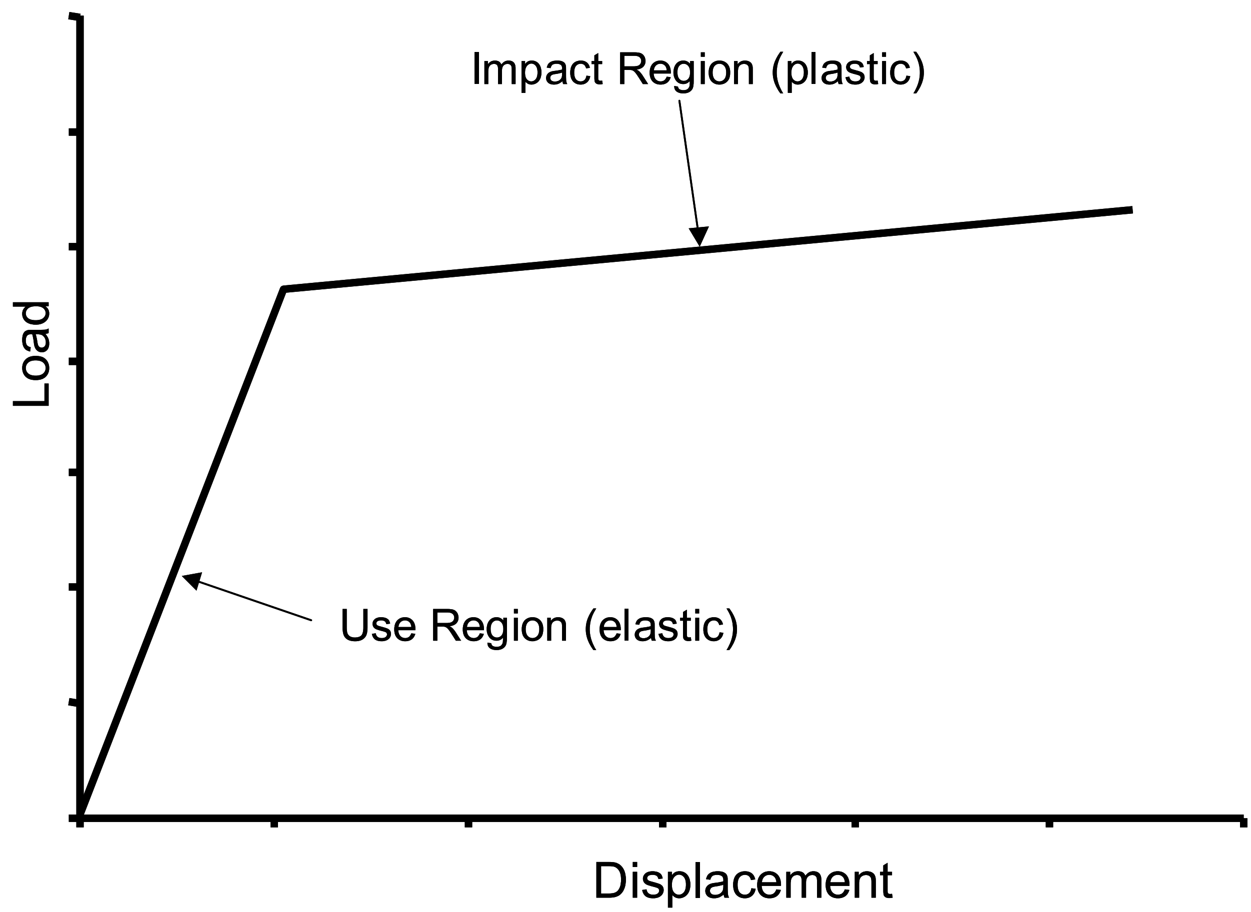

Figure 12.Desired load-displacement response of composite closures to be stiff in normal use but ductile in crash situations.