

Development of Enhanced Honeycomb Barrier Finite Element Model for Rear Crash Simulations

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ABSTRACT

This paper explains the development of an enhanced finite element barrier model for use in simulating the FMVSS 301 high speed rear crash test.

To create the barrier model, material testing was conducted on the aluminum honeycomb, cladding sheets, and adhesive which comprise the barrier. Particular emphasis was placed on the modeling of the aluminum honeycomb, which has been traditionally very challenging to model due to its highly anisotropic behavior. Recently developed modeling features were used to capture the complex behavior of the honeycomb material and extensive testing was conducted to define its behavior.

To validate the barrier model, a series of specification impact tests were conducted. These tests were chosen to represent the various load conditions the barrier might experience during crash testing. Each impact test was simulated and the barrier model was correlated to the test results.

Finally the barrier model was used in a full-vehicle crash simulation for verification. In this full-vehicle crash simulation, a significant improvement in the correlation of the model to test results was achieved. The results clearly indicate that improved predictive accuracy in crash test simulations can be obtained with the use of this new barrier model.

1. Introduction

Many automotive crash tests involve impact with a honeycomb barrier as a surrogate for another vehicle. During these crash test events, the honeycomb barrier typically undergoes severe deformations and extreme non-linear behavior. The simplicity of the construction of these barriers can lead one to believe that modeling them would be rather straightforward, but this simplicity

is deceptive. To capture the behavior of these barriers with a finite element model has been, and continues to be, a major challenge for the automotive industry.

The new FMVSS 301 high speed rear crash test uses the same Moving Deformable Barrier (MDB) as the FMVSS 214 side impact test⁽¹⁾. The MDB has a honeycomb barrier face mounted to the front of the cart. In the new high speed rear crash test, the MDB impacts the vehicle at 50 mph with 70% overlap. As Fig. 1



Fig. 1 Typical damage to honeycomb barrier seen after FMVSS 301 high speed rear crash test

shows, the severity of this collision causes extreme deformation of the honeycomb barrier face. The current barrier model is not able to capture this behavior accurately; so as a result, there is poor correlation of the simulation model.

To enhance the predictive accuracy of rear crash test simulations a new barrier model was created. This model utilizes recently developed features in LS-DYNA for modeling aluminum honeycomb to more accurately capture its off-axis strength and shear behavior. Also, a new approach for modeling the adhesive that bonds the honeycomb to the cladding was developed. This model was correlated to a number of different specification tests and has shown significant improvement to rear impact simulation correlation.

2. Barrier Modeling

2.1. Barrier Construction

The barrier used in the rear impact testing consists of a face assembly and a bumper assembly⁽²⁾. The face assembly is comprised of the main honeycomb block and cladding sheets. The crush strength of the face assembly honeycomb is 45 psi. This assembly has two aluminum cladding sheets with a thickness of 0.812 mm. The face sheet is bonded to the front side of the main honeycomb block and wraps around the top of the block (no adhesive is applied to the top portion). The main honeycomb block is also bonded to an aluminum backing sheet. The bumper assembly consists of the honeycomb bumper having a crush strength of 245 psi and two aluminum cladding sheets with a thickness of 3.175 mm. The front cladding sheet is bonded to the front face of the bumper honeycomb while the bumper backing sheet is bonded to the back face of the bumper honeycomb. Finally the bumper assembly is bonded to the face assembly. This barrier construction and adhesive layers are detailed in Fig. 2.

The barrier is mounted to a cart designed to meet specified values for center of gravity and inertia. This cart is typically a space frame style design made from steel or aluminum tubes. The cart has four wheels with pneumatic tires mounted to it, but no suspension.

2.2. Barrier Model Construction

The aluminum honeycomb material is modeled using solid elements. In LS-DYNA, a solid element formulation is assigned that allows for the elements to undergo the extreme shear behavior possible in honeycomb material. The cladding is modeled with shell elements, and all adhesive layers are modeled with solid elements. The material modeling used for these components will be described in the next sections.

The cart for the barrier is modeled as a rigid body. Rigid solid elements are used to represent the basic space frame structure of the cart and the proper values for the inertia and center of gravity are applied using an inertial card in LS-DYNA. Each tire is modeled with shell elements and an air volume is defined between the tire and wheel. Each tire is attached to the cart using revolute joints to allow for rotation.

2.3. Aluminum Honeycomb Modeling

The deformation behavior of aluminum honeycomb is extremely difficult to capture accurately in a finite element model. This material is extremely anisotropic in its behavior: it can exhibit high crush strength in the strong direction (T direction), while showing extremely weak crush strength in an orthogonal direction (W and L directions). These directions are illustrated in Fig. 3.

While many recent published attempts to model aluminum honeycomb have used shell elements to provide an explicit representation of the cell structure⁽³⁾⁻⁽⁵⁾, the model described here uses brick elements to limit the model's size and run time. Recently developed

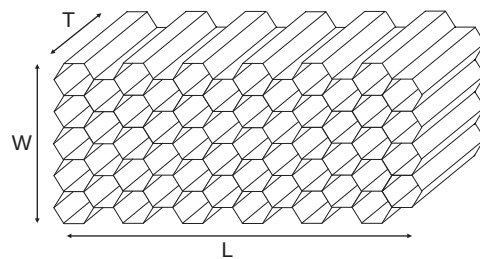


Fig. 3 Description of aluminum honeycomb

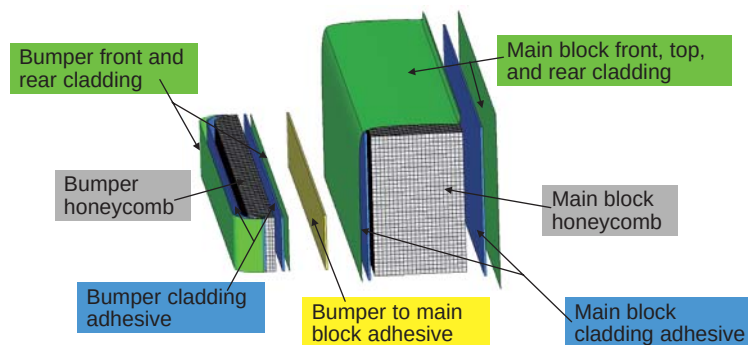


Fig. 2 Barrier construction

features in LS-DYNA are used to allow the brick elements to capture the honeycomb behavior.

With the traditional material model for aluminum honeycomb, a user could define the crush strength of the honeycomb in the strong and the weak directions. This material modeling method was found to over predict the material strength in an off-axis loading case⁽⁶⁾. To address this issue an improved honeycomb material model was developed by Kojima et. al. and implemented in LS-DYNA with the Mat_Modified_Honeycomb material model^{(6), (7)}. With this material model, a yield surface can be defined such that the limit stress, σ^y , is a function of the angle, φ , with the strong axis and the volumetric strain, ε^{vol} :

$$\sigma^y(\varphi, \varepsilon^{vol}) = \sigma^b(\varphi) + (\cos \varphi)^2 \sigma^s(\varepsilon^{vol}) + (\sin \varphi)^2 \sigma^w(\varepsilon^{vol}) \quad (1)$$

In LS-DYNA, load curves are used to define σ^b , σ^s , and σ^w in Eq. (1) with respect to volumetric strain. The crush strength of the honeycomb with respect to the angle of crush is defined by σ^b . Stiffening effects observed in the honeycomb as it is crushed to its fully compacted state are defined by σ^s and σ^w in the strong axis or weak axes respectively.

Defining σ^b is critical to the accuracy of this material model and is not a trivial undertaking⁽⁶⁾. To produce this, load curve samples must be cut from the honeycomb block at a variety of angles. Figure 4 shows



Fig. 4 Samples cut from honeycomb block at different angles

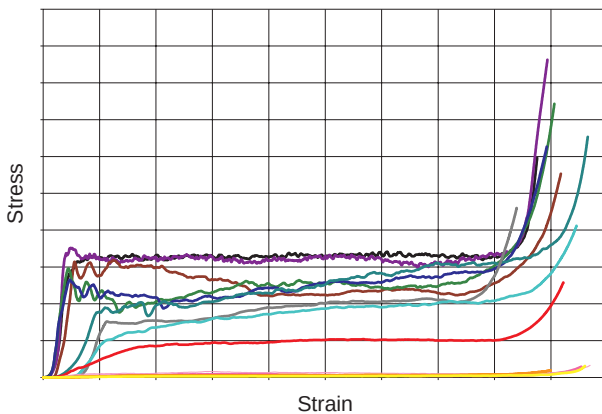


Fig. 5 Load versus displacement curves for honeycomb samples

the samples removed from the honeycomb block. Each sample was crushed, and a load versus displacement graph was generated. A number of the resulting curves are shown in Fig. 5. From these curves, the plateau strength of the honeycomb can be determined for each sample. Finally, a curve can be generated which shows the strength versus angle of crush. A representation of this curve is shown in Fig. 6. By using this curve, a steady decrease in honeycomb strength can be obtained as the orientation of the crush direction transitions from the strong direction to a weak direction. Thus, the off-axis loading can be accurately defined.

2.4. Cladding Modeling

The aluminum cladding sheets were tested using uniaxial samples to provide a stress-strain curve. This curve was adjusted to a true stress versus effective plastic strain curve and smoothed using a power law fit. Finally, it was sampled at 100 equally spaced intervals and used with a piecewise-linear plasticity material model in LS-DYNA. This curve is shown in Fig. 7. Failure was allowed using an effective plastic strain value beyond which the element would be eliminated. This failure strain was adjusted from the tested value to provide reasonable correlation of the cladding failure in each of the specification tests.

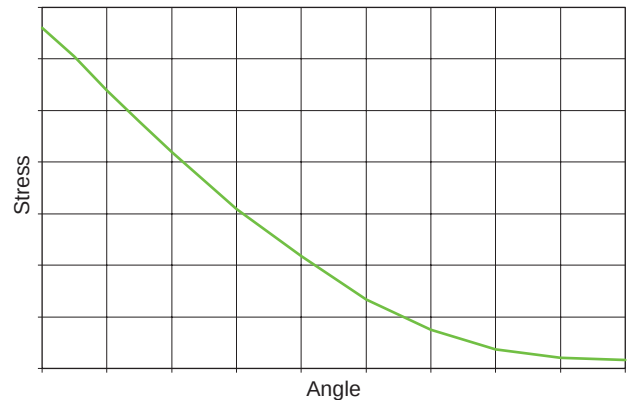


Fig. 6 Representation of curve defining crush strength versus angle of crush

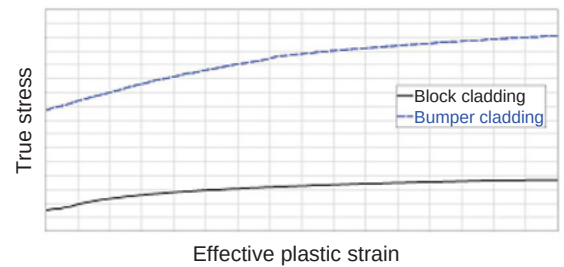


Fig. 7 True stress versus effective plastic strain for aluminum cladding material

2.5. Adhesive Modeling

2.5.1. Honeycomb to cladding adhesive

The honeycomb to cladding adhesive, indicated in Fig. 2, is modeled as a single layer of solid elements that is attached to the honeycomb and cladding using a tied contact. The adhesive layer material definition is identical to the main honeycomb block with the exception that failure parameters are defined using tensile and shear strain limits. As Fig. 8 shows, the specification tests demonstrate that the failure mode is the tearing of the honeycomb material rather than the separation of the adhesive layer. Therefore, the model represents the failure in the honeycomb, and the adhesive is represented as the tied contact.

2.5.2. Cladding to cladding adhesive

The bumper rear cladding and block front cladding are attached using an adhesive. This is represented in the model as a thin layer of solid elements which are attached to the cladding sheets through a tied contact definition. The solid adhesive layer material model includes the following failure function to represent the adhesive failure:

$$\left[\frac{\max(N_{rr}, 0)}{N_{rrf}} \right]^2 + \left[\frac{N_{rs}}{N_{rsf}} \right]^2 + \left[\frac{N_{rl}}{N_{rlf}} \right]^2 + \left[\frac{M_{rr}}{M_{rrf}} \right]^2 + \left[\frac{M_{ss}}{M_{ssf}} \right]^2 + \left[\frac{M_{ll}}{M_{llf}} \right]^2 - 1 = 0 \quad (2)$$

The numerators in the failure definition are the resultants calculated in the model, and the denominators are the failure values specified in the material model⁽⁷⁾.

The failure parameters for all adhesive layers in the barrier model were determined using barrier specification tests that were conducted in order to validate the material models. Each barrier specification test produced unique failures of the adhesive layers. By adjusting the failure parameters in Eq. (2), the simulation could match the adhesive failure seen in the specification test. It was found to be impossible to exactly match the adhesive failure seen in all specification tests with the same failure parameters. This is likely due to the variability seen in the barriers where the adhesive bond between the honeycomb and cladding is not consistent. Ultimately, a single set of failure parameters was selected where the adhesive layer showed reasonable failure correlation for all specification tests.

3. Barrier Specification Testing and Modeling

3.1. Flat Wall Specification Test

The flat wall specification test validates the material properties for the main block honeycomb material. There is no failure in the honeycomb block since the test applies a uniform load on the face of the barrier. Since there is no block failure in the test, the simulation model and the test show a high level of correlation as shown in Fig. 9.

3.2. Offset Flat Wall Specification Test

The 70% offset wall specification test showed no cladding failure. The plastic failure strain for the cladding material was adjusted so that little or no

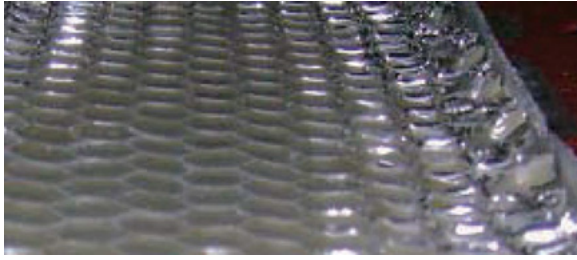


Fig. 8 Honeycomb layer torn away with cladding (note undisturbed layer of adhesive present under torn honeycomb layer)

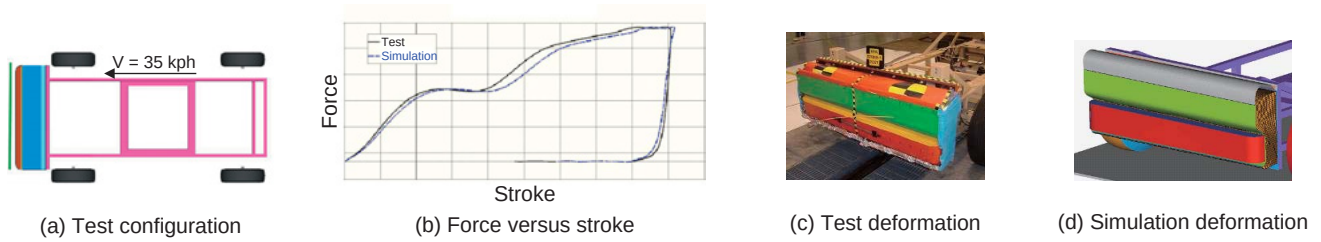


Fig. 9 Flat wall specification test

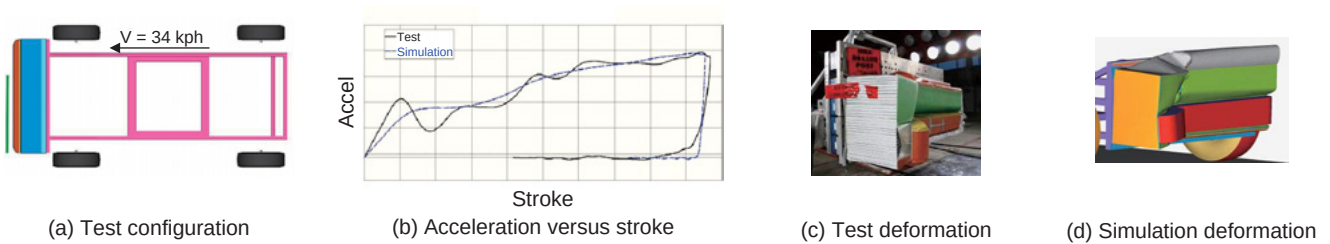


Fig. 10 Offset wall specification test

cladding failure was present in the model. The failure parameters from Eq. (2) for the adhesive layer between the block front cladding and bumper rear cladding were also set in order to correlate to this test. Although separation of the bumper assembly from the block does not occur in the simulation model as is does in the test, the correlation level shown in Fig. 10 is judged to be well within the variability for the barrier's performance.

3.3. Pole Specification Test

In the initial stages of the pole impact, the test and the simulation model correlate very well. However, towards the end of the event, the simulation model diverges from the test results by behaving stiffer than the physical barrier. Although the honeycomb material definition allows the user to define various failure functions, the main honeycomb block does not have a defined failure behavior. Failure was not added to the honeycomb material at this point to try and ensure that the barrier model would behave very robustly in full vehicle simulations (this is discussed further in Section 4.1). As can be noted in Fig. 11 (c), the main honeycomb block clearly has some failure that allows the pole fixture to punch into the honeycomb block. Since the simulation model correlates very well until late into the event, the discrepancy is judged to be reasonable, and the overall correlation level is judged to be acceptable.

3.4. Offset Bumper Test

The overall deformed shape of the offset bumper simulation model compared to the test result shows an acceptable level of agreement as shown in Fig. 12. The bumper component remains attached to the block face as the block cladding tears at the impact point. However, there is a great deal of failure of the honeycomb block in this test. If failure in the honeycomb block were to be modeled, the correlation to the test would become very close. However, in order to maintain contact stability and overall robustness of the simulation model, failure is not applied to the main block honeycomb. This results in a stiffer response to this load case. This type of isolated failure in the barrier block is not usually noted in a full vehicle testing, and the overall correlation level is judged to be acceptable.

3.5. Angle Wall Specification Test

With the selected material model used for the honeycomb material, shear stability can at times be poor. This is noted in Fig. 13 where the barrier model was used in a FMVSS 214 side impact full vehicle simulation. With this test mode, the barrier impacts the vehicle in a "crabbed" manner which introduces a shear load into the honeycomb block. In the simulation model, the barrier block was sheared in a manner that was not physically representative of the actual behavior.

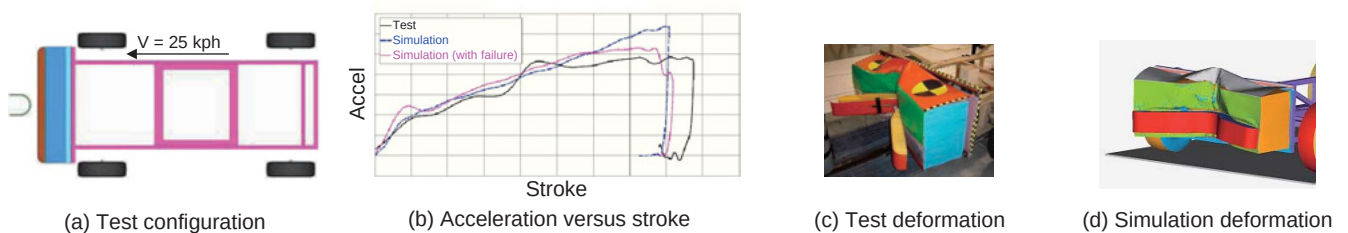


Fig. 11 Pole specification test

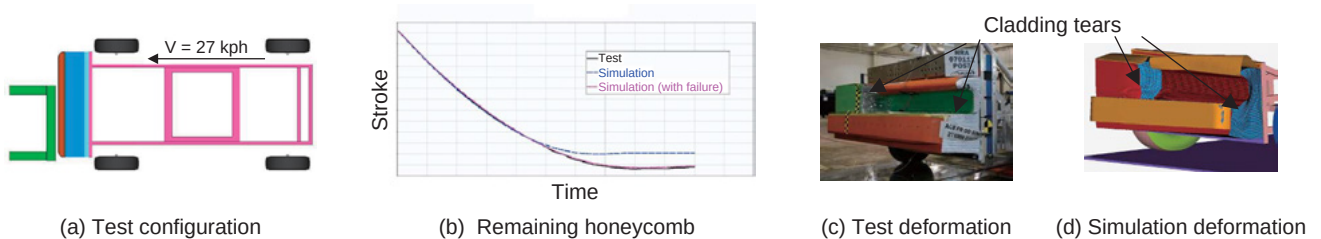


Fig. 12 Offset bumper test

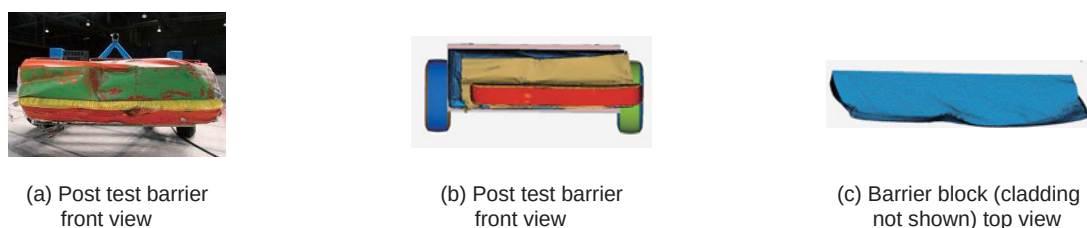


Fig. 13 Top view of initial model's barrier block illustrating non-physical shearing behavior

To prevent this type of unstable shear behavior, LS-DYNA has the option to apply limits to the shear and hydrostatic stresses⁽⁷⁾. These limits allow for the material to develop resistance to shear and hydrostatic stress while the uniaxial response remains unaffected and is still governed by Eq. (1). The hydrostatic and shear limit stresses are given as functions of volumetric strain by Eqs. (3) and (4) respectively:

$$\sigma_p^Y(\epsilon^{vol}) = \sigma_p^Y + \sigma^s(\epsilon^{vol}) \quad (3)$$

$$\sigma_d^Y(\epsilon^{vol}) = \sigma_d^Y + \sigma^s(\epsilon^{vol}) \quad (4)$$

The same load curve defined for Eq. (1) is represented by σ^s , which provides for stiffening of the material as it is crushed to its fully compacted state. The parameters σ_p^Y and σ_d^Y were determined using the offset bumper specification test from Fig. 12 and the angled wall specification test shown in Fig. 14.

For the angle wall impact test, the barrier model without any limits to the shear or hydrostatic stresses shows the unstable shear behavior noted in the side impact test. This can be seen in Fig. 15 (b) where the simulation model shows excessive shearing of the honeycomb elements to the side versus the actual behavior shown in the test barrier of Fig. 15 (a). Applying the limit stresses can cause excessive stiffening in the shear behavior of the honeycomb so a compromise must be implemented. By adjusting the limit stresses for the angle wall specification test while monitoring their effect on the offset bumper impact, values were obtained that provided the needed shear stability, and also kept the correlation of the offset bumper impact at an acceptable level. The result for the angle wall simulation is shown in Fig. 15 (c).

4. Model Robustness and Efficiency

4.1. Model Robustness

A major goal for updating the barrier models, other than enhanced accuracy, is improved barrier robustness. This is a critical issue when running large models such as full vehicle crash models. With the material models and element formulations chosen for this model, the new barrier has proven to be very robust in full vehicle simulations. It can undergo the severe deformations seen in the actual barriers and still remain stable. Thus, the new barrier model can be applied in production use.

It has been shown that adding failure to the honeycomb block can improve the correlation to the specification tests. Also, honeycomb failure in the main block can be present in rear offset tests as is evidenced by Fig. 1. This may lead to the desire to incorporate honeycomb material failure into the material model, but adding this failure to the honeycomb block can lead to stability issues and unexpected results if the barrier model were to experience a deformation mode significantly different from those encompassed by the specification tests. To avoid these troubles, an attempt was made to avoid applying failure to the honeycomb block material model. This has proven to be successful as the barrier shows good correlation for all specification tests and for full vehicle simulations (detailed in Section 5). Thus, the goal of achieving a barrier model with excellent robustness and accuracy has been achieved.

4.2. Model Efficiency

Another goal for the barrier model is to maintain computational efficiency while enhancing accuracy. Ultimately, barrier models should be a shell mesh of the aluminum foil that makes up the actual honeycomb

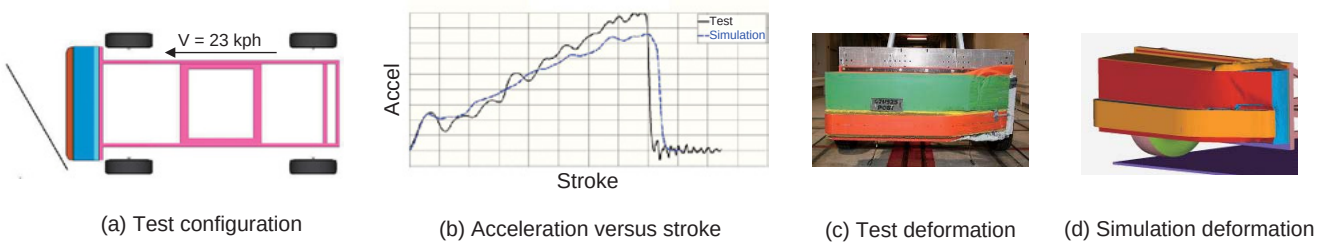


Fig. 14 Angle wall test

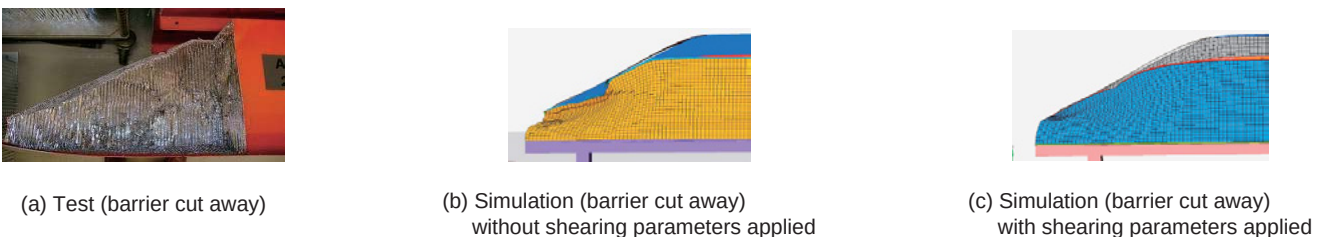


Fig. 15 Top view of section cut of test barrier compared to simulation

structure; however with current techniques this would be far too computationally expensive (the run time penalty factor would be approximately 15), so compromises must be made. One possibility is to use a shell mesh of the of a honeycomb structure where the cells are scaled up from their actual size. This leads to a lower cell density, fewer elements, and thus, improved computational efficiency over a barrier with a shell mesh at the actual cell density⁽³⁾⁻⁽⁵⁾. But, for the rear impact barrier this would still lead to a barrier with a large computational expense penalty over the current barrier model. Therefore, an attempt was made to develop a barrier model utilizing solid elements to keep the computational cost penalty to a minimum. With the barrier model developed here, the computation time is increased by a factor of 1.25 compared to the old barrier model. This is an acceptable increase, given the improvements in accuracy, because this increase is well with in the range that can be overcome by adding additional CPU's for each simulation.

5. Full Vehicle Verification

With the barrier properly correlated to spec tests, its performance in full-vehicle rear crash models was evaluated. The old barrier showed significant weakness in rear crash simulations - often producing results with excessive deformation to the vehicle and even incorrect deformation modes. It was thought that an improved barrier model would resolve these issues.

The new barrier model has shown a significant improvement to full-vehicle simulation accuracy. The difference in intrusion between the simulation prediction

and the test result has been greatly reduced with the use of the new barrier model. Also, the deformation modes appear much closer to that of the test. These results are shown in Fig. 16.

6. Conclusion

A new barrier model for rear crash simulation has been developed. This model takes advantage of new modeling features in LS-DYNA to more accurately capture the behavior of the aluminum honeycomb. The model was correlated to a number of specification tests. While perfect correlation to every specification test was found to be impossible, a reasonable compromise in correlation to each specification test was achieved. This new barrier model has been used in full-vehicle, rear crash simulations where it has shown significant improvements in its correlation to test results. The barrier model has proven to be very robust in actual usage by avoiding any instabilities that could lead to incomplete or pre-maturely terminated simulation runs. The barrier does increase the computational time needed to run a model. However, in comparison to an approach that would introduce computationally intensive shell elements, the increase in time is deemed reasonable. These improvements to the barrier model provide for an accurate, predictive, rear crash simulation tool that can be used in vehicle development.

There are of course still areas where further enhancements could be made to the barrier model. Future work should address items such as 1) incorporating failure into the aluminum honeycomb block in a robust accurate manner, 2) moving toward a

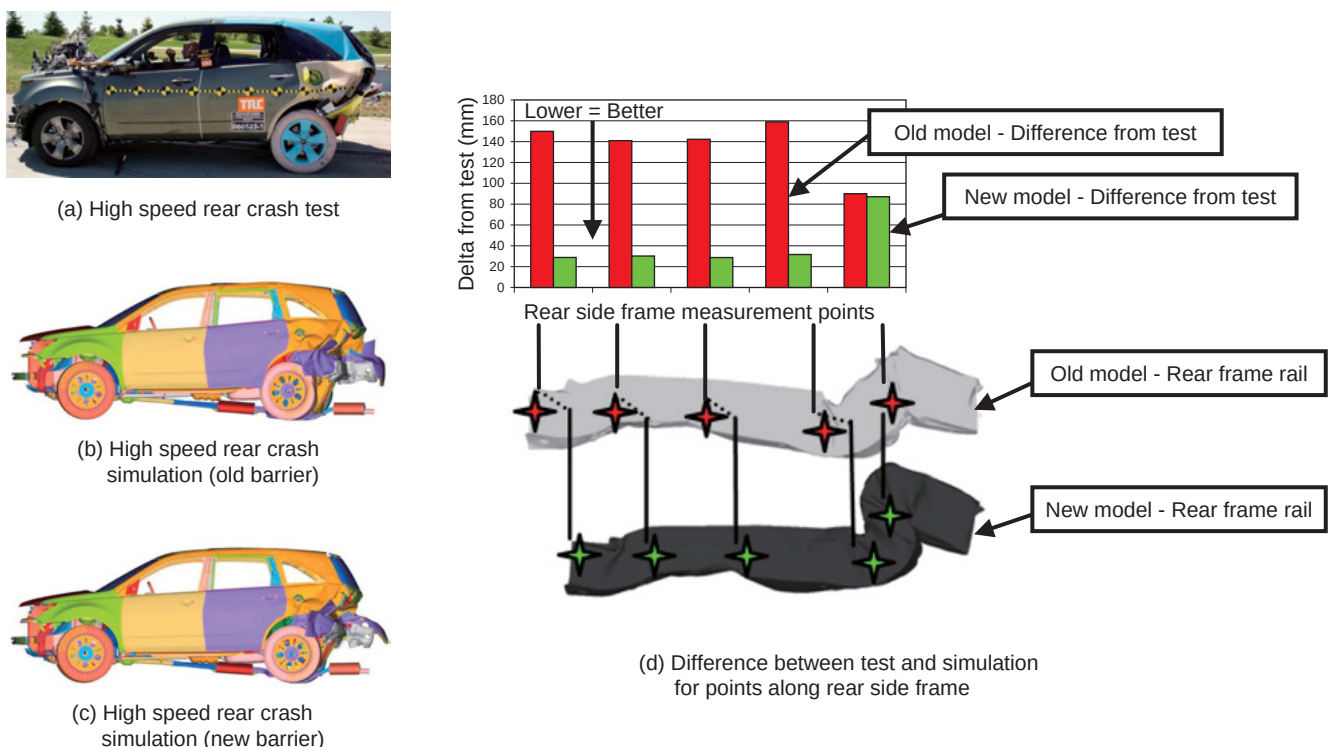


Fig. 16 Correlation of rear frame rail with new barrier model

shell element model when computational speed increases, and 3) accounting for any dynamic effects present in the barrier at high speeds.

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