Using Barrier Load Cell Data to Generate Stiffness Coefficients

Brian Gilbert, Ron Jadischke, Joe McCarthy
McCarthy Engineering Inc. / Vehiclemetrics Inc.

Abstract

The analysis and modeling of vehicle crush in accident reconstruction has traditionally been based upon the use of linear crush-based, stiffness coefficients. Residual crush is used to develop these coefficients.

This paper expands upon a technique used to generate non-linear stiffness coefficients (Pressure model) previously presented by Gilbert et al. [1,2]. This pressure model uses time-specific load cell and accelerometer data from frontal barrier crash tests along with the undamaged vehicle geometry to develop a pressure versus deflection curve for that vehicle. This curve is then used to generate the stiffness coefficients for the vehicle.

The array of barrier load cells provides a means to establish stiffness coefficients for specific areas of the frontal portion of a vehicle. This creates the potential to generate multiple crush zones which could be beneficial in modeling pole impacts or override/underride collisions. Modifications to HVE would be required to accommodate multiple crush zones. Recommendations are suggested which would allow DyMESH to utilize this model better.

Introduction

Stiffness coefficients have traditionally been calculated using residual crush which has been documented in barrier crash tests.

An example of calculating A and B stiffness values using residual crush is Campbell's method [3,4], which is shown in equations 1, 2, and 3. These equations use an impact speed where no residual crush occurs (b_0, 5 mph for frontal collisions), the change in velocity or delta-V (Δv) of the vehicle, and average crush (C_{avg}), in order to assess the change in velocity per unit crush (b_1). Campbell used the b_0, b_1 values with vehicle weight (m_t), gravitational acceleration constant (g, 32.2 ft/s^2), and damage width (W) in order to calculate the A and B stiffness values.

$$b_1 = \frac{\Delta v_{test} - b_0}{C_{avg}} \quad (1)$$

$$A = \frac{m_t \; b_0 \; b_1}{g \; W} \quad (2)$$

$$B = \frac{m_t \; b_1^{\,2}}{g \; W} \quad (3)$$

An example calculation is shown in Table 1.

Table 1. Sample calculation of A and B coefficients by Campbell's method for a 2008 Jeep Liberty, NHTSA test 5211.

Variable	Value
b_0	5 mph
Δv	38.4 mph
C_{avg}	18.1 in
m_t	4493.8 lb
w	60.0 in
b1 (Equation 1)	32.4 Units/s
A (Equation 2)	553.4 lb/in
B (Equation 3)	204.2 lb/in^2

Force, in pounds per unit width, is calculated by Equation 4, where x is equal to the crush, in inches, of the vehicle.

$$F = A + Bx \quad (4)$$

A plot of force versus crush is shown in Figure 1.

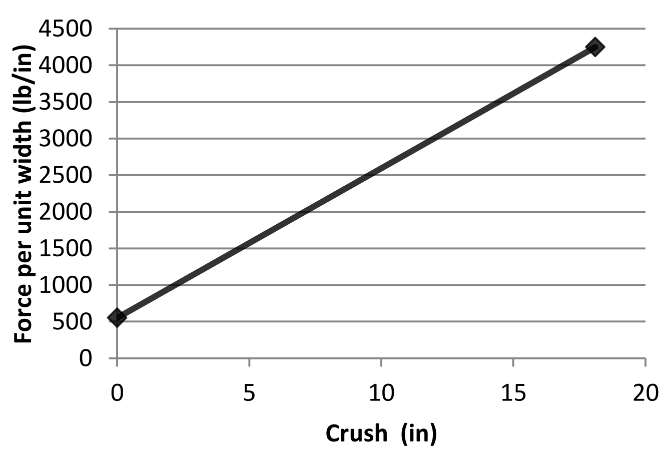

Figure 1 - Sample force versus vehicle crush.

The traditional method simply looks at residual vehicle crush.

In the past, stiffness coefficients in HVE were linear. However, recent changes to the program allow for the use of a 3rd order polynomial curve to improve the modeling of the relationship between impact force and vehicle crush.

Since DyMESH models the 3-dimensional crush (deflection) of the vehicle, the stiffness coefficient represents the relationship between force per unit area (pressure) and deflection. Current stiffness models are generated by using an average cross-sectional area for the deflection zone.

Non-Linear Pressure Model

Model Overview

The calculation method of this model is summarized in the three steps below:

1. Establish the force to cause the vehicle to deform based upon barrier load cell data or accelerometer data from the vehicle tested.
2. Establish a pressure (force/unit area) versus deflection curve using:
   a. The force calculated in 1.) above,
   b. The cross-sectional area of the crush zone at various depths of deflection, and
   c. The displacement of the vehicle which was obtained from its accelerometer data. The deflection or deformation of the front of the vehicle is equal to the vehicle's displacement after impact.
3. Fit the pressure versus deflection curve using a 3rd order polynomial which then represents the stiffness coefficients in DyMESH.

This model departs from the traditional method of using residual crush, instead relying on time-specific information regarding the impact force and vehicle deformation.

As a force comparison can be performed by simply multiplying the acceleration of a vehicle by its mass (Newton's Second Law), as displayed in Equation 5, load cell barrier collisions provide a secondary verification of data.

$$F_{Vehicle} = m_{Vehicle} * a_{accelerometer} \tag{5}$$

A force comparison between the barrier load cell data and a vehicle accelerometer is shown in Figure 2.

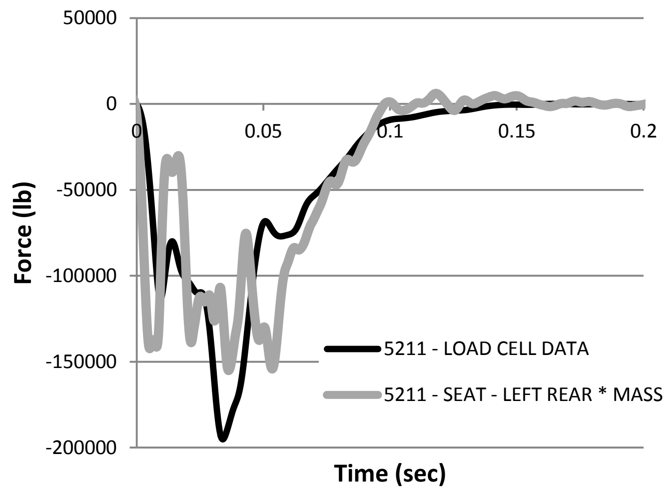

Figure 2. Sample force versus time graph.

Figure 2 illustrates that accelerometer data can produce a similar curve, but the data is not as smooth as the load cell data.

In addition to smoother curve appearance, the load cells on the barrier provide location-specific force data for a vehicle impact which can be broken down in many ways. This is explored in later sections.

Derivation of Pressure versus Deflection

At each time interval of the collision, both the total force from the load cell barrier and the vehicle displacement from the accelerometer are obtained. The undamaged cross-sectional area of the vehicle for the displacement value is then calculated. The force is then divided by the cross-sectional area to obtain pressure. The deflection value is equal to the vehicle displacement value calculated from the accelerometer data.

A key component of the pressure model is the calculation of the cross-sectional area of the crush zone. When an average area was used, the shape of the curve was significantly different. An example of this is shown in Figure 3. For the pressure model figures, NHTSA test 5211 was used with the accelerometer listed as "SEAT – LEFT REAR".

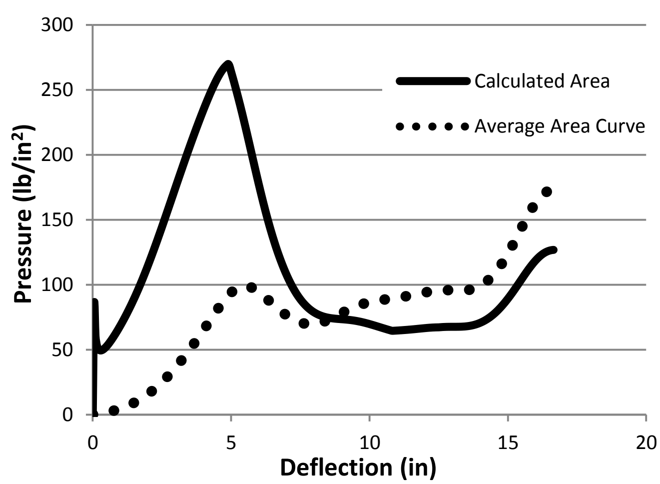

Figure 3. Sample comparison of average and calculated area curves graph.

Plotting a graph of pressure versus deflection allows for the curve fitting of the data to a 3rd order polynomial. The equation of the curve fit can be expressed as in Equation (6)

$$\boldsymbol{P} = \boldsymbol{A}' + \boldsymbol{B}'x + \boldsymbol{C}'x^2 + \boldsymbol{D}'x^3 \tag{6}$$

It should be noted that the linear model incorporates a y-intercept (A') which represents the force at which permanent crush begins. In contrast, the pressure model looks at the deflection instead of permanent crush. This method, therefore, does not require a y-intercept to represent the onset of permanent crush since it uses deflection which commences upon impact (i.e., elastic compression of bumper). As a result, we set the A' coefficient to zero. An example of this is shown in Figure 4.

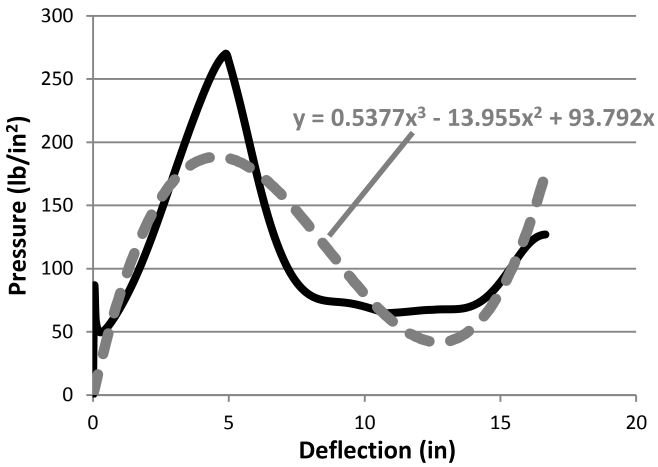

Figure 4. Sample pressure versus deflection graph. In this graph, the coefficients are 0, 93.792, -13.955, and 0.5377 for A', B', C' and D,' respectively.

Figure 5 shows a sample comparison between traditional linear stiffness coefficients which are divided by the HVE default conversion height of 30 inches to obtain the same units as pressure, and the crush value is set to the deflection.

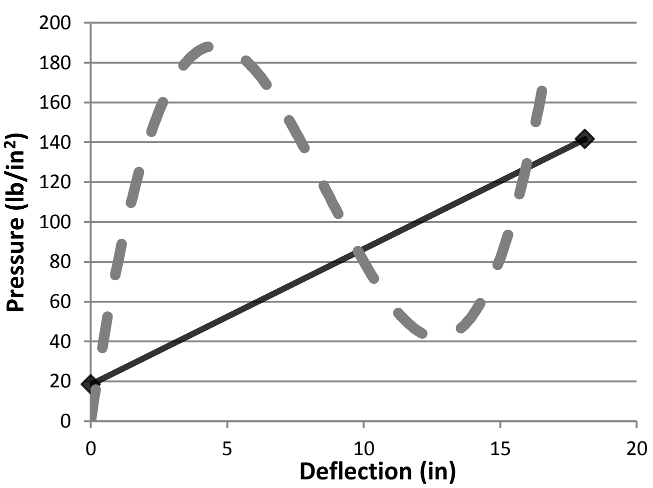

Figure 5. Sample comparison of linear and pressure models.

Potential Future Uses

Higher Order Coefficients

With the capabilities of spreadsheet programs such as Microsoft Excel, it is possible to display a curve fit up to a 6th order polynomial graphically. This would allow for a potentially closer representation of the crash test data. A sample of 3rd order and 6th order polynomials is shown in Figure 6.

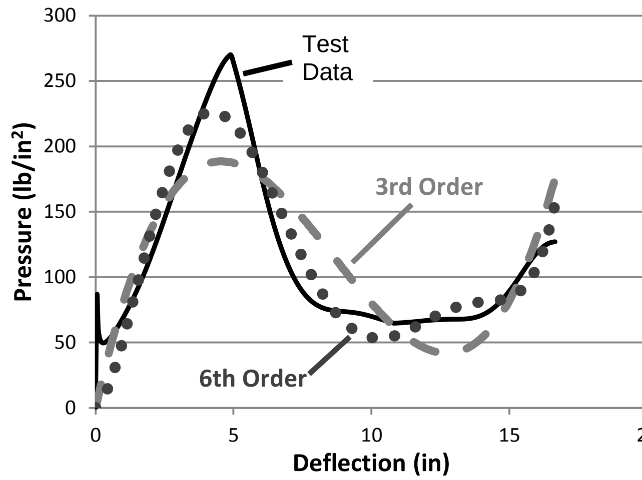

Figure 6. Sample 3rd order and 6th order curve fits.

Location Specific Coefficients

Load cell barrier testing provides force data for a specific area of the front of the vehicle. This provides the potential to generate stiffness coefficients that are specific to certain frontal regions or zones.

An example of a collision where multiple crush zones may be desired would be an underride/override impact. Separation the front of the vehicle into zones which correspond to the height of specific load cells allows for the calculation of stiffness coefficients for each of these zones. Figure 7 illustrates a sample zone configuration for a load cell barrier impact.

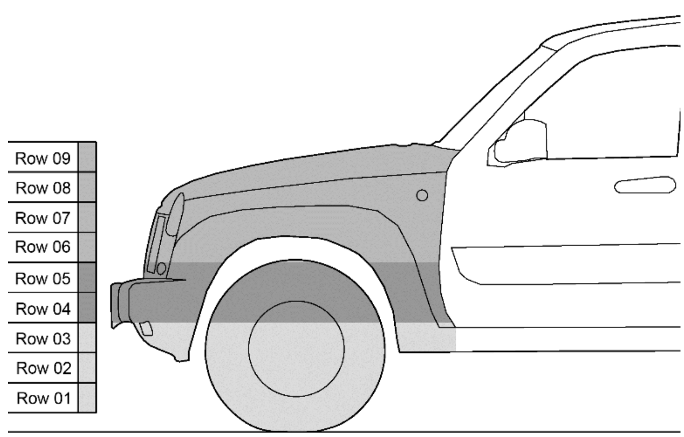

Figure 7. Sample vehicle zone designation.

Figure 8 shows the calculated forces on the load cells in each zone for the duration of the crash test.

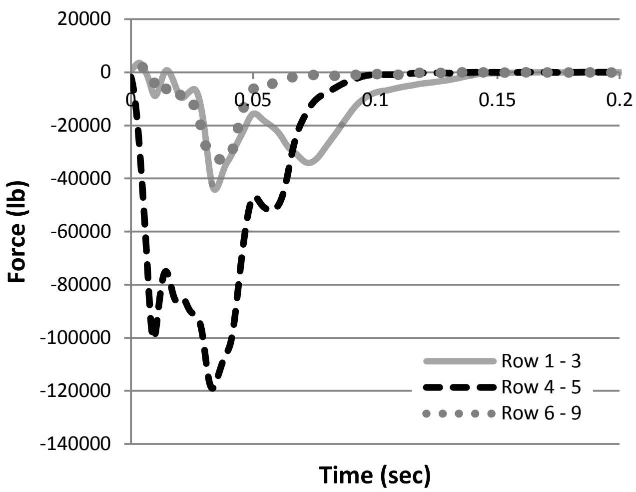

Figure 8. Sample zone force versus time.

Stiffness coefficients can be calculated using the pressure model for each zone with the appropriate forces and areas.

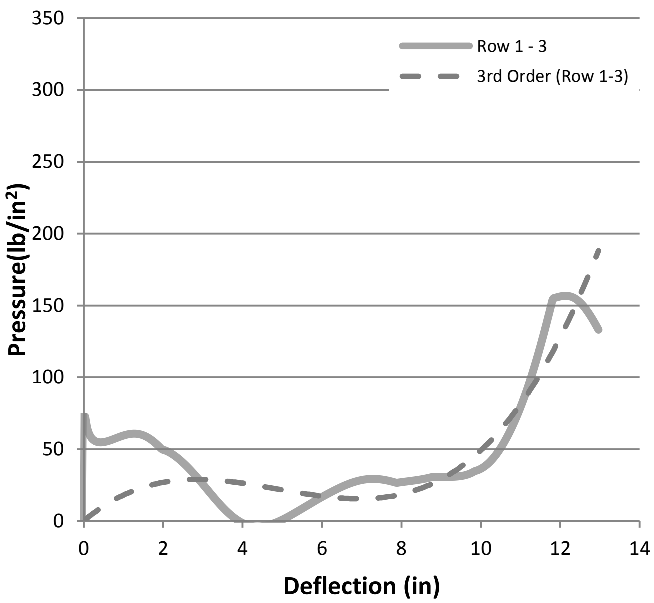

Figure 9. Sample zone stiffness curve, row 1-3.

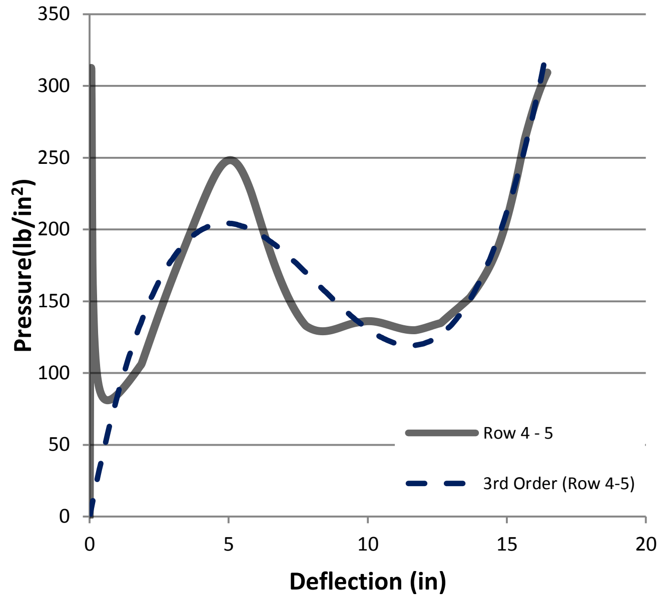

Figure 10. Sample zone stiffness curve, row 4-5.

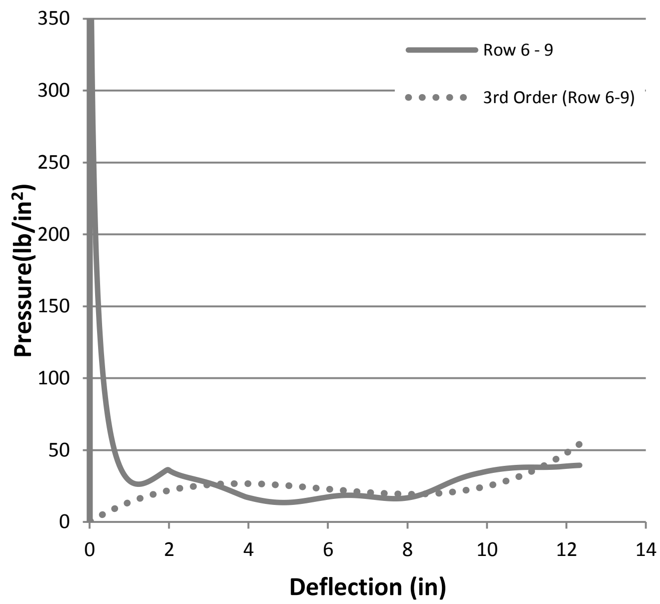

Figure 11. Sample zone stiffness curve, row 6-9.

Using the methods described above, we could establish a number of different crush zone. Theoretically, every load cell could be associated with a separate crush zone to the front of the vehicle.

Figures 12 – 15 show the force distribution pattern on the load cell barrier at specific vehicle deflections. These figures illustrate the variation of the stiffness across the front of a vehicle. The implementation of multiple crush zones may provide a user the ability to model more complex impact configurations.

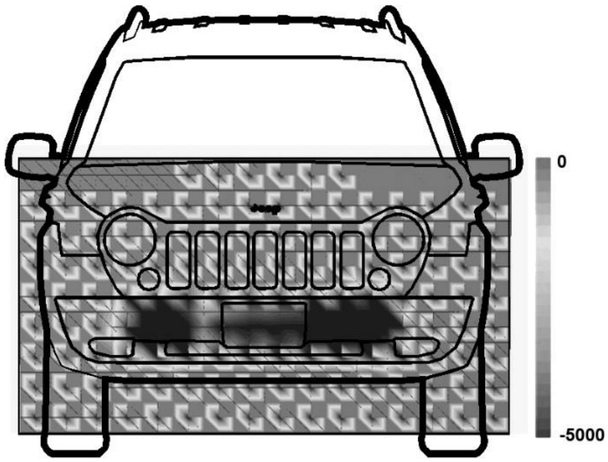

Figure 12. Force distribution on load cell barrier at a deflection of 2“.

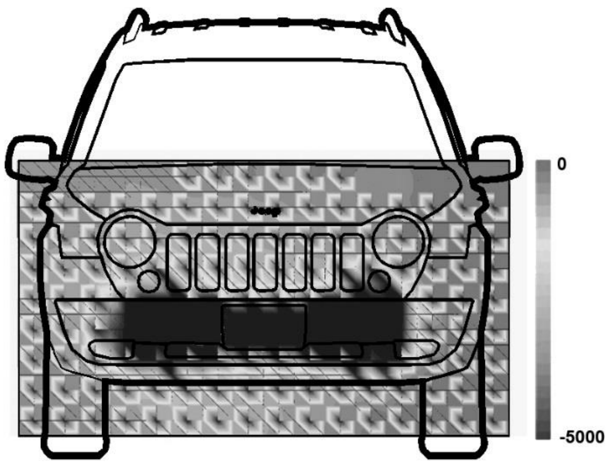

Figure 13. Force distribution on load cell barrier at a deflection of 5“.

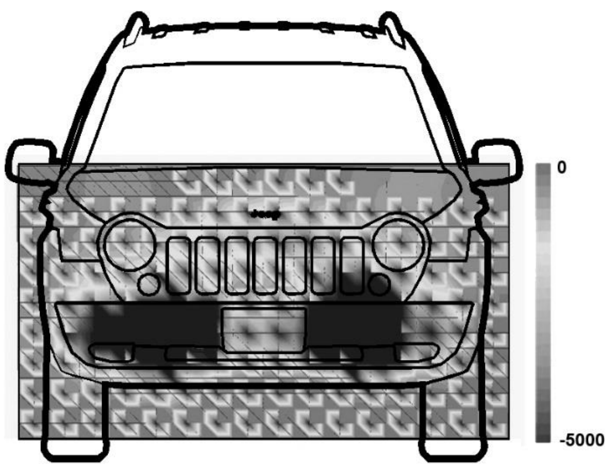

Figure 14. Force distribution on load cell barrier at a deflection of 10”.

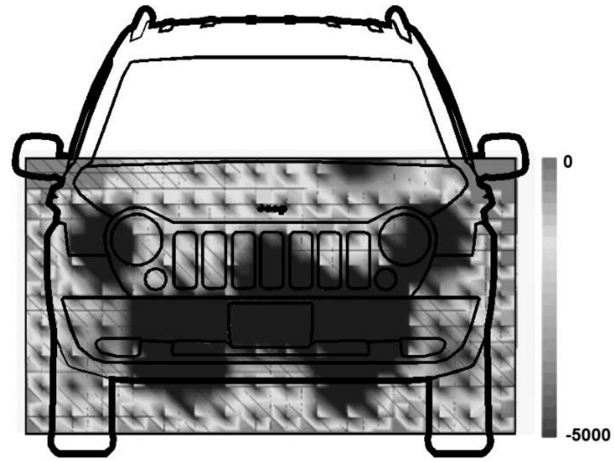

Figure 15. Force distribution on load cell barrier at maximum total force (195,114 lb).

Summary/Conclusions

The use of barrier load cell data allows for a different method (pressure model) of creating stiffness coefficients for use in DyMESH.

The most significant differences between traditional linear stiffness coefficients and the non-linear pressure model are:

- The linear model uses permanent crush to establish the relationship between impact force and deflection whereas the pressure model uses the force and deflection time-history obtained through accelerometer data and load cell barrier data.
- The linear model uses an average cross-sectional area for the vehicle whereas the pressure model incorporates a changing cross-sectional area which varies with the depth of the deflection (crush).
- The linear models allows using only a 1st order polynomial, the pressure model allows for representing the stiffness coefficient using a 3rd order polynomial which provides a better correlation over a greater range of impact severities.

The use of barrier load cell data provides a user the potential to calculate the stiffness coefficient for a very specific region of the front of a vehicle. This methodology would allow for the creation of stiffness coefficients for multiple crush zones. Modification to HVE would be required to accommodate the use of stiffness coefficients for multiple frontal crush zones.

Increasing the order of the stiffness coefficient from 3 to 6 could result in a better correlation between the simulation results and crash test data. A potential alternative to curve fitting would be the modification of HVE to accommodate a look-up data table based directly upon the pressure versus deflection curve created using the barrier test data.

References

1. Gilbert, B., Jadischke, R., McCarthy, J., "A Method to Determine Non-Linear Crush for Use in HVE," 2013 HVE Forum, WP-2013-4, 2013.
2. Gilbert, B., Jadischke, R., McCarthy, J., "Calculating Non-Linear Frontal Stiffness Coefficients," SAE Technical Paper 2014-01-0474, 2014.
3. Campbell, K., “Energy as a Basis for Accident Severity – A Preliminary Study,” Doctoral Thesis, The University of Wisconsin, 1972.
4. Campbell, K., "Energy Basis for Collision Severity," SAE Technical Paper 740565, 1974, doi:10.4271/740565.

Contact Information

Brian Gilbert, P.Eng.
McCarthy Engineering Inc.
2280 Ambassador Drive
Windsor, Ontario, Canada
N9C 4E4
(519) 966-3149
bgilbert@mccarthyengineering.ca
bgilbert@vehiclemetrics.com