

Crush Energy and Stiffness in Side Impacts

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ABSTRACT

Crash tests of vehicles by striking deformable barriers are specified by Government programs such as FMVSS 214, FMVSS 301 and the Side Impact New Car Assessment Program (SINCAP). Such tests result in both crash partners absorbing crush energy and moving after separation. Compared with studying fixed rigid barrier crash tests, the analysis of the energy-absorbing behavior of the vehicle side (or rear) structure is much more involved. Described in this paper is a methodology by which analysts can use such crash tests to determine the side structure stiffness characteristics for the specific struck vehicle. Such vehicle-specific information allows the calculation of the crush energy for the particular side-struck vehicle during an actual collision – a key step in the reconstruction of that crash.

Based on fundamental principles of physics and engineering, this methodology provides transparency in the calculation of side structure stiffness parameters for the particular vehicle of interest. Additionally, sample calculations are presented. Utilizing widely available computational tools and publicly available test data, the method was applied to a representative sample of recent-model vehicles.

The results of this study show that variability in side structure stiffness from vehicle to vehicle appears to be real – not an artifact of computational method or data uncertainty – and not necessarily related to vehicle size or weight, for example. Independent tests of comparable vehicles, while few in number, produce remarkably similar stiffness results.

Supported by sensitivity analyses, various simplifications are presented that in most cases will allow a good approximation to more rigorously-derived results.

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INTRODUCTION

Why the Study was Needed

A widely accepted technique for reconstructing crashes is based on the determination of the energy absorbed by both crash partners, as reflected in the damage done to both. Beyond the depth and extent of damage, the knowledge of the stiffness characteristics of the crushed structures is also required. This research focuses on vehicle side structure stiffness.

It is well known that stiffness characteristics vary widely among vehicles, even when they are lumped together in the same category (however that category is defined). It follows that the application of generalized class category stiffness parameters introduces variability into the calculation of crush energy for a specific vehicle in a specific crash.

The determination of vehicle-specific side structure stiffness parameters is complicated by the facts that both crash partners absorb energy, and both crash partners dissipate additional kinetic energy through post-impact motion. Perhaps for these reasons, the techniques used to derive published side structure stiffness parameters have either never been adequately described in the open literature, or have exhibited flaws in their methodology [1]. The derivation of commercially available side structure stiffness parameters has also not been published.

To provide transparency to the analysis, and to avoid skepticism of the results, accident reconstructionists need to utilize well-established engineering principles, publicly-available crash test data and commonly-used calculation techniques, such that the results can be reproduced by others – a fundamental requirement of engineering investigation.

BACKGROUND

Crush Energy Overview

With regard to automotive reconstruction, crush energy analysis can trace its roots back to the seminal work of Kenneth Campbell in 1974 [2]. Campbell's approach stemmed from the observation that for a given vehicle, the residual crush depth (the crush measurable after a crash) is linearly proportional to the closing speed of the impact, which means, following from fundamental principles of physics, that the residual crush is proportional to the resistive force of the vehicle structure [3]; i.e., the force-deflection relationship is also linear. Generalization of this approach to non-linear structural models has also been proposed [4, 5]. To explore the existence and nature of non-linearities, data points up and down the range of impact severities are required, and the repeated-test technique [6, 7] may be utilized to achieve those data points.

Among the reconstruction algorithms utilizing Campbell's work were Crash3 [8] and WinSMASH [9]. The purpose of these and similar programs was to provide a means to estimate accident severity for use in mass databases such as the National Accident Sampling System (NASS) [10]. As such, they were intended to provide unbiased crash severity statistics, as opposed to producing the best possible severity assessment of a specific accident [9]. Accordingly, the vehicle population was subdivided into categories, to each of which were assigned default values for computer program inputs. Among these default values were stiffness parameters for front, side, and rear structures in the various categories. The shortcomings of using default parameters, and applying Crash3 (as it was originally formulated) for reconstructing specific accidents, has been discussed previously [11].

Default side stiffness values for Crash3 were updated in 1987, based on a series of side impacts conducted by the National Highway Traffic Safety Administration (NHTSA) [12]. Default parameters were again updated by Siddall and Day in 1996 [13] and by Osterholt et al. in 2010 [14], but with no information provided in either case as to how the side stiffness values were derived. New categories were proposed and average parameter values were given by Lee et al. in 2014 [15], but again there was no explanation of how those values were determined.

Deriving Stiffness Coefficients from Impacts with Fixed Rigid Barriers

For vehicles involved in crashes, neither the crush nor the structural stiffness can be assumed to be uniform or homogeneous, in general. Therefore these quantities are expressed as functions of position on the vehicle. Crush energy (and force) are then obtained by a process of integration (and/or summation) across the crush profile.

For the most part, our discussion focuses on linear (also known as constant-stiffness) structures. In such cases, the crush force F per unit width may be written:

$$F = A + Bc, \quad (1)$$

where F is in pounds per inch, A is the force offset (per unit width) in pounds per inch, B is the stiffness (per unit width) in pounds per square inch, and $c = c(x)$ is the depth of crush in inches at location x (also in inches). In terms of the average crush $\bar{c}$, we can write:

$$c(x) = \bar{c}f(x), \quad (2)$$

where $f(x)$ is a dimensionless shape function (identically equal to unity for the special case of uniform crush). In a differential slice of the crush profile, integrating the force-deflection curve over the residual crush c yields the differential crush energy:

$$d(CE) = \left(Ac + \frac{1}{2} Bc^2 + G \right) dx, \quad (3)$$

where G is a constant of integration in the units of pounds per inch per inch, or simply pounds. Assuming that A , B and G are uniform with respect to x (i.e., assuming the structure is homogeneous across the whole of the crush width), integration over the crush width L gives us:

$$CE = \frac{L}{2B\beta} (A + B\beta\bar{c})^2, \quad (4)$$

where β is a dimensionless form factor (describing the non-uniformity of the crush profile), given by:

$$\beta = \frac{1}{L} \int_0^L f^2(x) dx, \quad (5)$$

and where G is not independent, but depends on A and B according to the formula:

$$G = \frac{A^2}{2B\beta}. \quad (6)$$

(If A , B and G are not constant over L , then the integrations have to be subdivided into sections over which they can be taken as constant.) Details of this derivation are found in Reference [3].

Equation (4) may be re-written as:

$$\sqrt{\frac{2\beta(CE)}{L}} = \sqrt{B}(\beta\bar{c}) + \frac{A}{\sqrt{B}}. \quad (7)$$

The above relationship can be treated as a linear function between the left-hand side (dependent variable) and the independent variable $\beta\bar{c}$. A graph of this linear function will have the following attributes:

$$\text{Ordinate} = \sqrt{\frac{2\beta(CE)}{L}} = ECF \quad (8)$$

$$\text{Abscissa} = \beta\bar{c} \quad (9)$$

$$\text{Slope} = \sqrt{B} \quad (10)$$

$$\text{Intercept} = \frac{A}{\sqrt{B}}, \quad (11)$$

where ECF is the Energy of Crush Factor. Such a graph is known as a crash plot and relates impacts of individual severities.

For a given crash test into a fixed rigid barrier, the crush energy is simply the loss in kinetic energy (initial minus rebound kinetic energies). For uniaxial (or co-linear) impacts, we can write:

$$CE = \Delta KE = \frac{1}{2} m_V (1 - \varepsilon^2) V_{CL}^2, \quad (12)$$

where m_V is the mass of the vehicle, ε is the coefficient of restitution and V_{CL} is the initial impact velocity. If, for a given vehicle design, a number of barrier crash tests have been performed, and the impact velocity, restitution coefficient, form factor, average crush, and crush width are known for each of them, then each test may be represented by a data point on a crash plot. Subsequently, a regression line may be fitted among the points, from which A and B can be determined from [Equations \(10\) and \(11\)](#).

Deriving Stiffness Coefficients from Uniaxial Impacts with Rigid Moving Barriers

In the case where the rigid barrier has finite mass and can move, then momentum is conserved, in addition to energy. Enforcing these conditions produces the analog of [Equation \(12\)](#):

$$CE = \frac{m_B m_V (1 - \varepsilon^2) V_{CL}^2}{2(m_B + m_V)}, \quad (13)$$

where the subscripts B and V refer to the barrier and the vehicle, respectively, and where V_{CL} is the initial closing velocity between the crash partners. A complete derivation can be found in Reference [3]. If we define the effective vehicle mass as:

$$m_{EFF} = \frac{m_V}{1 + m_V/m_B}, \quad (14)$$

then [Equation \(13\)](#) becomes:

$$CE = \frac{1}{2} m_{EFF} (1 - \varepsilon^2) V_{CL}^2, \quad (15)$$

which in fact reduces to [Equation \(12\)](#) for the special case of an infinitely massive barrier. The crash plot analysis proceeds in the same way as described above.

The approach embodied in [Equation \(15\)](#) can be applied to side impacts, particularly perpendicular impacts by rigid moving barriers, such as the tests discussed in References [12] and [16]. The test mode described in those references did not result in significant post-impact vehicle rotations, but other modes may involve rotational energies that should be accounted for. In side impacts, some accounting may also be required for tire scrub as the struck vehicle slides sideways, particularly in low speed tests where energy losses from tire scrub are more significant with respect to the kinetic and crush energies.

What Happens when Both Crash Partners Absorb Energy

In a uniaxial impact between a vehicle and another vehicle, or between a vehicle and an MDB, both structures crush – and absorb energy in so doing. The two crushable structures are in series with each other and together may be viewed as a single crushable element. [Equation \(15\)](#) still applies, but now the left-hand side of the equation must be interpreted as the total crush energy for both crash partners. Thus, we can write:

$$CE_{TOT} = CE_V + CE_B = \frac{1}{2} m_{EFF} (1 - \varepsilon^2) V_{CL}^2. \quad (16)$$

The fact that [Equation \(16\)](#) derives from [Equation \(7\)](#) opens the door to crash plot analysis of the vehicle structure, as long as CE_{TOT} and CE_B are known quantities. For such an approach to yield information on the vehicle structure, the total crush energy in the crash must be computed, the structural behavior of the MDB must be known, and the residual crush of both crash partners must be documented.

Analyzing Lateral Crash Tests with Moving Deformable Barriers

Beginning in 1997, the US Government began performing side impact crash tests as part of the New Car Assessment Program (NCAP). These tests were not like those in References [12] and [16], which specifically focused on stiffness parameters for the reconstruction of side impacts. Rather, Side Impact NCAP (SINCAP) tests are focused on occupant crash protection and simulate a perpendicular intersection crash with both vehicles moving. The embodiment of this concept is a crabbed MDB striking the side of a stationary vehicle placed at an angle to the tow track, but perpendicular to the MDB [17], as seen in [Figure 1](#), copied from Reference [17].

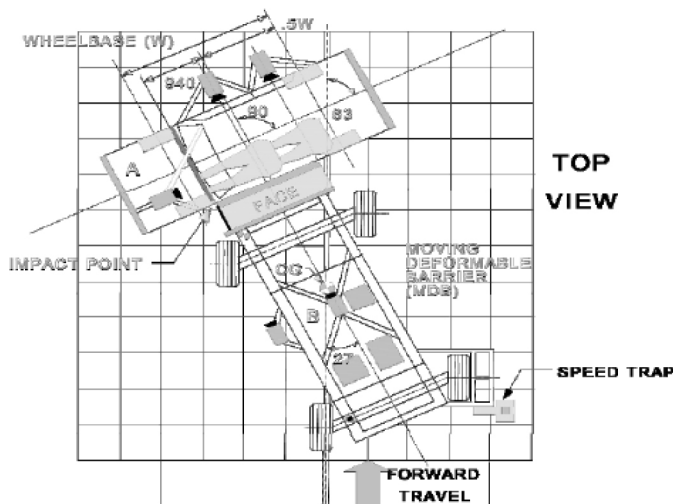


Figure 1. SINCAP test configuration

This crash mode complicates the analysis of structural behavior due to the presence of an additional energy-absorbing structure and the angles involved. However, in US-market vehicles, it is nearly the only source for side impact data. Even so, the SINCAP tests (and the similarly configured FMVSS 214D compliance tests) have produced a wealth of data, which if analyzed properly, could yield valuable insights into vehicle structural stiffness. First, the necessary analytical tools must be developed, which is the subject of this research.

Previous Research

As mentioned above, a key step in developing a methodology for analyzing SINCAP tests is acquiring knowledge of the stiffness parameters A and B for the MDB, so that the MDB contribution to the crush energy can be determined, based on the measured crush post-test. In 1984 the NHTSA published a dynamic force-deflection curve for the MDB [18], and various researchers [19] claimed that its A and B values were thus known quantities. However, the MDB A and B values presented in Reference [18] were based on square-on frontal barrier tests that do not produce the combined compressive and transverse loads on the crushable honeycomb barrier face that are present in the SINCAP tests. The structural differences have a significant effect on the prediction of the energy absorbed by the barrier.

An excellent discussion of the state of affairs in 1998 was provided by Strother et al. [20]. In 2001 a study by Struble et al. [1] analyzed some SINCAP-style crash tests of advanced instrumentation MDBs [21] that properly loaded the barrier face, and from which its A and B values could be determined. As a result, the MDB stiffness values were found to be $A = 54.3$ pounds per inch, $B = 224.4$ pounds per square inch, and the saturation crush C_s was 9.54 inches. (There will be more discussion about saturation later on.) The damage onset speed was determined to be 0.04 miles per hour. By contrast, the values used in the sample calculation of Reference [19] were $A = 357$ pounds per inch, and $B = 172$ pounds per square inch, corresponding to a damage onset speed of 4.5 miles per hour. This model also neglects any possible effects of force saturation in the barrier.

Once the MDB was characterized, its crush energy and the force acting on it during a crash test could be calculated. The next step in the analysis as presented in Reference [1] required a careful accounting of the kinetic energy of both crash partners as they emerged from the impact. Energy conservation was enforced by subtraction: the initial kinetic energy minus the kinetic energies at separation, tire friction, and the MDB crush energy. This process produced the crush energy absorbed by the struck vehicle.

Enforcing energy conservation and force balance provided the two conditions by which the vehicle side stiffness parameters A and B could be discovered (through an iterative process). The iterative process converged most of the time, but not always.

In this method, there was no accounting in the analysis for the no-damage threshold of the side structure. Consequently, while the derived A and B parameters fit the crash test data point (i.e., they produced proper valuations of crush energy and force in the test), they did not consider the implications for structural behavior at low impact severities.

Rigorous accounting for rotational effects is a process fraught with complications, requiring analysis of eight channels of acceleration data per test (X- and Y-accelerations from each of two accelerometer packs mounted on each crash partner). For the side impacts analyzed in Reference [1], rotational kinetic energy at separation averaged about 10 per cent of the translational kinetic energy. Based on the variability of A and B , it is not clear that teasing out the rotational effects and exactly matching force levels between the crash partners actually improved the results. An alternative approach to determining both crash partner's post-impact yaw rate would be to analyze the overhead video, although that process too can be fraught with complications.

Nature of the Vehicle Fleet

The 2010 Osterholt study [14] addressed the obsolescence of the vehicle population studied by Siddall and Day [13] in 1996, at least for frontal impacts. Again, generic results were published for the same 11 vehicle categories specified in the earlier study, rather than specific vehicles. Reference [14] confirmed the trend that many observers have seen over the years: namely, frontal stiffness of vehicles continues to increase with time [22]. However, there was a lot of scatter within each category. The B value averages, taken as their own population, had a standard deviation of just under 15 pounds per square inch. This was less than the standard deviation within any of the individual categories. In other words, there was more variation within a given category than between categories. Almost the opposite was true for A (possibly because of fairly uniform assumptions for no-damage threshold speeds). The variables defining the categories (wheel base and vehicle type) do not seem reliable predictors of either A or B for reconstruction purposes. It is better to use calculated parameters for a specific vehicle, compared to relying on averaged data from broad vehicle categories. Publicly-available specific crash test reports are available for most high-volume vehicles.

The 2014 update by Lee et al. [15] re-defined the categories in terms of Department of Energy fuel economy guidelines. Market trends were used to select the vehicles to represent the categories. Again, stiffness was shown to be increasing over time, and much scatter was indicated in frontal A and B values. Rear and side stiffness parameters were also shown (with notably less scatter for the side A values), but no information was provided as to how they were derived. Credibility of the results requires an understanding of where the underlying parameters came from.

Approach for this Study

1. Determine a means of extracting the vehicle crush energy from the MDB crush data and the vehicle dynamics at separation, when the vehicle is struck in the side by a moving deformable barrier (MDB).
2. Extend the theoretical basis of crash plots to impacts in which both collision partners develop crush energy.
3. Develop a crush energy computation protocol suitable for accident reconstruction, compatible with the crush measurements documented in crash test reports.
4. To the extent possible, discern the no-damage threshold of crash severity in side impacts, i.e. find the test speed below which no residual damage is seen, and above which permanent damage is incurred.
5. Determine the vehicle stiffness parameters that correctly predict the crush energy in a crash test, while producing an appropriate no-damage threshold. For a crash test, such a procedure effectively reverses the crush energy calculations used in reconstructions, and may require iterative methods.
6. Explore the nature and effects of force saturation on the determination of stiffness parameters.
7. Apply this procedure to a representative sample of side impact crash tests to discern what trends may be present, if any.

METHODOLOGY

The present approach uses Equation (16) to analyze SINCAP test results, since both crash partners absorb energy in structural crush. Rotational effects are assumed to be small, in keeping with the findings of Reference [1]. (After all, the impacted area of the struck vehicle straddles its center of mass.) Separation velocities are obtained by integrating the appropriate accelerometer channels, from which the restitution coefficient (not accounted for in Crash3) is easily calculated. In accordance with Equation (16), the residual energy that gets dissipated in crush (total crush energy) can be expressed in terms of impact velocity, restitution coefficient, and the masses of the vehicle and barrier. Energy dissipation due to the lateral scuffing of the struck vehicle tires is not included, since Reference [1] found the contribution to be negligible in SINCAP tests (typically less than one percent of the total kinetic energy of the event).

The linear structural model developed in Reference [1] for the MDB is used to calculate the crush energy absorbed by the MDB, based on the reported bumper-level crush "...because the MDB bumper is so much stiffer than the main honeycomb stack. Despite that stiffness, the mid-bumper crush is easily the highest, because the bumper

initially protrudes 4 inches forward of the rest of the honeycomb..." [1]. The MDB crush energy is subtracted from the residual energy to obtain the crush energy assignable to the vehicle.

A crash plot is then constructed with a straight line drawn between the crash test data point and an intercept based on a no-damage threshold of 2.1 mile per hour change in velocity, or ΔV . (The threshold is based on the results of repeated side impact tests, discussed later.) A and B are then calculated using Equations (10) and (11).

Obtaining Separation Velocities and Restitution

Kinetic energy loss is computed by comparing the MDB kinetic energy at impact versus the kinetic energies of the vehicle and the MDB when they separate. Rotational kinetic energies have generally been found to be small compared to crush energy and the translational kinetic energies at separation, so the fundamental kinetic energy formula $KE = \frac{1}{2}mV^2$ is applied to each crash partner at separation, where V is the resultant velocity. Each resultant is computed from the vector sum of the longitudinal and lateral velocity components.

To determine the time of separation (i.e., the end of the contact phase), the velocity-time ($V-t$) curves of the vehicle and the MDB are compared to see when the local extrema occur; usually they closely coincide in time. If a local minimum exists for the MDB x-axis $V-t$ curve, that time value is chosen; otherwise, the local maximum of the vehicle y-axis $V-t$ curve may be used. In either case, the selected time value is applied to both crash partners.

The $V-t$ curves are obtained by using Signal Browser, one of the applications included in the NHTSA Signal Analysis Software package, available on the NHTSA website¹. To use it, the appropriate accelerometer channel(s) for the test of interest are selected from a structured list of channel identifiers. The data are immediately graphed (at CFC 1000). The accelerometer traces are then filtered to the appropriate Channel Frequency Class (CFC) according to the test protocol (vehicle and barrier accelerometer data are typically filtered to Class 180 before integration [23]) by clicking on the appropriate numeric icon.

To obtain the $V-t$ curve(s), the integration function is used. Velocity and time coordinates can be displayed, which allows the user to pinpoint a velocity at a desired time value (separation, for example).

The resultant velocities and kinetic energies are then readily calculated. Relative velocities between the vehicle and MDB at impact and separation, lateral to the vehicle, are then computed. By treating the crash test as an essentially uniaxial collision, the restitution coefficient can be calculated from these relative velocity components.

Findings from Repeated Impact Tests

In 1991 Prasad [16] reported on a test program in which each of five vehicles was subjected to a series of perpendicular side impacts by a rigid moving barrier shaped similarly to an MDB, but full crash test reports were not available for those tests, and the data presented in [16] was insufficient to perform a full analysis. Similar repeated test series of two additional vehicles were found in the NHTSA cash test database. These tests were of a 1984 Audi 5000: DOT 1644 – 1647 (four repeated impacts at 15.2, 20.1, 20.0, and 40.1 miles per hour) and a 1985 Ford Escort: DOT 1823 – 1826 (four repeated impacts at 20.0, 20.0, 20.0, and 34.7 miles per hour). Analysis of these tests provides insight in the force-deflection behavior of these vehicles across a broad spectrum of severities, particularly on the low end.

Repeated-impact tests are analyzed in References [3] and [6]. The speed of a single test S that is equivalent in crush energy to R repeated impacts in a test series and is given by:

$$(V_{cl})_S^2 = \frac{1}{1 - \varepsilon_R^2} \sum_{K=1}^{R-1} (V_{cl})_K^2 + (V_{cl})_R^2 \quad (17)$$

The various equivalent impact speeds are determined by setting $R = 2 \dots 3$ or 4 in Equation (17) for these series. The various restitution coefficients were calculated from Signal Browser information, which gives the speeds in kilometers per hour. For the four Audi 5000 tests, the restitution coefficients were 0.173, 0.151, 0.114, and 0.015 – a decreasing trend with increasing closing speed that many observers have reported. It appears that a reasonable restitution coefficient in a no-damage impact would be given by:

$$\varepsilon_0 = 0.2. \quad (18)$$

If a regression line were fitted to the resulting data points for the Audi 5000, it would have a typically high correlation coefficient. For this vehicle, however, we would see a definite bend in the data point pattern at the second test, as illustrated in Figure 2. This is a typical indicator of force saturation, wherein the force stops increasing at some level of crush. In other words, the test data may be explained better by a structural model that is constant stiffness only up to a certain point – the saturation crush – beyond which the force remains constant – the saturation force [5, 20].

Instead, consider another crash plot, one containing an imaginary “no-damage” data point, as shown in Figure 3. Its coordinates would be derived from the y-intercept of a line running through the data points corresponding to the first two tests: (5.00, 57.40) and (8.59, 89.11). The resulting point would have an ordinate of 13.3178 (and a corresponding abscissa of zero, as there is zero average crush). The test speed required to produce this “no-damage” condition (the closing speed between the stationary target vehicle and the moving rigid contoured barrier) would be 3.53 miles per hour (5.7 kilometers per hour). The ΔV of the struck vehicle works out to be 2.10 miles per hour. While the no-damage threshold varies from vehicle to vehicle,

as seen in the few repeated-impact test series available, it is representative of the values typically assumed by analysts. Thus a no-damage threshold ΔV of 2.1 miles per hour was utilized for all side impacts (including those by an MDB). The closing speed corresponding to this ΔV would vary according to the masses of the collision partners in the various crash tests.

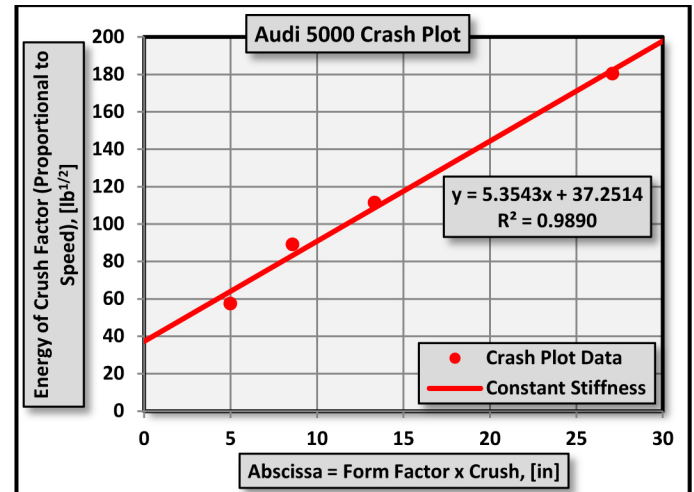


Figure 2. Crash plot for Audi 5000 repeated test series, DOT 1644 - 47.

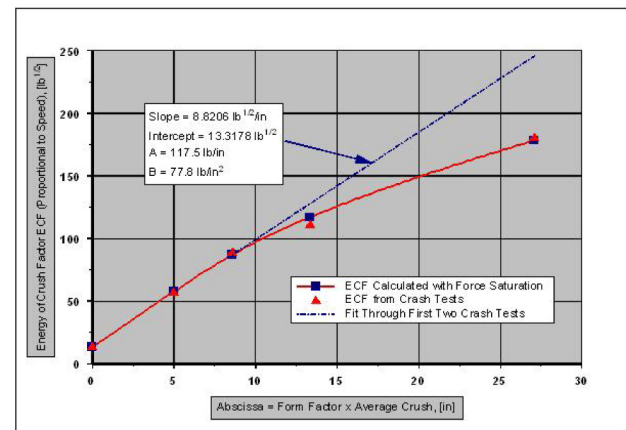


Figure 3. Crash plot for Audi 5000 repeated test series (with no-damage data point), DOT 1644 - 47.

The saturation crush C_s for this vehicle/test series was 7.1 inches, which was the average crush corresponding to the bend in the crash plot at the second impact. Again, this value was chosen to be representative of all side impacts (including those by an MDB). Sensitivity to this choice is discussed in Appendix B. The A and B values derived from the first two actual tests represented on the crash plot were 117.5 pounds per inch and 77.8 pounds per square inch, respectively.

Figure 3 shows that a force saturation model can provide adherence with low-speed crash behavior, while still retaining fidelity in high-severity impacts. The maximum error magnitude in predicting the crash test ECF was 5% (for Test 1646); the error magnitudes in the remaining tests were less than 2½%.