A Comparison of Crush Stiffness Characteristics from Partial-Overlap and Full-Overlap Frontal Crash Tests

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ABSTRACT

The CRASH3 computer program models a vehicle structure as a homogeneous body with linear force-deflection characteristics. Crush stiffness coefficients determined from full-overlap crash tests, when used in this computer program, allow for an accurate reconstruction of collisions where the accident damage profiles are full-overlap. In the past, partial-overlap frontal crash tests were not performed. The lack of partial-overlap frontal crash tests meant that a reconstructionist only had crush stiffness coefficients available that were determined from full-overlap frontal crash tests. In a reconstruction, the assignment of stiffness coefficients to a partial-overlap damage profile required engineering judgement. Often the basis of such judgement was questioned because of the lack of supporting partial-overlap test data.

Recently partial-overlap crash tests have been performed and the test data has been made available to the public. A comparison of crush stiffness characteristics from partial-overlap, and full-overlap, frontal crash tests is presented in this paper.

INTRODUCTION

Vehicle structures are modeled in the CRASH3 damage algorithm as having a linear force-deflection relationship. A review of available data reveals that this relationship is valid for full-overlap frontal collisions with rigid, non-deformable barriers up to the speed of 35 miles per hour (mph) which is used in the NHTSA New Car Assessment Program (NCAP) test *[1]. During these tests, the crush is essentially limited to the engine compartment. Rarely are vehicles tested in full-overlap mode at speeds greater than 35 mph. Consequently, the available full-overlap crush stiffness coefficients are based upon an impact severity that results in crush essentially occurring only in the engine compartment.

EDCRASH [2] allows the damage profile to be divided into zones and the assignment of different stiffness coefficients in each zone. The EDCRASH damage model is based upon each zone of damage being homogeneous. Employing this feature requires engineering judgement regarding the magnitude of the stiffness coefficients. This is due to a lack of stiffness coefficients that have been determined separately for each zone.

In the past, the lack of partial-overlap frontal crash tests meant that reconstructionists only had crush stiffness coefficients available that were determined from full-overlap frontal crash tests. In a reconstruction, the assignment of full-overlap stiffness coefficients to the...
direct damage portion of a partial-overlap profile required engineering judgement (see Appendix for definitions). With no partial-overlap test data available, the basis of such judgement was often questioned. In addition, assignment of full-overlap stiffness coefficients to the entire partial-overlap profile, both direct and induced damage, created concern with regard to consistency with the CRASH3 damage model. The CRASH3 model is based upon damage caused by an external force being applied to the exterior surface of a vehicle. In the full-overlap test, an external collision force is applied to the full-width of the damage profile. The entire profile, therefore, is direct damage. The use of full-overlap stiffness coefficients in a CRASH3 analysis of a real-world full-overlap collision is consistent with the CRASH3 damage model. However, in a partial-overlap collision, no external force is applied to the exterior surface of a vehicle in the induced damage area. Applying full-overlap stiffness coefficients to the induced damage in a CRASH3 analysis of a real-world partial-overlap collision is not completely consistent with the CRASH3 damage model.

Recently data from partial-overlap frontal collisions have become available. The number of partial-overlap tests, however, is few and most vehicles probably will never be tested. Therefore, a need exists for an understanding of the degree to which vehicle frontal structures are homogeneous and behave in a linear manner in a collision. These new crash tests provide the basis for a comparative analysis of full-overlap crush response versus partial-overlap crush response.

DISCUSSION

Background

Previously published methods were employed in the analysis of the full-overlap, and partial-overlap, frontal crash tests. The full-overlap crash test data was analyzed using the method specified in reference [3]. The partial-overlap crash test data was analyzed using the method specified in reference [4]. Both methods use a lumped parameter approach and are based upon the CRASH3 damage model where restitution effects are considered negligible. In addition, in both methods, only the direct damage sustained by the test vehicle was used to determine the crush stiffness. The reason for using direct damage only is two-fold. First, it is required by the method used to analyze the partial-overlap tests [4]. Secondly, the CRASH3 damage algorithm is based upon damage caused by an external force being applied to the exterior surface of a vehicle. No external force is applied to the exterior surface of a vehicle in the induced damage areas.

CRASH Plots were used to compare the crush response of the test vehicles. In a CRASH Plot, a normalized damage energy term, $E_{\text{Norm}}$, is graphed against the equivalent uniform crush, $\beta$, sustained by the test vehicle (figure 1). Where necessary, the crush from these tests was ‘air-gap’ adjusted (see Appendix).

\[
E_{\text{Norm}} = \sqrt{\frac{2 \times E_{\text{Damage}}}{L}}
\]

Where:

- $E_{\text{Damage}}$ = The kinetic energy converted to work in damaging the test vehicle.
- $L$ = The width of the direct damage profile.

\[
\beta_6 = \frac{C_1 + 2 \times (C_2 + C_3 + C_4 + C_5) + C_6}{10}
\]

Where:

- $\beta_6$ = The equivalent uniform crush for a six point damage profile.
- $C_1 \ldots C_6$ = The direct damage crush measurements.

\[
B = (\text{Slope})^2
\]

\[
A = E_{\text{Norm}_0} \times \sqrt{B}
\]

Full-Overlap Crash Tests

The CRASH3 stiffness coefficients, A & B, can be determined from the CRASH Plot. The B-coefficient is equal to the square of the slope of the graphed line. The A-coefficient is equal to the intercept with the y-axis, $E_{\text{Norm}_0}$, times the square root of the B-coefficient. This graphical approach also allows for a quick qualitative and quantitative comparison of the stiffness of several test vehicles.

\[
\beta_6 = \frac{C_1 + 2 \times (C_2 + C_3 + C_4 + C_5) + C_6}{10}
\]

Ford Explorer 4X4

\[
E_{\text{NORM}} [\text{Sqrt(lbf)}]
\]

1995-96 Full Frontal 1996 Offset Frontal

\[
\beta_6 = \frac{C_1 + 2 \times (C_2 + C_3 + C_4 + C_5) + C_6}{10}
\]

Where:

- $\beta_6$ = The equivalent uniform crush for a six point damage profile.
- $C_1 \ldots C_6$ = The direct damage crush measurements.

\[
B = (\text{Slope})^2
\]

\[
A = E_{\text{Norm}_0} \times \sqrt{B}
\]

Vehicles are rarely tested at speeds greater than 35 mph. A few vehicles, for example the 1981-85 Ford Escort/Mercury Lynx [5], have been tested up to 50 mph
This vehicle demonstrates a linear force-deflection characteristic for speeds up to 35 mph. At test speeds greater than 35 mph, the vehicle is no longer linear and has lower crush stiffness (figure 3). This lower stiffness corresponds to a saturation of crush in the engine compartment and crush being produced by a buckling of the occupant compartment. The Escort/Lynx occupant compartment apparently has a lower stiffness than the engine compartment. This vehicle has bi-linear characteristics with a deflection point in the crush stiffness occurring at a test speed of 35 mph. The vehicle can be modeled as two linear springs in series where the second spring does not compress until the first spring bottoms out. In this case, the first spring (engine compartment) is stiffer than the second spring (occupant compartment). The crush response characteristics of this vehicle can be divided into two regions, the engine compartment region and the occupant compartment region (figure 3).

The Escort/Lynx vehicle full-overlap crush response is consistent with line #2B, the engine compartment is stiffer than the occupant compartment. The Escort/Lynx vehicle full-overlap crush response is consistent with line #2B.

The engineering model used by CRASH3 could be improved to better address bi-linear characteristics associated with impacts of high severity. This can be accomplished with an extension to the existing engineering model. Engineering Model No. 1, line #1 in figure 4, is the linear, homogeneous structure of the CRASH3 model. Vehicles fitting this model have equal stiffness in the engine and occupant compartments. Engineering Model No. 2 is a homogeneous structure with a bi-linear crush response. There are two configurations for Model No. 2. In the first, the engine compartment is softer than the occupant compartment as shown by line #2A. In the second configuration, shown by line #2B, the engine compartment is stiffer than the occupant compartment. The Escort/Lynx vehicle full-overlap crush response is consistent with line #2B.

The Insurance Institute for Highway Safety (IIHS) has performed the vast majority of the available partial-overlap crash tests. The IIHS test involves a collision at 40 mph into a fixed deformable barrier. Although the IIHS test impact speed is 40 mph, a significant portion of this initial kinetic energy is not converted into work damaging the vehicle. Kinetic energy remains post-impact in the form of rotational, and translational, energy as the vehicle moves toward its point of rest. The direct damage energy of the IIHS test has been found to be equivalent to the direct damage energy of a NHTSA Compliance (COM) full-overlap test performed at 30 mph (figure 5). Figure 5 is a histogram that shows the frequency of occurrence of the Equivalent (full-overlap) Barrier Speed (EBS) for the partial-overlap tests.

E_Norm, a measure of the energy converted into work damaging a vehicle that has been normalized per unit width of the damage profile, provides a measure of impact severity. The CRASH3 crush stiffness coefficients, A & B, which also are normalized per unit width, are a measure of the crush response.
characteristics of a vehicle [3]. In this paper, E_Norm will be used as a measure of the severity of an impact. For a given vehicle, the impact severity (E_Norm) of a 35 mph full-overlap test is 17% greater than the impact severity of a 30 mph full-overlap test.

\[
E_{\text{Norm}35} = \sqrt{\frac{2 \times (1/2 \times m \times 35^2)}{L}} = \frac{35}{30} \approx 1.17 \quad (5)
\]

Where:

\[ m = \text{The mass of the vehicle.} \]

In a full-overlap test, the direct damage energy is distributed across the entire width of the vehicle. In the IIHS test, the direct damage sustained by the test vehicle generally involves 50% of the width of the vehicle. In a full-overlap test of a given vehicle, the term \( L' \) used in equation (1) will be twice the magnitude of \( L' \) for that same vehicle when tested in a 50% partial-overlap mode. Given that the damage energy of a 30 mph COM test is essentially the same as a 40 mph IIHS test, the impact severity (E_Norm) of an IIHS test is 41% greater than the impact severity of a 30 mph full-overlap test and 21% greater than a 35 mph full-overlap test. The impact severity, E_Norm, of an IIHS test being 21% greater than a NCAP test means that, in most cases, the partial-overlap test will result in deformation to the occupant compartment.

\[
E_{\text{Norm Partial}} = \sqrt{\frac{2 \times E_{\text{Damage Full}}/2}{L_{\text{Full}}}} \quad \text{or} \quad \sqrt{2} = 1.41 \quad (6)
\]

\[
E_{\text{Norm Partial}} = \sqrt{\frac{2}{35}} = \frac{30 \sqrt{2}}{35} \approx 1.21 \quad (7)
\]

When only one partial-overlap test is available for a vehicle, four engineering models can be used to describe the possible crush response characteristics. Engineering Models No. 1 and No. 2 represent a homogeneous structure. A homogeneous structure is one where the stiffness characteristics are the same across the full width of the structure. Engineering Models No. 3 and No. 4 are used for bi-homogeneous structures. Engineering Models No. 1 and No. 4 have linear force-deflection characteristics. This means that the stiffness of the engine and occupant compartments is the same. Engineering Model No. 2 and No. 3 represent bi-linear vehicles where the stiffness of the engine and occupant compartments is different.

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<th>Structure</th>
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<tr>
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<td>Bi-Linear</td>
<td>Homogeneous</td>
</tr>
<tr>
<td>No. 3</td>
<td>Bi-Linear</td>
<td>Bi-Homogeneous</td>
</tr>
<tr>
<td>No. 4</td>
<td>Linear</td>
<td>Bi-Homogeneous</td>
</tr>
</tbody>
</table>

**TABLE 1: Possible Engineering Models**

A single IIHS test performed in either the engine compartment crush region, or the occupant compartment crush region, will not fully define the crush response characteristics of the vehicle in a partial-overlap collision. Tests need to be performed in both the engine, and the occupant, compartment crush regions.

**Partial-Overlap Crash Test, Occupant Compartment Only**

If a single data point from a partial-overlap test falls on an extension of the full-overlap crash test line, then either Engineering Models No. 1 or No. 3 could apply (figure 6). Engineering Model No. 1 is the linear, homogeneous structure used in CRASH3. Engineering Model No. 3 has bi-linear force-deflection characteristics where the engine compartment crush stiffness is different from the occupant compartment stiffness. In addition, the engine compartment crush stiffness, in the partial-overlap mode, is different from the engine compartment crush stiffness in full-overlap mode. This indicates that the stiffness is not uniform across the entire width of the engine compartment. Engineering Model No. 3, therefore, is bi-homogeneous.

When a single partial-overlap data point does not fall on the extension of the full-overlap crash test line, then Engineering Models No. 2, No. 3, or No. 4 could apply. In Engineering Model No. 2 is bi-linear and homogeneous (see figure 4). The engine compartment stiffness is the same for both partial-overlap and full-overlap collision modes. In addition, the occupant compartment does not have the same stiffness as the engine compartment. Engineering Model No. 4 has a linear force-deflection and is bi-homogeneous (figure 6). The stiffness is the same for the engine compartment and the occupant compartment. The vehicle, however, is bi-homogeneous with the crush stiffness in the partial-overlap mode different from the engine compartment crush stiffness in full-overlap mode.

**Partial-Overlap Crash Test, Engine Compartment Only**

When a single partial-overlap data point falls on the full-overlap crash test line, then either Engineering Models No. 1 or No. 2 could apply. This single test would indicate that the engine compartment is homogeneous since the stiffness is the same in both collision modes. In other words, the stiffness of the left
portion of the engine compartment is the same as the stiffness across the full-width of the engine compartment. However, without a partial-overlap test within the occupant compartment crush region, it can not be determined whether the vehicle is linear or bi-linear.

In the case where a single partial-overlap data point does not fall on the full-overlap crash test line, then either Engineering Models No. 3 or No. 4 could apply. This single test would indicate that the engine compartment is bi-homogeneous since the stiffness is the different between the two collision modes. Again, without a partial-overlap test within the occupant compartment crush region, it can not be determined whether the vehicle is linear or bi-linear.

ANALYSIS

The crush stiffness of the available vehicles has been charted in figure 7. The data demonstrates that the crush stiffness for a given vehicle usually is different between the NHTSA full-overlap, and the IIHS partial over-lap, collision modes. For example, a 1995 Chevrolet Cavalier (figures 7 & 8) is stiffer in an IIHS partial-overlap test than in a full-overlap test collision. A 1996 Isuzu Rodeo (figures 7 & 9) is stiffer in a full-overlap test than in an IIHS partial-overlap collision. The 1996 Ford Taurus (figures 7 & 10), on the other hand, has the same stiffness in both collision configurations.

The 1988 Ford Taurus (figure 7) has been subjected to a repeat-impact test procedure by the NHTSA in a partial-overlap mode. Figure 11 shows that this vehicle is essentially linear in both the full-overlap and partial-overlap test modes. In addition, the crush stiffness is nearly the same for each mode. These tests support the homogeneous structure with linear force-deflection characteristics used in CRASH3 to model the crush response of vehicles (Engineering Model No. 1). It should be noted that, the front end of the Taurus was supported by resting the vehicle frame on a tow dolly during the repeat tests. This raised the front tires off the ground. As the engine compartment crushed, the left front tire was deflected downward away from the occupant compartment structure. This made available an additional area for crush within the engine compartment before saturation would occur. Consequently, the collision force was not directed into the occupant compartment structure until later in the crushing process. This probably prevented some deformation of the occupant compartment that otherwise would have occurred had the tire not been deflected downward.
There are three possible engineering models for the 1996 Isuzu Rodeo (see figures 9 & 12). Due to the lack of partial-overlap tests at intermediate impact severity, it is uncertain whether this vehicle is linear, or bi-linear in its crush response in the partial-overlap test mode. The vehicle could be bi-linear and homogeneous based upon the Engineering Model No. 2 with a two linear-series spring system. In this case, the engine compartment has the same stiffness as determined from the full-overlap tests and is stiffer than the occupant compartment. In addition, due to the severity of the IIHS tests, it is uncertain whether this vehicle is homogeneous, or bi-homogeneous in partial-overlap collision. Engineering Model No. 3 is a bi-homogeneous structure that has two linear springs of different stiffness representing the engine compartment. One spring represents the vehicle in a full-overlap collision and the other spring represents the vehicle in a 50% partial-overlap collision. Engineering Model No. 4 is a bi-homogeneous two linear-series spring arrangement where the partial-overlap stiffness of the engine compartment is different from the stiffness determined from full-overlap tests and the stiffness is not uniform across the width of the vehicle.

For the 1995 Chevrolet Cavalier (figures 8 & 13), the IIHS test severity (E_Norm) is higher than the full-overlap tests at 35 mph yet the crush from the IIHS test is less. In the bi-linear Engineering Models, the first spring (engine compartment) must bottom out before the second spring (occupant compartment) begins to compress. The IIHS test crush being less than the crush from the 35 mph full-overlap tests indicates that the engine compartment has not reached the crush saturation point in the IIHS test. Consequently, it can not be determined whether the crush response of the vehicle is linear, or bi-linear. In addition, the partial-overlap test data point does not fall on the full-overlap line within the engine compartment crush region. This indicates that the stiffness is not uniform across the width of the vehicle. Therefore, the vehicle front end structure is bi-homogeneous.

There are two possible engineering models for the 1995 Chevrolet Cavalier. Engineering Models No. 3 or No. 4 can describe the front-end structure of the 1995 Chevrolet Cavalier. Both models are bi-homogeneous. Model No. 3 is bi-linear while Model No. 4 is linear. Further partial-overlap testing in the occupant compartment region is required to determine the linearity of this vehicle.

The partial-overlap crash tests that have been analyzed provide some additional insight into the crush response of vehicles. These tests show that vehicles usually have different stiffness in partial-overlap tests versus full-overlap tests. The analysis presented in this paper supports the existing CRASH3 model relative to engine compartment region damage. Modifications to the CRASH3 damage model could allow the program to better address the bi-linear characteristics associated with occupant compartment region damage.

A word of caution is required regarding any conclusions from this comparison. It is important to recognize that this comparison is based upon partial-overlap test data that had a direct damage overlap of approximately 50%. Vehicle crush response may be different in partial-overlap collisions that have a direct damage overlap other than 50%, for instance 25% or 75%.
CONCLUSIONS

1. The available data demonstrates that the crush stiffness for a given vehicle usually is different between the NHTSA full-overlap, and the IIHS partial overlap, collision modes.
2. The engineering model used by CRASH3 could be improved to better address bi-linear characteristics associated with impacts of high severity.
3. The analysis presented in this paper supports the existing CRASH3 model relative to engine compartment region damage. Modifications to the CRASH3 damage model could allow the program to better address the bi-linear characteristics associated with occupant compartment region damage.
4. In high severity collisions, the crush response characteristics of a vehicle can be divided into two regions, the engine compartment region and the occupant compartment region. The vehicle can be modeled as two springs in series where the second spring (occupant compartment) does not compress until the first spring (engine compartment) bottoms out.
5. The impact severity, E_Norm, of an IIHS test is 21% greater than the severity of an NCAP test. This means that, in most cases, the partial-overlap test will result in deformation to the occupant compartment.
6. A single partial-overlap test performed in the engine compartment crush region, or the occupant compartment crush region, will not fully define the crush response characteristics of the vehicle in a partial-overlap collision. Tests need to be performed in both the engine and occupant compartment crush regions. When only one partial-overlap test is available for a vehicle, four different engineering models can be used to describe the possible crush response characteristics.
7. It is important to recognize that this comparison is based upon partial-overlap test data that had a direct damage overlap of approximately 50%. Vehicle crush response may be different in partial-overlap collisions that have a direct damage overlap other than 50%, for instance 25% or 75%.
8. Repeat testing should be performed with the front end of the vehicle supported by resting the front tires on a tow dolly. This will keep the front tires in their normally loaded position and should provide for normal loading of the occupant compartment structure.

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7. Chevrolet Cavalier crash tests: NHTSA #2253, 2528, *2291; TC #96-114, 97-110.
9. Chevrolet Lumina crash tests: NHTSA #2222, *2288; TC #95-104.
10. Chevrolet C1500 crash tests: NHTSA #1144, 1686, 1741, 2180, 2181, 2182, 2183, 2184, 2230, 2240, 2407; TC #91-108.
12. Dodge Stratus crash tests: NHTSA #2252.
24. Saab 900 crash tests: NHTSA #2198, 2374, *2294

* Test performed at IIHS.

APPENDIX

Definition of Terms

Vehicle Contact Plane
A vertical plane parallel to, and inline with, the exterior side of a vehicle. The length of the plane is equal to the length of the corresponding side of the vehicle.

Center of Length Projection Line
A line normal to the vehicle contact plane that passes through the mid-point of the vehicle contact plane.

Collision Oriented
Term used to describe a condition relating to all the involved vehicles, objects, etc.

Vehicle Oriented
Term used to describe a condition relating to a specific involved vehicle.

Offset
Distance measured between the center of length projection lines of the vehicle contact planes. The offset distance is collision oriented for non-oblique collisions.

Direct Damage
The portion of the damage profile in which contact occurred between the vehicle and barrier. In other words, the vehicles surface where that involved the primary loading by the other vehicle or object. It does not include regions with minor scratches, etc.

Induced Damage
The portion of the damage profile upon which an external collision force was not applied.

Direct Damage Overlap
A measurement of the length of the direct damage along the vehicle contact plane of the striking/struck vehicle or object. The overlap is related to a specific vehicle in a collision. The overlap can be express as a distance value or percent. A percent overlap is based upon the overall vehicle width (W103) for front and rear impacts, and the overall vehicle length (L103) for side impacts.

Crash Test Alignment Overlap
A measurement of the length along the vehicle contact plane on the vehicle, or object, that overlaps the contact plane of the other involved vehicle, or object, based upon the test setup alignment.

Damage Onset Speed
A damage onset speed is the maximum speed at impact of a vehicle in a full-overlap collision with a non-energy absorbing fixed barrier that will not produce any residual crushing of the vehicle structure.

Bumper Cover Rebound, The ‘Air-Gap’ Problem

After a crash test, the rubber bumper covers on some newer vehicles are rebounding back to their pre-crash shape while the underlying vehicle structure remains crushed. This creates an ‘air-gap’ between the bumper cover and the underlying vehicle structure. Correct crush measurement procedure would require the removal of this ‘air-gap’ prior to taking the damage measurement. The test facilities for Transport Canada and the Insurance Institute for Highway Safety are following this procedure. Crush measurements are made while pushing the rubber bumper cover inward until a solid structure is contacted.

The NHTSA test facilities are measuring the post-test vehicle damage in a manner that may not account for all the damage sustained in the test. Their current method measures the damage to the outer surface of the rubber bumper cover at its rebounded position without removal of the ‘air-gap’. When an ‘air-gap’ is present, the crush measurements indicate a level of damage that is less than the damage that was sustained in the crash test. For example, in NHTSA test #2368, the extent of the ‘air-gap’ is 9 inches (figures A & B).

NHTSA crash tests that were used in the comparison presented in this paper are based upon ‘air-gap’ adjusted crush. The extent of the ‘air-gap’ was estimated by employing both the reported damage measurements and the post-test vehicle photographs. The ‘air-gap’ was then added to the reported damage measurements to produce the ‘air-gap’ adjusted crush.

FIGURE A: Results of Air-Gap Adjustment
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</table>

**FIGURE B: Crash Test Photographs**