# Development of a High Strain-Rate Dependent Vehicle Model

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**Summary:**

Vehicle collisions can be considered as a highly dynamic deformation process, where structural steel deforms under different strain rates. Therefore, an appropriate material model, which takes rate affects into account, has to be chosen for a good numerical model. In this study, five different strain-rate sensitive material models are investigated and their influence on vehicle simulations is compared.

The main objective of this investigation is to include strain rate effects for the evaluation of crashworthiness response of components and a full-scale vehicle with the use of various constitutive equations. Chevrolet-C2500 pickup truck model, is utilized as a test platform for this comparison. Corresponding NCAP test results for this particular vehicle are used to compare the numerical response. LS-DYNA [1] is used for the finite element simulations as a non-linear explicit dynamics numerical solver.

**Keywords:**

High strain rate, crash test, material model, Johnson-Cook, Zerilli-Armstrong, Cowper-Symonds.

## 1    Introduction

Thin walled components are the key structural component for the majority of transportation vehicles. During a crash, the passenger compartment has to sustain abnormal loadings without excessive deformations that compromise the passenger safety. At the same time, other thin-walled components have to dissipate the impact energy in a controlled manner to decelerate the vehicle within tolerable limits. Under such conditions, strain rate effects have a significant influence on the crash behaviour of a steel member. The deformation mode of a single component, as well as the overall crash behaviour of a vehicle may change if the strain rate effects are not incorporated in the numerical model.

In this paper, five different material models are used. The high strain-rate sensitive material models and the corresponding parameters are implemented in a full-scale crash test simulation of a vehicle model. The necessary stress-strain curves for high strain-rates are received from the Auto/Steel Partnership [2].

## 2    Materials of Interest

It is not practicable to evaluate the strain rate properties of every different steel type used in automotive engineering practice. Thus, the Auto/Steel Partnership, a cooperative group comprised of representatives from Ford Motor Company, General Motors, Daimler-Chrsyler and U.S. steel mills, took effort to show that steel belonging to a particular category will have the same strain rate hardening parameters even though the yield stresses of the steels vary within each category [3]. This observation is important because the test results of the Auto/Steel Partnership as well as from the American Iron Steel Institute could now be extended to other steels within the same category, which were not tested but are comparable to each other.

The Auto/Steel Partnership provided the necessary stress strain data for the DQSK mild steel. The material testing was conducted at Los Alamos National Lab using servo-hydraulic MTS machines and Split-Hopkins Pressure Bar method. The data for the HSLA 350 and the TRIP 590 steel were published by the American Iron Steel Institute. The servo-hydraulic testing was done at the Rheinisch-Westfaelische Technische Hochschule Aachen and the Split Hopkins tensile tests have been conducted at the University of Dayton Research Institute (UDRI).

### 2.1    DQSK Mild Steel

The drawing-quality, special-killed (DQSK) mild sheet steel, which is applied in this research, has been tested and analyzed by Cady et al. [4]. This low-carbon steel is commonly used in the automobile manufacturing. This material has a static yield strength of 270 MPa, which corresponds well to the main material that is used in the C2500 pickup truck finite element model. The stress-strain relation for this material can be seen in Fig. 1 depending on the strain-rate.

### 2.2    HSLA 350

The second steel identified in the C2500 Pickup Truck is a High Strength Low Alloy (HSLA) steel with a yield strength of 350 MPa. High strain rate data has been published for that kind of steel by the American Iron Steel Institute [3]. The stress-strain relation for this material can be seen in Fig. 2 depending on the strain-rate.

### 2.3    TRIP 590

Another steel type used in the Pickup truck was a Transformed-Induced Plasticity (TRIP) steel with a yield strength of 450 MPa. The work-hardening rates of TRIP steels are substantially higher than those of conventional high-strength steels. They provide a significant stretch-forming ability. Therefore, TRIP steel is recommended for medium strength structural parts responsible for crash energy management whenever superior formability is required. High strain rate data for this steel has also been published by the American Iron Steel Institute [3]. The stress-strain relation for this material can be seen in Fig. 3 depending on the strain-rate.
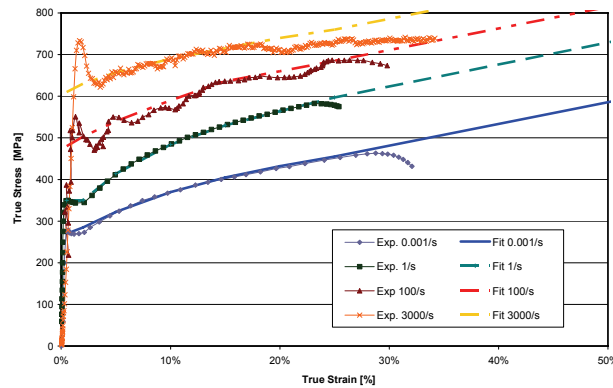
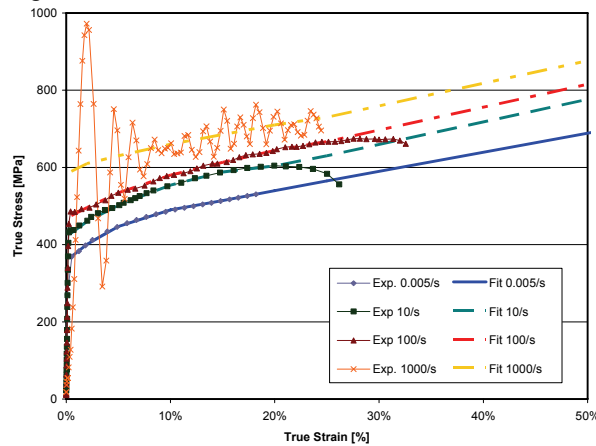Fig. 1: Stress-Strain Relation for DQSK Mild Steel.
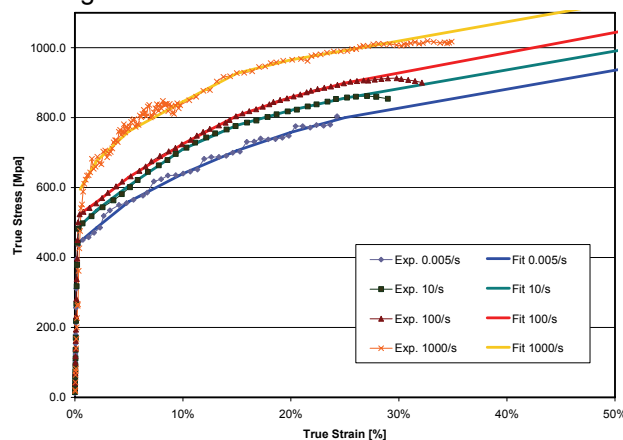


Fig. 2: Stress-Strain Relation for HSLA 350.



Fig. 3: Stress-Strain Relation for HSLA 350.

## 3    Material Models

The implementation of strain rate effects of material models used in LS-DYNA can be fulfilled in a variety of different ways. Besides a table like input of piecewise linear stress strain curves for different strain rates, a choice of different constitutive equations is available. The choice of these constitutive equations and the determined constants affect the ability to accurately predict the behaviour of the steel components during the crash event. Five different models for strain hardening and strain-rate hardening are presented. Among them are the piecewise linear formulation (PL), Cowper-Symonds (CS) , Johnson-Cook (JC) and Zerilli-Armstrong (AZ) constitutive equations, as well as a mixed piecewise linear Cowper-Symonds model (PL-CS). According to Xu et al [5], the JC and CS models are based on mathematical formulations of the work hardening and strain rate sensitivity. From a mathematical point of view, they are a multiplicative type of equation. Thus, the calculated stress strain curves at different strain rates are divergent. On the other hand, the equation of the ZA model is additive. The calculated stress strain at different strain rates therefore is parallel.

### 3.1    Piecewise Linear Plasticity

According to Simunovic et al [6], the most commonly used strain rate dependent material model in automotive impact engineering is the piecewise linear plasticity model. In this approach, effective strain-stress curves are directly fed into the material model. Therefore, it requires the least amount of effort for the material model development.

In LS-DYNA, a table is used to define for each strain rate value a load curve ID that gives the stress versus effective plastic strain for the rate. The lowest strain rate given in the table is applied if the strain rate falls below that minimum value. Likewise, the highest strain rate of the experimental data is used as a saturation plateau for the strain rate effects. In the simulation, the strain rate for each element is calculated and a linear interpolation between the experimentally determined strain rates is utilized to calculate the resulting stress in the plastic region. Even though it has been shown that the stress increment relation is logarithmic, the effects of the linear interpolation will not be significant, if the gradation between the different strain rates is sufficiently low. Figures 1-3 show the stress-strain relation that is fit to raw data.

### 3.2    Plastic Kinematic Hardening (Cowper-Symonds)

The plastic-kinematic hardening model is a strain-rate dependent elastic-plastic model. It is suited to model isotropic and kinematic hardening plasticity. In this model, strain rate is accounted for using the Cowper-Symonds model which scales the yield stress by the strain rate dependent factor as shown below [7],[8]:

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}\right] \cdot \sigma_0 \tag{1}$$

where $\sigma_0$ is the initial yield stress, $\dot{\varepsilon}$ is the strain rate; $C$ and $P$ are the Cowper-Symonds strain rate parameters.

### 3.3    Piecewise-Linear with Cowper-Symonds

Instead of stress-strain curves for each different strain rate, it is possible to only input the quasi-static stress-strain curve, which then will be used as a basis on the Cowper-Symonds coefficients that will empose the strain-rate effects. However, the data for the lowest strain rate has to be scaled down using the Cowper-Symonds equation (Eq. 1) to get the quasi-static stress-strain curve.

### 3.4    Simplified Johnson-Cook

Johnson and Cook model is a strain-rate and temperature-dependent (adiabatic assumption) visco-plastic material model [9]. This model is suitable for problems where strain rates vary over a large range, and temperature change due to plastic dissipation causes material softening. The model is expressed in a multiplicative form of strain, strain-rate and temperature terms. The consequence of the multiplicative form is that the strain-hardening rate at a certain strain will increase when the strain rate increases. Therefore, strain-stress curves for increasing strain rates will tend to "fan out" [10]. In the simplified model, thermal effects and damage are ignored and the maximum stress is directly limited since thermal softening is not available. The simplified model is 50% faster than the full Johnson-Cook implementation. The simplified J-C model represents the flow stress with an equation of the form [7], [9]:

$$\sigma_y = \left(A + B \cdot \varepsilon^n\right) \cdot (1 + C \cdot \ln \dot{\varepsilon}^*) \tag{2}$$

where $\sigma_y$ is the effective stress, $\varepsilon$ is the effective plastic strain, $\dot{\varepsilon}^*$ is the normalized effective plastic strain rate (typically normalized to a strain rate of 1.0 s$^{-1}$), $n$ is the work hardening exponent and $A$, $B$, $C$, and $m$ are constants.

### 3.5    Modified Zerilli-Armstrong

The Zerilli-Armstrong material model is a rate and temperature sensitive plasticity model. It accounts strain hardening, strain rate hardening and thermal softening effects in metals by developing a dislocation-mechanics based constitutive relationship. Zerilli and Armstrong hoped to overcome some of the shortcomings of the Johnson-Cook model by utilizing the theoretical basis of dislocation-mechanics.

The Zerilli-Armstrong material model expresses the flow stress for bcc materials as follows [7], [11]:

$$\sigma = C_1 + C_2 \cdot e^{\left(-C_3 + C_4 \cdot \ln \dot{\varepsilon}^*\right)T} + \left[C_5 \cdot \left(\varepsilon^p\right)^n + C_6\right] \cdot \left(\frac{\mu(T)}{\mu(293)}\right) \tag{3}$$

where: $C_1$, $C_2$, $C_3$, $C_4$, $C_5$, $C_6$ and $n$ are constants, $T$ is the temperature in degree Kelvin, $\varepsilon_p$ is the effective plastic strain and $\dot{\varepsilon}$ is the strain rate and;

$$\left(\frac{\mu(T)}{\mu(293)}\right) = B_1 + B_2 \cdot T + B_3 \cdot T^2 \tag{4}$$

with $B_1$, $B_2$ and $B_3$ being constants. As thermal softening is not regarded $C_6 = B_1 = 1$ and $B_2 = B_3 = 0$.

### 3.6    Comparison of the Different Material Models

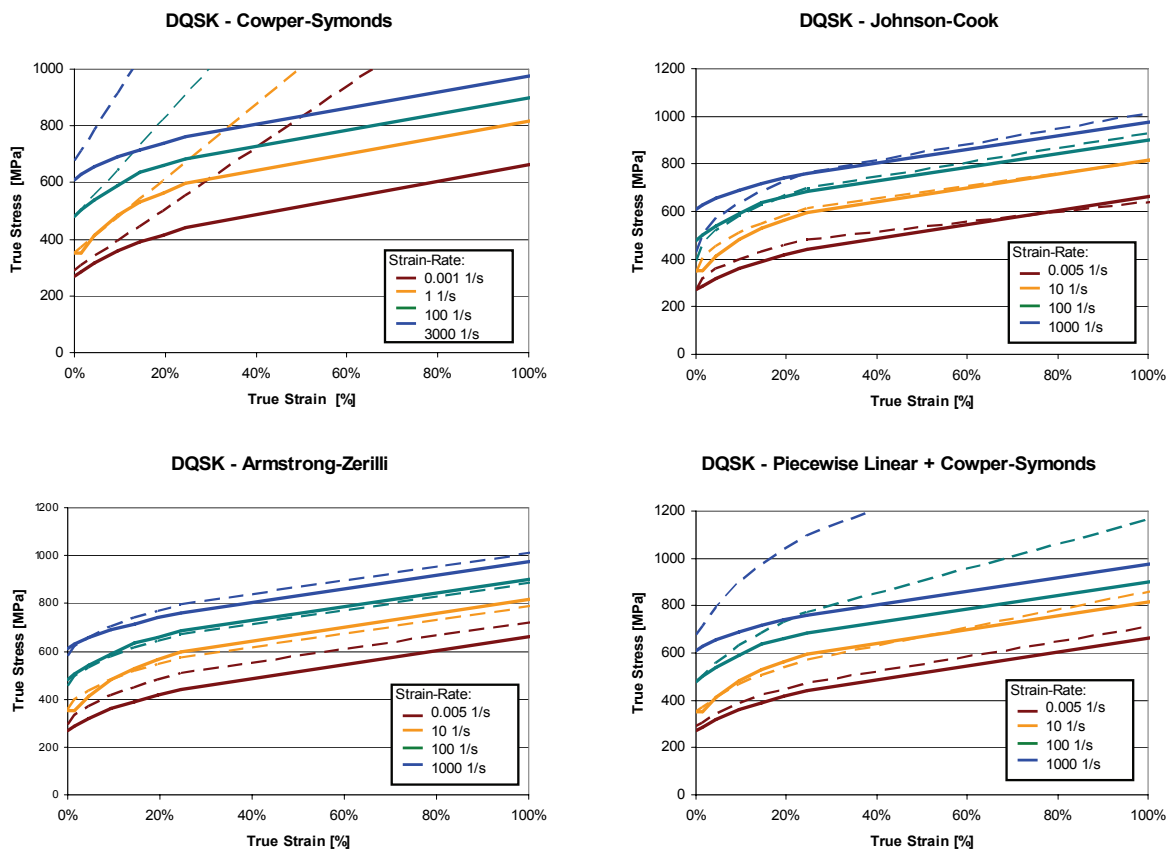Fig. 4-6 represents the stress-strain relations for the investigated materials and material models.



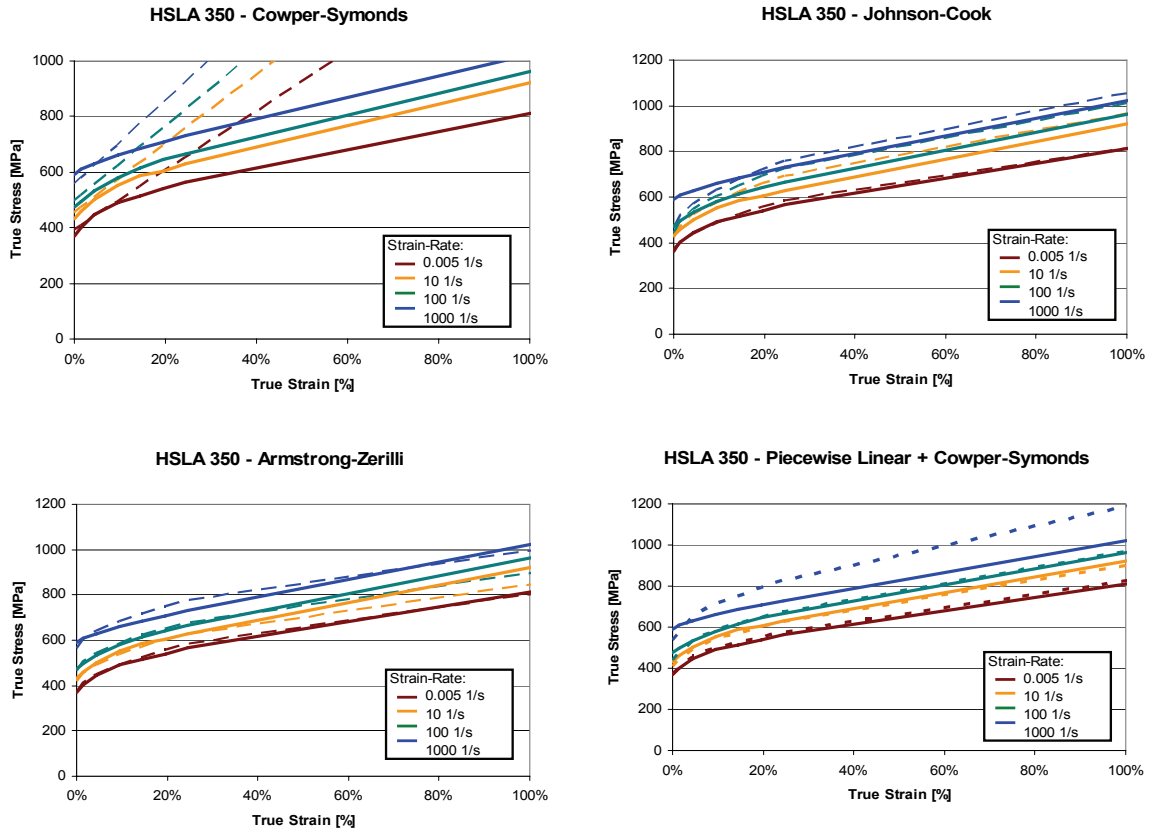Fig. 4: Stress-Strain Relation for DQSK Mild Steel.
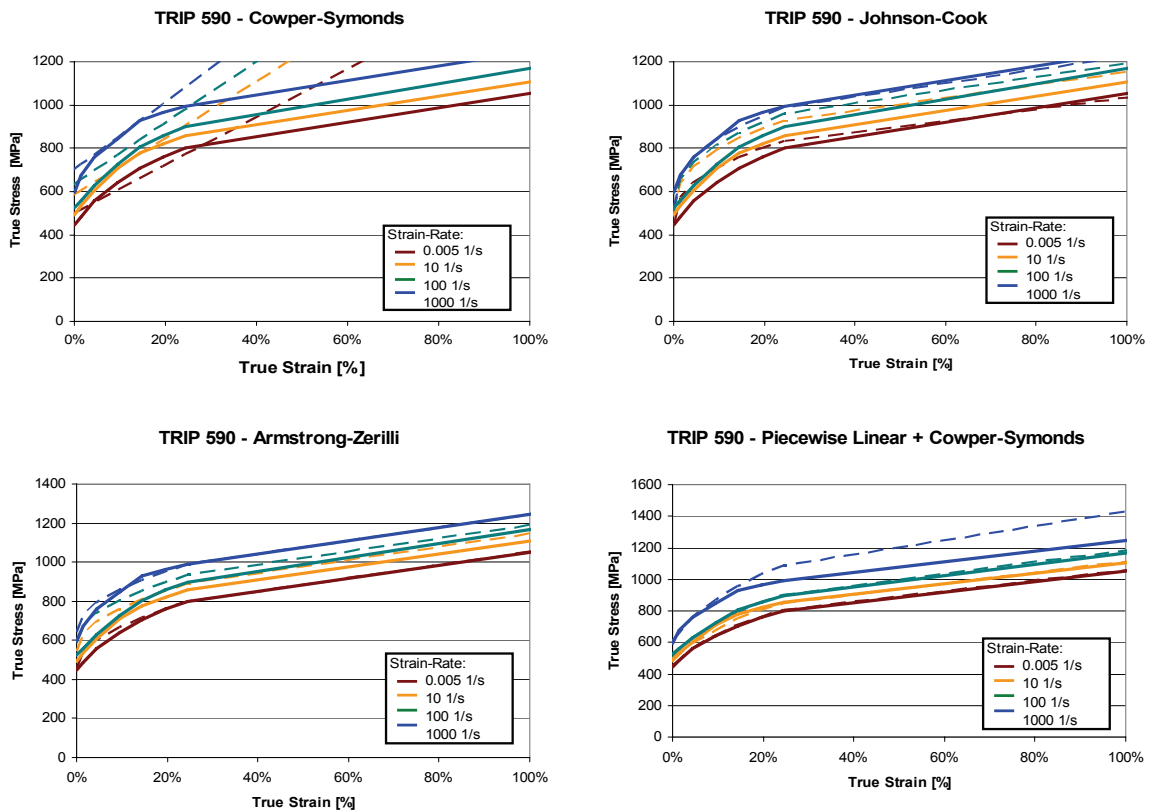
Fig. 5: Stress-Strain Relation for HSLA 350.



Fig. 6: Stress-Strain Relation for TRIP 590.

## 4      C-2500 Vehicle Finite Element Model

Current automobile body structures include two categories: body-over-frame or unit-body structure. The Chevrolet C2500D, as a light duty truck, is a typical representative of the body-over-frame structure, which usually consists of a frame, cab, and a box. The three structural modules are bolted together. The cab is designed as an occupant cell to minimize injury in the event of a crash. The chassis frame supports the engine, transmission, power train, suspension and accessories. In frontal impact, the frame and front sheet metal absorb most of the crash energy by plastic deformation and prevent intrusion into the occupants' compartment. The vehicle finite element model that is shown in Fig.7 is developed at the FHWA/NHTSA National Crash Analysis Center for multi-purpose impact scenarios [12]. It is validated for numerous impact conditions such as; frontal impact into a rigid barrier, corner impact into a New Jersey shaped concrete barrier and into a vertical concrete barrier [13], [14]. The entire vehicle model contains 57727 elements, where 53991 shell elements are used for a total of 201 components.  The distribution of the materials that is used to model the vehicle can be grouped as it is shown in Fig. 8
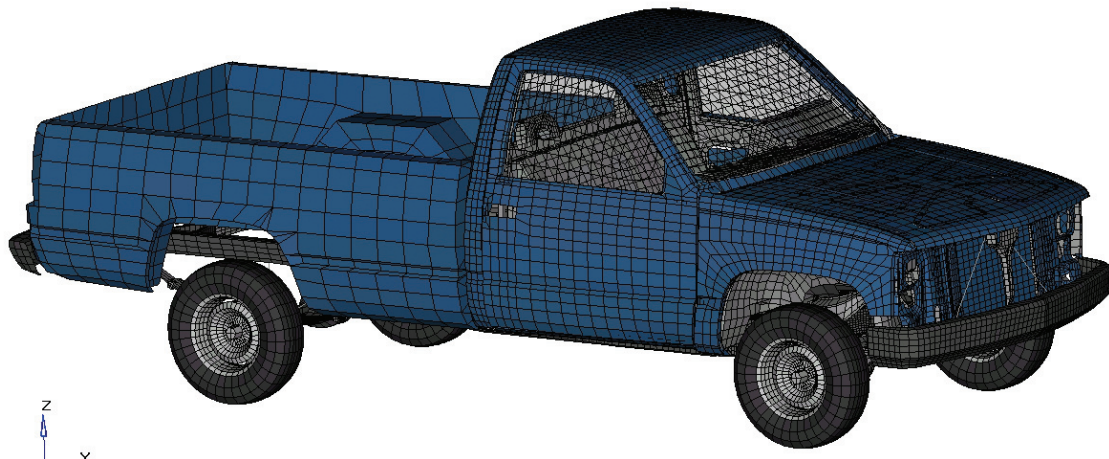


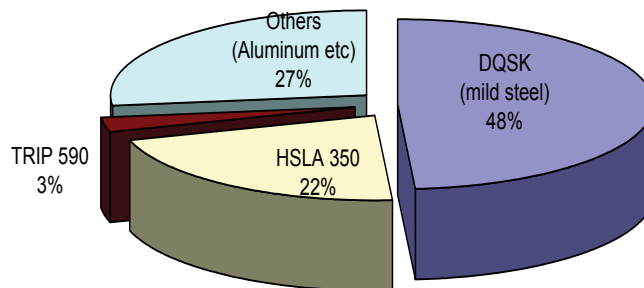Fig. 7: Chevrolet C2500D Pick-Up Truck Finite Element Model.



Fig. 8: Chevrolet C2500D Pick-Up Truck Finite Element Model Material Distribution.

## 5      NCAP Test

The New Car Assessment Program (NCAP) test was initiated by the National Highway Traffic Safety Administration (NHTSA) in the early 1980's. It is identical to FMVSS 208, except for increasing the pre-impact speed of the vehicle to 35 mph (56 km/h = 15.6 m/s). NCAP test is also a full-scale barrier test, in which the guided vehicle is propelled into a load cell wall as it can be seen in Fig 9a. The vehicle is instrumented with numerous loads cells, accelerometers and dummies in the driver and passenger seats and impacts into a rigid wall at a 90 degrees angle to the barrier surface. The dummies are typically restrained with a three-point lap/shoulder belt system in addition to the supplemental restraint airbag. The barrier face is instrumented with 36 load cell to monitor the impact force-time history. The 36 load cells are divided into 6 groups as shown in Fig. 9b. The analysis of the data provided give information about the effectiveness of the restraint system and the overall behaviour of the vehicle structure under high deceleration loads.
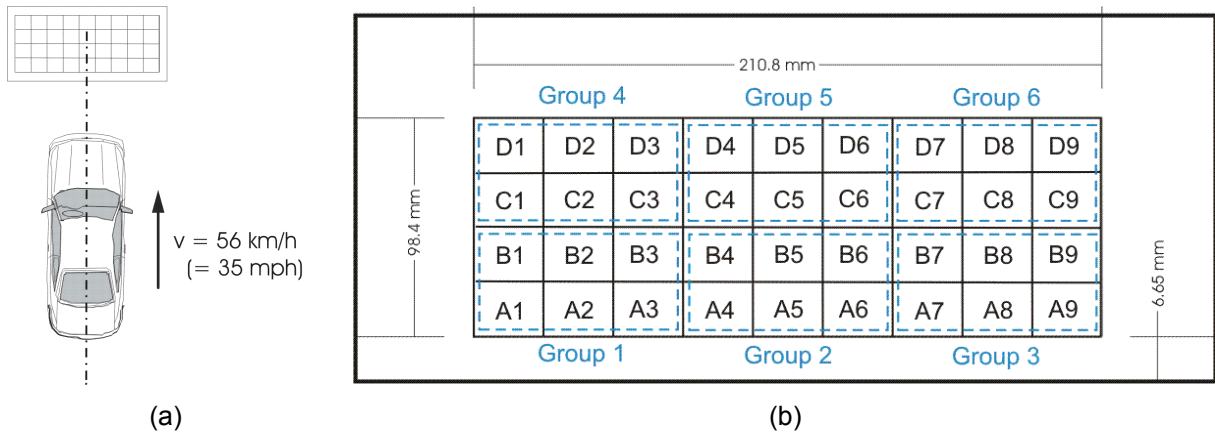
(a)

| | Group 4 | | | Group 5 | | | Group 6 | |
|---|---|---|---|---|---|---|---|---|
| D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 |
| C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 |
| B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 |
| A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 |
| | Group 1 | | | Group 2 | | | Group 3 | |

v = 56 km/h (= 35 mph)

210.8 mm

98.4 mm

6.65 mm

(b)

Fig. 9: (a) NCAP Test Configuration, (b) Load Cell Wall.

## 6.     Results

The general differences in the behaviour of the vehicle model depending on the high strain-rate material implementation can be seen in Fig. 10. Two acceleration readings from seat cross-member and dashboard panel are also compared for each material model and test in Fig. 11.
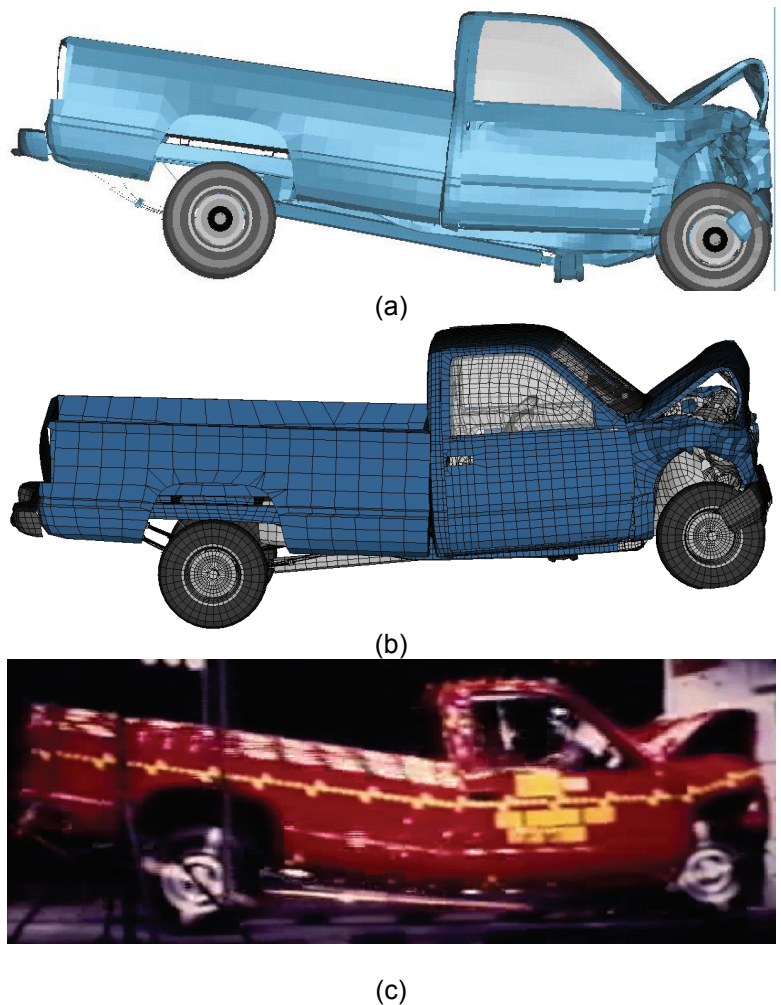


(a)



(b)



(c)

Fig. 10: (a) Without Strain-Rate Effects, (b) With Strain-Rate Effects, (c) NCAP Test
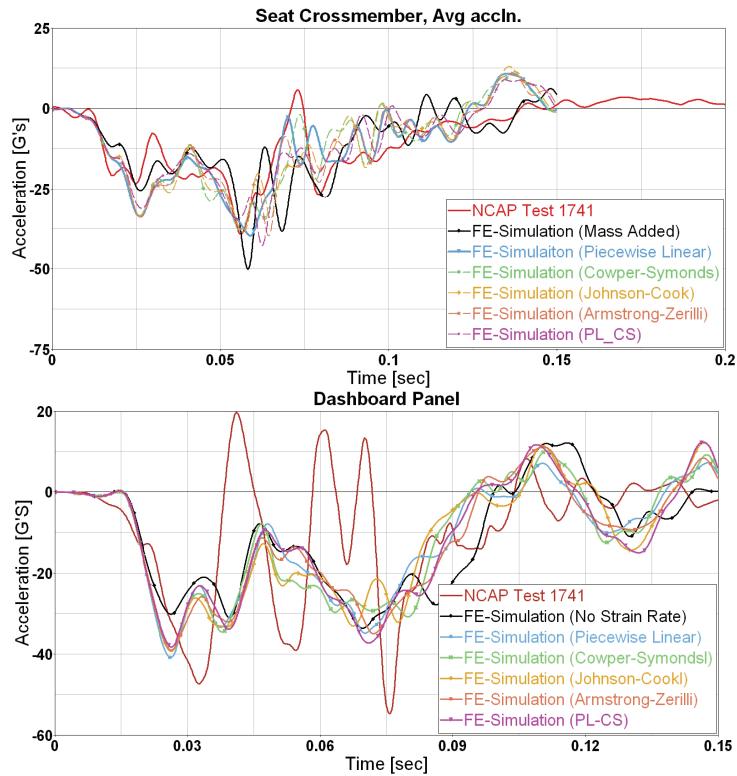
Fig. 11: Acceleration Comparison.

Fig. 12a illustrates the difference in the deformation pattern that is obtained for front-rail, where Figures 12b and 12c show the internal energy comparison.
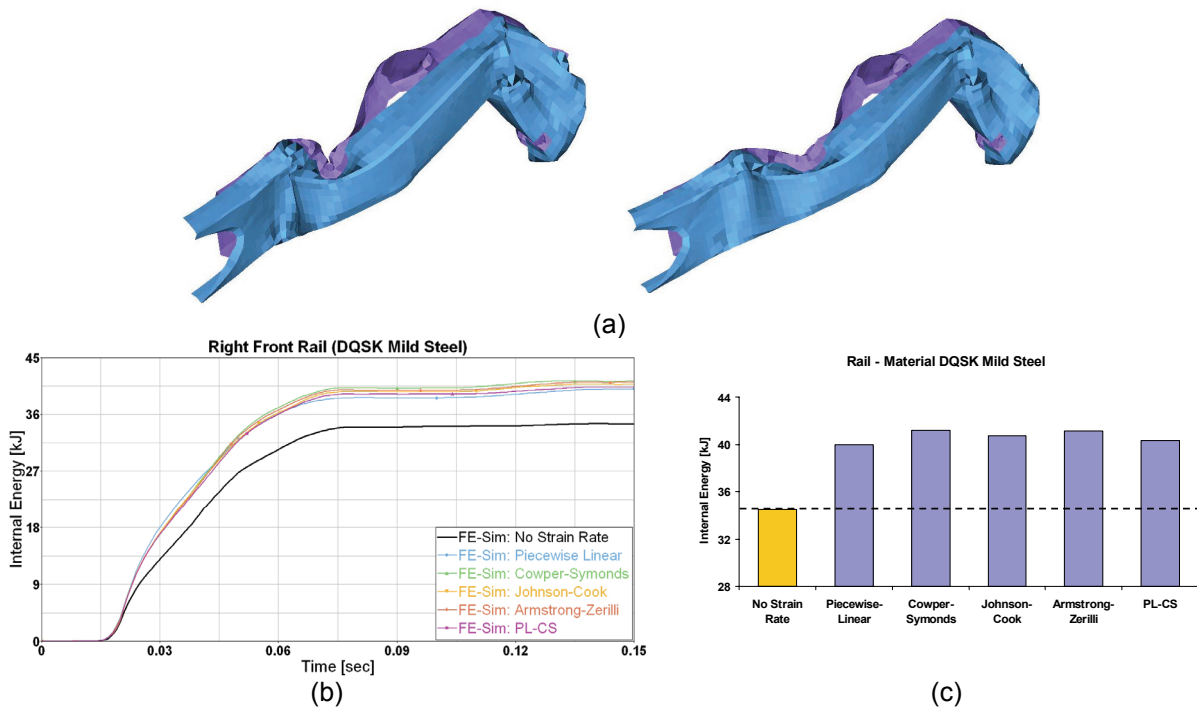


(a)



(b)

(c)

Fig. 12: (a) Front Rail deformation (Left) Without Strain-Rate Effects (Right) With Strain-Rate Effects, (b), (c) Front Rail Internal Energy Comparison.

## 6    Conclusion

In this paper, different strain-rate sensitive constitutive equations are integrated in finite element simulations of a crash event in order to investigate their influence on the result. However, the effects of the strain rate dependent material model on the crash behaviour of the NCAP test are found to be relatively small.

This may be explained by the fact that even though, individual parts are showing considerable effects when they are exposed to high strain rate loading, like experienced by the front rail, this behaviour is only found in a limited number of parts of the whole vehicle. In addition, since large strain-rates are not present in the overall part, but only at localized spots, the contribution at the end is not at significant amounts. Therefore, the overall response of the vehicle is not affected as much as we would expect from an individual component under high-strain rate loading.

To improve the prediction accuracy of frontal impact analysis, the consideration of strain rate effects on all the critical components of the vehicle is still recommended.

## 7    Literature

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