International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

Elasto-Plastic Strain Rate Dependent Material Characterization of Steel Grade for Crash Simulation

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Abstract: ***Strain rate sensitivity is an important material property in the formability of sheet metal. In this study, strain rate sensitivity is evaluated for grade of mild steel.. Material testing standards for quasi-static rates are relatively well established. The increasing need for high strain rate material properties is now focusing the engineering community's attention on the test methods used to generate data. The lack of industrial standards for high strain rate testing makes it vital that the end-user understands the valid applications and limitations of high strain rate material data. Current test methods, proper specimen selection, strain measurement methods, data analysis techniques, and interpretation of high strain rate data are reviewed. This paper deals with the effects of approaches for modeling of strain rate effects for mild steel on impact simulations. The material modeling is discussed. The characteristics of piecewise linear plasticity strain rate dependent material model are analyzed and sub-models for modeling of impact response of steel structures are investigated.***

Keywords: Material, Ls-Dyna,crash

1. Introduction

In the current automobile engineers have more depended on the numerical simulation to help predict the crashworthiness of new vehicle designs, One of the benefits of using numerical simulation is not only to predict the crash behavior of vehicles, but also to understand and the effect of various design variables on the vehicles crash performances. Also replacing the expensive prototype testing with cost effective numerical simulation can not only reduced design and development times but also create opportunities for cost saving in the design and development process, Therefore by using numerical simulation tools effectively the potential exists for automotive engineers to be able to quickly design lower cost and better vehicles. In the recent years commercially available explicit finite element method or codes have been used to perform detailed numerically crash simulations. Several codes like Radioss, PamCrash, and LS-Dyna are being used today in the automotive industry for crash simulation.

Because an automotive crash is a complex dynamic phenomenon the accuracy of a finite element simulation depends on a large number of factors. For example boundary conditions element size and formulations, and material constitutive model all may ha e an influence on the accuracy of any given simulation. The effect of mesh size can be quantified by varying the mesh density of a given model and comparing the results to either known solution or to experimental data. However varying the mesh size for an entire automotive vehicle system made up of several components would be impractical Likewise, evaluating the materials constitutive laws for the every material in an automobile, over entire range of strains and temperature experiences during the crash event would also be very difficult. However, large portion of an automobile comprised of steel and thus a large portion of the crash performance can be expected to be determined by steel material properties. Because crash event is dynamic, it can be expected that the material behavior of steel during crash will be strain –rate dependent. Currently, piecewise linear formulation (PL), Cowper-Symonds (CS) , Johnson-Cook (JC) and Zerilli-Armstrong material models are used for material modeling for numerical analysis.

This study deals with the effects of various approaches for modeling of strain rate effects for mild steels on impact simulations. In this context to modeling the strain dependent material we tested four to five standard specimens on high strain machine, at different strain rate and generate the stress-strain curve at each strain rate. 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 behavior of the steel components during the crash event. The material modeling is discussed in the context of the finite element method (FEM) modeling of progressive crush of energy absorbing automotive components. The characteristics of piecewise linear plasticity strain rate dependent material model are analyzed and various sub models for modeling of impact response of steel structures are investigated. The models are compared to the experimental results from drop tower tests or sled test. Thus by analyzing and testing a small steel component subjected to crash event and some influence of constitutive relation on the finite element analysis result can be discussed.

Methodology to Validate Strain Rate dependent Material Data for Crash Simulation:

a) Generate the material data-
Test the standard specimen on high strain rate machine at various strain rates and convert data in to effective stress-strain data.

b) Digital image correlation-

By using digital image correlation measure deformation (engineering), displacement, strain and stress and it is used to validate the converted stress strain data in LS-Dyna.

c) Validate stress –strain data in FEM-

In this step create the standard specimen in Hypermesh and apply boundary condition as same applied during material testing and apply strain rate same which applied during the physical test, this process repeat for all physical tested specimen.

d)Validate the stress-strain at dynamic loading-

In this step after validating the stress- strain data on standard specimen in the FEM, same material data need to validate for dynamic loading. For this create a small crush box and simulating in LS-Dyna for dynamic load. Once the boundary condition finalizes then same crush box data releasing to physical prototype.

e) Physical validation-

After finalize the size, shape and boundary condition for small crush box in FEM then by using this data will go for the physical test.

f) Correlation-

After analyzing the physical test data it will again incorporate in LS-Dyna and if require to do any modification/assumption in CAE input will update accordingly. Once will get good correlation, then finally this generated strain rate dependent material data released for crash simulation for dynamic loading.

2. Strain Rate Characterization

Strain is a measure of the amount of deformation that occurs when an object is placed under stress. Strain rate is defined as the change in strain over the change in time. All materials will undergo some change in their dimensions when exposed to stress. The deformation caused by stress can be fully reversible or permanent, depending on the amount of stress applied. Elastic strain occurs when a material under stress returns to its original dimensions once the stress is removed. Plastic strain occurs when an object has been exposed to very high levels of stress and will no longer return to its original shape after the stress is removed. In many materials, the reversal of elastic strain is instantaneous, meaning it occurs without a perceptible duration of time. Deformation that is fully recoverable, but occurs over time, is described in terms of the strain rate. Strain rate varies widely for different materials, and will often change at different temperatures and applied pressures. Steel is an example of a material that returns to its original state immediately after stress is removed. Conversely, in geology, stresses are applied over millions of years and the rate of strain in rock is typically very low. A material whose rate of strain changes a large amount at different temperatures and pressures has high strain rate sensitivity. This rate is also dependent on the way the force or stress is applied. For many plastics, if a gradual stretching force is applied the material will elongate a large amount before it breaks. This is because the molecules in the plastic have enough time to reorient themselves and move past each other, causing the stretching to occur. If an impact or sudden force is applied to a plastic, it will break immediately and behave like a brittle material. The same plastic material can react very differently because of the different rates of strain caused by the way the stress is applied.

Strain rate can be measured in the laboratory using special test equipment that applies very precise loads to a sample, while measuring the deformation and recovery that occurs after the stress is removed. Since the strain rate of a material will influence how it behaves, it is important to understand its sensitivity to the type of load, amount of stress, and temperature. Understanding the strain rate of a material will ensure that it meets the performance specifications required in the end-use application.

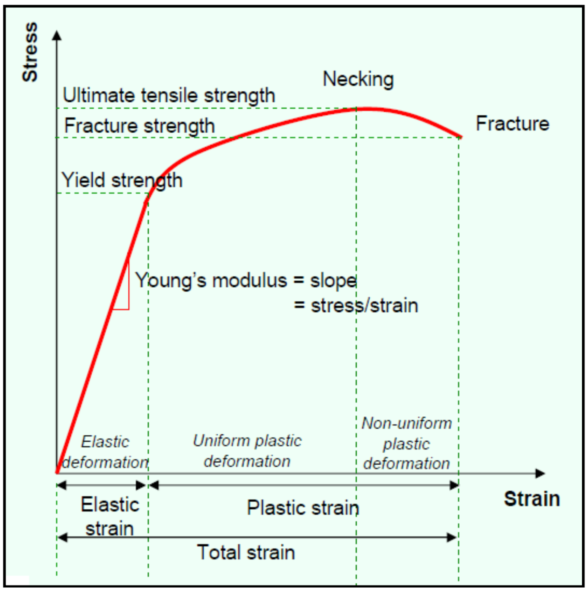


Figure 1: Engineering stress-strain curve

3. Generate Material Data

3.1 High Strain Rate Machine

Crashworthiness is a key part of the design of a modern automobile. Under crash conditions, structural materials are subject to very high rates of strain and loading. Many material properties, including those of the steel or aluminum used in the automobile body, are strain rate sensitive. Consequently, quasi static stress strain data may not produce accurate predictions of behavior at high strain rates, and the use of such data in the analysis and design of dynamically loaded structures can lead to cautious overweight designs or premature structural failure. Our servo hydraulic VHS high rate systems provide metals researchers with extensive capabilities for impact and high strain rate testing. The VHS systems are also able to be configured to perform tests from quasi static to impact speeds, as well as providing a cyclic testing capability. The systems incorporate a very high performance hydraulic actuator, featuring hydrostatic bearings and a seal less piston rod. With high performance control valves, these systems can be configured for speeds up to 25 m per second. Combined with a high stiffness two or four column load frame, the advanced 8800 control system and Profiler software can assist you in achieving near constant velocity. Patented 'Fastjaw' grips are utilized to instantaneously grip the specimen once the actuator has reached the correct velocity for the test. Testing forces are measured using high stiffness piezoelectric load cells and a high speed data collection system that records the entire stress strain curve at rates up to 5 MHz. These features allow metals researchers to evaluate their materials at a level of detail never before possible. In order to perform high rate tests, we suggest using our High Rate software Program operating under Console software. These provide a single user interface for test set up, firing, data collection and viewing. We suggest using Impulse Software for advanced analysis technique.

Figure 2: High Strain Rate machine by INSTRON

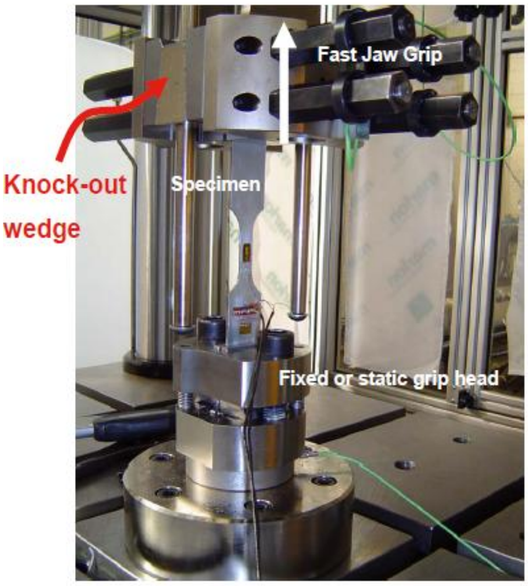


Figure 3: High Strain Rate machine by INSTRON

Features:-

- Capacity: 40 kN to 100 kN
- Capable of velocities up to 25 m/s
- Specialized measurement transducers
- Patented FastJaw gripping techniques
- High-speed data acquisition package
- VHS8800 controller package
- High-Rate Software
- Unique profiling capability
- Systems are contained by a protective enclosure to ensure operator safety
- High-stiffness load frames
- Unique actuator packages featuring hydrostatic bearings, hydraulic end cushions and a seal-free design
- Operates at a 280 bar supply pressure that results in higher acceleration velocity and load performance

4. Specimen Design for High Strain Rate Testing:

Tensile testing, also known as tension testing, is a fundamental materials science test in which a sample is subjected to a controlled tension until failure. The results from the test are commonly used to select a material for an application, for quality control, and to predict how a material will react under other types of forces. Properties that are directly measured via a tensile test are ultimate tensile strength, maximum elongation and reduction in area. From these measurements the following properties can also be determined: Young's modulus, Poisson's ratio, yield strength, and strain-hardening characteristics. Uniaxial tensile testing is the most commonly used for obtaining the mechanical characteristics of isotropic materials.

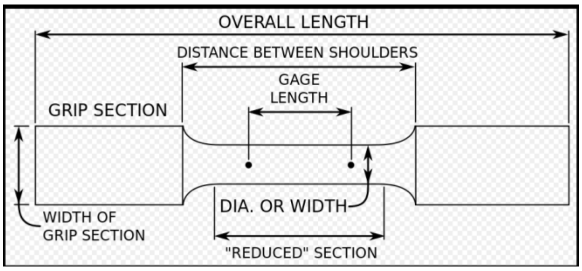
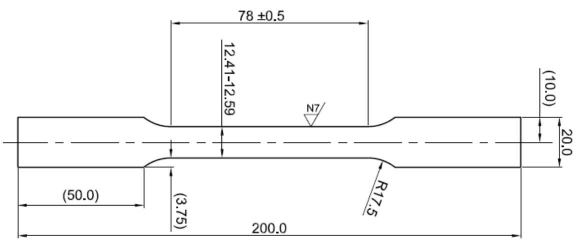


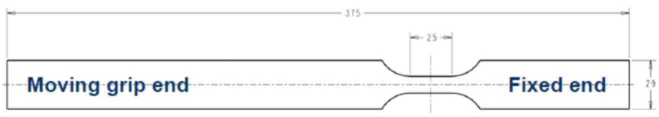
Figure 4: Nomenclatures for standard specimen

A tensile specimen is a standardized sample cross-section. It has two shoulders and a gauge (section) in between. The shoulders are large so they can be readily gripped, whereas the gauge section has a smaller cross-section so that the deformation and failure can occur in this area. The shoulders of the test specimen can be manufactured in various ways to mate to various grips in the testing machine (Refer figure 3). Each system has advantages and disadvantages; for example, shoulders designed for rerated grips are easy and cheap to manufacture, but the alignment of the specimen is dependent on the skill of the technician. On the other hand, a pinned grip assures good alignment. Threaded shoulders and grips also assure good alignment, but the technician must know to thread each shoulder into the grip at least one diameter's length, otherwise the threads can strip before the specimen fractures. In large castings and forgings it is common to add extra material, which is designed to be removed from the casting so that test specimens can be made from it. These specimens may not be exact representation of the whole work piece because the grain structure may be different throughout. In smaller work pieces or when critical parts of the casting must be tested, a work piece may be sacrificed to make the test specimens. For work pieces that are machined from bar stock, the test specimen can be made from the same piece as the bar stock.

Typical standard specimen for testing



(a) Standard specimens for slow strain rate



(b) Standard specimens for high strain rate

Figure 5: Typical standard specimens for testing

5. Digital Image Correlation:

Digital image correlation and tracking is an optical method that employs tracking and image registration techniques for accurate 2D and 3D measurements of changes in images. This is often used to measure deformation (engineering), displacement, strain, and optical flow, but it is widely applied in many areas of science and engineering. Digital image correlation (DIC) techniques have been increasing in popularity, especially in micro- and nano-scale mechanical testing applications due to its relative ease of implementation and use. Advances in computer technology and digital cameras have been the enabling technologies for this method and while white-light optics has been the predominant approach, DIC can be and has been extended to almost any imaging technology.

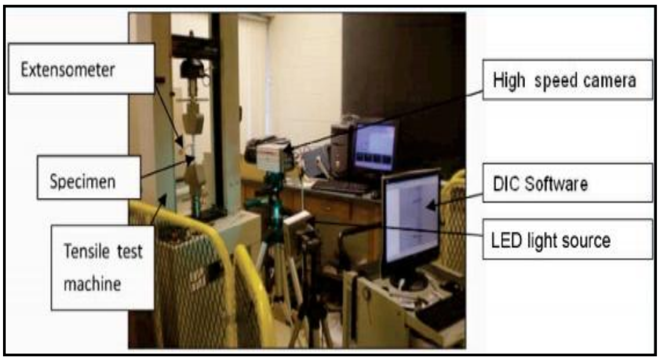


Figure 6: Setup for Digital image correlation

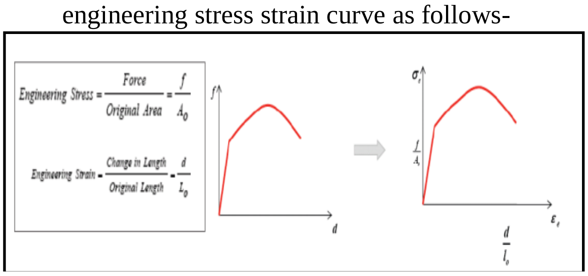
6. Material Modeling:

For the determining true stress-strain curves from flat tensile specimens beyond the onset of necking has been investigated based on finite element analyses under consideration of experimental accessible data using digital image correlation (DIC). The displacement field on the specimen surface is determined by deformation field measurement. A three-dimensional finite element study with different stress-strain-curves has been carried out to develop a formula, with which it is possible to calculate the true stress subject to the strain in the necking region. The method has been used to evaluate the true stress-strain curve with a flat tensile specimen, which is normally used to determine the material properties in the material gradient. Materials stress-strain curves necessary as input for finite element analyses cannot be determined straight forward from global load versus elongation curves beyond the onset of necking after maximum load, as the strain field becomes inhomogeneous and the stress state tri axial. An analytical solution derived by Bridgman is used for round tensile bars to determine the effective stress in the necked section. It requires the continuous measurement of the reduction of diameter and the necking radius during the test, which requires advanced testing techniques. Mostly, optical methods are applied. The specimen shape is photographed and the images are either evaluated manually or by electronic processing. The Bridgman correction does not work for rectangular specimens as the respective solution assumes an ax symmetric stress and strain field with constant plastic strain in the smallest necking section. The strain gradients in the cross section increase with the aspect ratio of rectangular bars. Difficulties also arise with the experimental determination of the cross section area. It cannot be evaluated from photos as the rectangular cross section takes the shape of a cushion, some procedures determining stress-strain curves from specimens with rectangular cross sections have been proposed in some research papers based on an extrapolation of the stress-strain curve before necking und thus not suitable for calculations with very high strains. The method uses the local thickness reduction in the necking areato determine the actual cross section area, but the triaxiality of the stress state after occurrence of local necking is not taken into account. The present methods of flat tensile specimens are favorably used for characterizing sheet metals. In these applications, standard round tensile bars cannot be used. Flat specimens can be tested in such cases instead. The determination of the true stress would additionally require a finite element simulation of the test. However, an approximate formula can be derived from numerical parameter studies which relate true stresses and applied load.

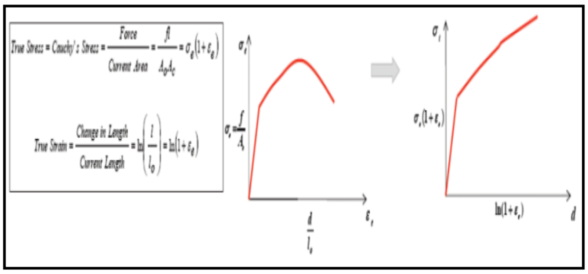
Figure 7: Typical tested standard specimen

Following is the typical procedure to convert the stress-strain data to crash application-

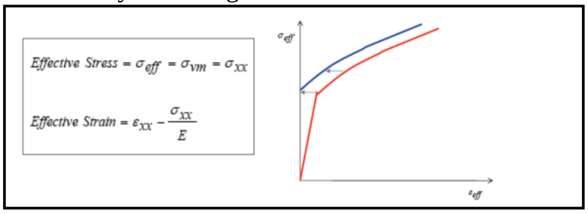
i. Standard coupons prepared for Uniaxial tension test to get Force-Deflection data
ii. Force-deflection curve data is converted in engineering stress strain curve as follows-



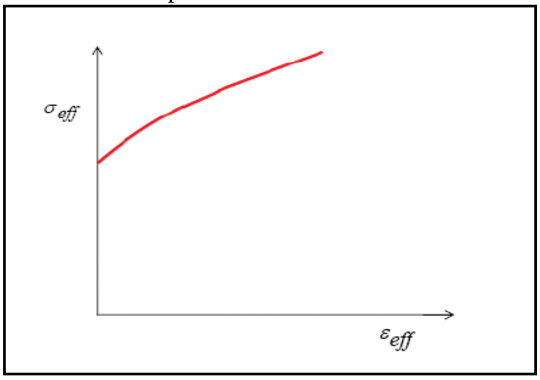
i. Engineering stress strain curve converted in True stress strain curve as follows



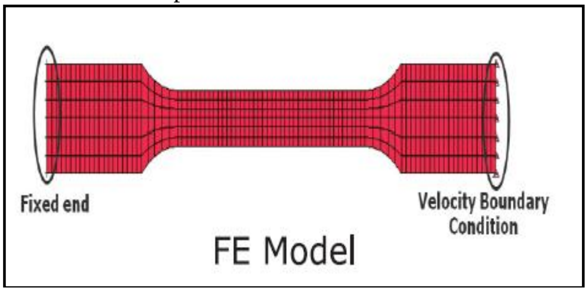
ii. True stress strain curve is converted to effective Stress-Strain curve by removing the elastic strains as follows-



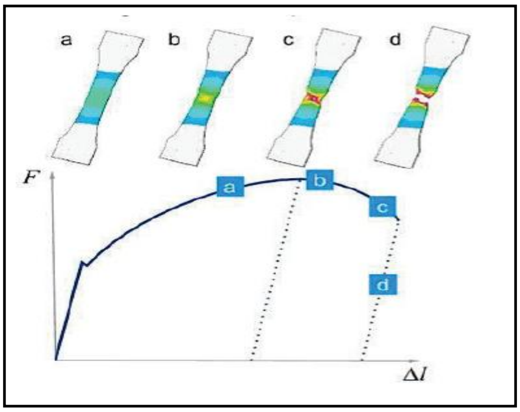
iii. Resulting hardening curves relate the yield stress as a function of effective plastic strain-



iv. Standard specimen FE model:



v. Modeling of elasto-plastic material behavior:



Typical Input True stress-strain curve of steel materials for LSDYNA:

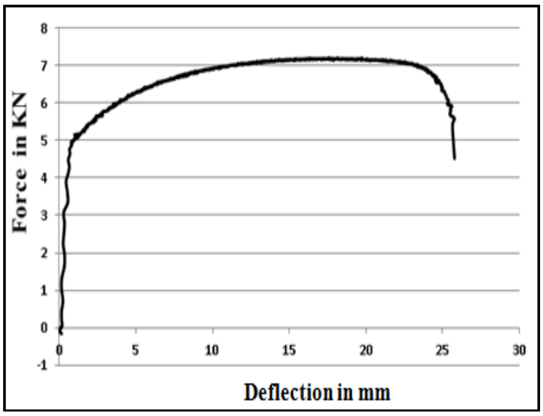


Figure 8: Input from test specimen
Force vs Deflection

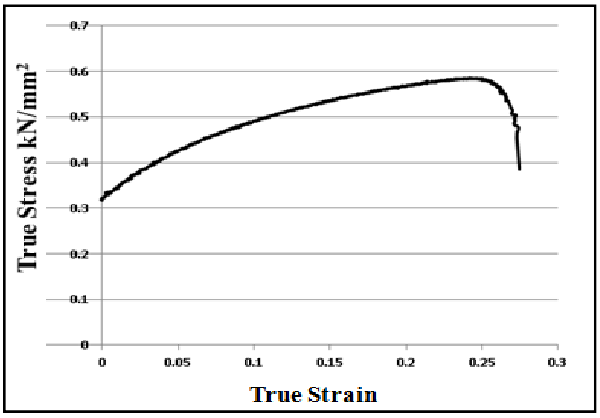


Figure 9: Output curve
True stress vs True Strain

7. Conclusion

Mechanical characterization for structural materials in dynamic uniaxial tensile loading condition is one of the most practical themes to be investigated thoroughly. In the current automobile industry material testing standards for quasi-static rates are relatively well established. The increasing need for high strain rate material properties is now focusing the automobile industry attention on the test methods used to generate data. Many automobile industries are using different procedures and analysis may yield information in apparent conflict with other published data. There is lack of industrial standards for high strain rate testing makes it vital that the end-user understands the valid applications and limitations of high strain rate material data. Currently using test methods, proper specimen selection, strain measurement methods, data analysis techniques, and interpretation of high strain rate data need to review and to validate for crash application.

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