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Parameter identification of GISSMO damage model for DOCOL 900M high strength steel alloy

Usage of a general damage model coupled with material modeling in LS-DYNA for Advanced high strength steel crashworthiness simulations.

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Summary

In the Automotive industry there is a need for high safety and also a need for weight reduction in order to reduce the CO_2 emissions, this led to the use of high strength steels because of its light weight and high strength properties. DOCOL 900M is a high strength steel manufactured by SSAB industries. It is a martensitic steel with yield strength higher than 700MPa. This steel is used to make chassis and also a few safety components to reduce the impact/damage in a car crash. DOCOL 900M is used to manufacture safety components around the battery box in one of the NEVS cars. The increasing demand of high strength steels and short development time has led to the requirement of improved predictions of the actual crash behaviour in the automotive industry because a full scale crash test is both expensive and time consuming [1].

GISSMO is the damage model preferred and used in such crashworthiness simulations. The current state of art here is the use of failure models that accumulate damage on an incremental basis. Most of the models are based on the observations of Bridgman [2], who had found that the failure strain in metallic materials depends on the hydrostatic pressure. The models used for crash simulations are usually isotropic and is based on the Gurson model with extensions by Tvergaard & Needleman (1984) or the failure model of Johnson and cook [3].

The mechanical properties of sheet metal parts for crashworthiness calculations are usually considered to be in material delivery state by default which disregards all the previous manufacturing treatments in the process chain of sheet metal part and also the changes in properties during manufacturing process. Usually these processes increases the flow stress due to work hardening which plays an important role especially in low speed crash cases [4].

For forming simulations an anisotropic description of yield loci based on Hill or Barlat (1989) criteria is considered important instead of isotropic models that is based on the von Mises flow rule. This makes it necessary to use different constitutive models for both parts of the process chain. The damage model should be suitable to be used for both of the disciplines and should be able to correctly predict the damage regardless of the details of the constitutive model formulation. The damage model GISSMO (Generalized Incremental Stress-State dependent damage MOdel) has been developed at Daimler and DYNAmore [5] [4]. GISSMO combines the proven features of failure description provided by damage models for crashworthiness simulations together with incremental formulation for the description of the material instability/localization. The accurate description of instability/localization has a great influence on the results in a crash simulations. GISSMO is a phenomenological damage mechanics model which is based on experimental results and does not consider voids and cracks. The different load cases are represented by the triaxiality which is the ratio between the mean stress and the von Mises stress [4].

Usually, the stress states will not be the same in a forming process compared to a crash loading and therefore the GISSMO model has the description of failure and also a functionality to provide an incremental and path-dependent treatment of instability/localization. The

conventional FLC cannot be used for multi stage deformation processes, for both forming and crash. This is because FLC has a limitation which considers only the final state of deformation that occurs at the end of the forming process and therefore it does not take possible changes in strain path into account [4].

At Daimler and DYNAmore an incremental formulation is developed for the treatment of arbitrary strain paths for the prediction of localization and failure. The idea here is to independently accumulate a measure for forming intensity F , and a measure for damage D [4].

From linear accumulation rule for damage proposed by Johnson and Cook [3] :

$$\Delta D = \frac{n}{\varepsilon_f(\eta)} D^{(1-\frac{1}{n})} \Delta \varepsilon_p$$

$$\Delta F = \frac{n}{\varepsilon_{p,loc}(\eta)} F^{(1-\frac{1}{n})} \Delta \varepsilon_p$$

In the above equations, $\Delta \varepsilon_p$ is the actual equivalent plastic strain and ‘ n ’ is an accumulating exponent. ‘ n ’ allows for non-linear accumulation of damage until failure and also allows a possibility to fit the model in to the data of multi-stage material tests, ε_f represents the tri-axiality dependent failure strain, $\varepsilon_{p,loc}$ represents the triaxiality dependent instability/localization. ε_f is used as a weighting function in failure criterion and $\varepsilon_{p,loc}$ is used as a weighting function for instability criterion. To allow an arbitrary definition of triaxiality-dependent failure strains the input data of failure strain is plotted as a load curve of fracture strain vs. triaxiality.

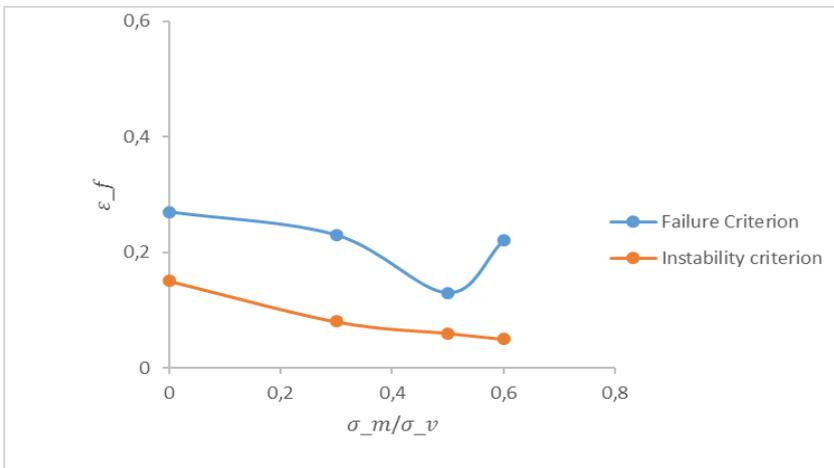


Figure 1: GISSMO damage model showing Failure and instability criterion. ΔD And ΔF represent the Failure criterion and instability criterion. The failure strain values are not from the Experiment.

When the forming intensity reaches unity, i.e. $F=1$, the accumulated damage is coupled to the stress tensor using the effective stress concept (proposed by Lemaitre, 1985). A curve of material instability dependent on the triaxiality is used for the accumulation of forming intensity and this value represents the onset of material instability and ending of mesh-size

convergence of results. For the practical application of the model to finite element simulations with limited mesh sizes requires regularization of different mesh sizes. In GISSMO, to regularize the amount of energy that is dissipated in the process of crack development and propagation the regularization treatment is combined with the damage model. For a finite element model this results in a variation of the rate of stress reduction through element fadeout [5].

Through a modification of Lemaitre's effective stress concept [4]:

$$\sigma^* = \sigma(1 - D)$$

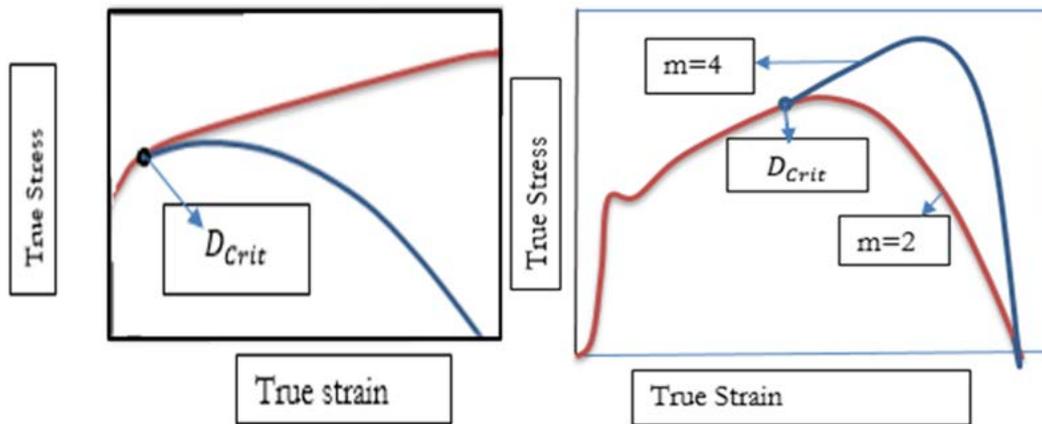


Figure 2: Graphs showing Coupling of Damage in the left and the influence of fading exponent in the right.

$$\sigma^* = \sigma \left[1 - \left(\frac{D - D_{crit}}{1 - D_{crit}} \right)^m \right] \quad \text{For } D \geq D_{crit}$$

Where, D_{crit} is the damage at the time step when 'F' reaches 1.0 and m is called the fading exponent, which can be defined depending on the actual element size that governs the rate of stress fading and thus influences the amount of energy that is dissipated during element fadeout which will allow possibility for regularization of fracture strain and also the energy consumed during the post-critical deformation [5].

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Preface

This master thesis was written as a course for Masters in Manufacturing Engineering in University West, and it was done in NEVS safety and crash department which is located in Trollhättan. It was a very good experience working in an Automobile industry.

Firstly, I would like to thank my supervisors Mats Larsson at University West and Lars Johansson in NEVS and my partner Yueyue Wang for their great patience, help and support. I would also like to thank my colleagues at NEVS who helped me finish this Thesis.

The reason to select DOCOL 900M for this thesis is because it is used as the safety beam on the sides of one of the upcoming model of NEVS electric car to protect the battery box in a crash scenario. Our supervisor at NEVS explained the basics and suggested to find suitable failure model in a crash scenario. I have started this thesis without having any idea on GISSMO. I came to know that DOCOL 900M is considered as ductile material even though it has high martensitic content and less elongation percentage. At first I got confused with GISSMO and DIEM and why they are preferred depending on the requirement. It took some time to understand that the DIEM is preferred in forming processes and GISSMO is preferred in crash simulations. In GISSMO we get failure curve and also localization/instability curve in fracture strain vs. triaxiality graph and in DIEM we get FLC (forming limit curve) curve in FLD. I was also confused by the usage of a general damage model coupled with material modeling in LS-DYNA. These were the few confusions I have faced during this thesis.

Affirmation

This master degree report, *Parameter identification of GISSMO damage model for high strength steel alloy DOCOL 900M*, was written as part of the master degree work needed to obtain a Master of Science with specialization in manufacturing degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

Signature by the author

Sai Krishna Chalavadi

Date

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Symbols and glossary

Acronyms

NEVS	National Electrical Vehicles Sweden
AHSS	Advanced High Strength Steel
GISSMO	General Incremental Stress-State dependent Damage Model

Symbols

A_0	Initial cross-sectional area	m ²
A_r	Effective area	m ²
A_c	area of cracks and voids	m ²
D_C	Critical damage value for ductile fracture	
σ_n	Nominal stress	Pa
σ_r	Effective stress	Pa
σ_m	Hydrostatic mean stress	Pa
σ_v	Von Mises stress	Pa
$\sigma_1, \sigma_2, \sigma_3$	principal stresses	Pa
ε	Strain	
$\varepsilon_1, \varepsilon_2, \varepsilon_3$	Principal strains	
ε_p	Equivalent plastic strain	
ε_f	Fracture strain	
$\varepsilon_{p,loc}$	Equivalent plastic strain to localization	
$\frac{\sigma_m}{\sigma_v}$	Stress Triaxiality	
$\left(\frac{\sigma_m}{\sigma_v}\right)_{av}$	Average stress triaxiality	

Abstract

In the Automotive industry there is a need for weight reduction in order to reduce the Energy consumption, CO_2 emissions and also the need for high safety, which has led to the use of high strength steels because of their light weight and high strength properties. The increasing demand of high strength steels and short development time has led to the requirement of improved predictions of the actual crash behaviour in the automotive industry because a full scale crash test is both expensive and time consuming.

The models used for crash simulations are usually isotropic and is based on the Gurson, Tvergaard & Needleman or the von Mises flow rule. GISSMO is the damage model has been developed at Daimler and DYNAmore used in such crashworthiness simulations. This paper is mostly based on the reference of various LS-DYNA Users conferences. GISSMO damage model has a number of parameters and curves that defines when necking and failure occurs. GISSMO is a phenomenological damage mechanics model which is based on experimental results and does not consider voids and cracks.

This paper gives an idea on how to obtain the GISSMO model for the Advanced high strength steel DOCOL 900M. There exists a failure criterion and also a localization/instability criterion. In GISSMO their also exists an equation that is used to find the total amount of energy absorbed by the material during a crash simulation. This damage model can be used similarly for other AHSS and High strength steels also.

1 Introduction

In an automobile the chassis is the underpart of the vehicle on which the body is mounted, it is also useful in decreasing the consequences from accidents which is done by various safety components in the chassis but the increasing weight in an automobile can lead to high fuel consumption and high CO_2 emissions and in an electric car scenario it consumes more energy/electricity. A modern car/Automobile has many safety components and it is not ideal to remove any of the safety components to reduce weight. So, to decrease the CO_2 emissions, the weight must be reduced on each component by implementing lightweight materials [1]. High strength steels such as DOCOL 900M are preferred instead of the traditional steels or aluminium because of their less weight and high strength. High strength steel components are highly preferred to support and protect the huge battery boxes in an Electric car especially in NEVS. Therefore automotive industries are now trying to increase the percentage of high strength steel components in their automobiles.

In the automotive industry the demand for accurate predictions regarding material behaviour and material failure has increased in the recent years and due to less time the Crashworthiness simulations are used to develop the safety components. Crashworthiness simulations of the car body is an important part of the CAE development for car design. The simulations can also give information about different phenomenon in a car crash since it is very expensive to crash a car in the real environment and also due to variations in manufacturing [1].

At Daimler and DYNAmore the usage of a general damage model coupled with material modeling in LS-DYNA is developed to speed up the crash simulations. This efficient way was preferred to find the GISSMO for DOCOL 900M in this thesis.

This thesis was performed at NEVS in Trollhättan with the aim to increase the predictiveness of crashworthiness simulations for DOCOL 900M. Initially, the material parameters for DOCOL 900M are identified to focus on the application in a crash simulation. A generalized scalar damage model (GISSMO) can be made with these parameters. In GISSMO, the different load cases are represented by the triaxiality which is the ratio between the mean stress and the von Mises stress. In GISSMO, separate treatment of plasticity formulation and also damage/failure prediction can be done. Both the failure/fracture limit criteria and instability/localization criterion exists in GISSMO and also an equation that is used to find the total amount of energy absorbed by the material during a crash simulation [5]. The main advantage of GISSMO is the possibility to include more fracture criterion like Wilkins (W) model, Cockroft-Latham, Johnson Cook, Bao Wierzbicki etc. which are focused on different parameters to find failure in a material [7].

2 Theory

2.1 Damage mechanics

Damage occurs when a material is subjected to mechanical loading and increases with increasing load resulting voids and micro cracks. Damage mechanics itself is a specific field of research that is active to incorporate damage in various constitutive model for materials. [1].

There are two types of damage mechanics models:

Damage mechanisms based on micro level such as voids and micro cracks and have a defined micromechanical criteria for damage growth are called Micromechanical damage mechanics models. This model can be derived to macroscopic models later [1].

Phenomenological damage mechanics models are based on actual experiments. The selected material is subjected to different load cases and their respective stresses and strains or forces and displacements are recorded [1].

The damage is hard to measure often and it is an estimation done from changes in material properties like for example changes in stiffness. Therefore these types of models should be used with extra attention when tested for other load cases [1].

One common way to describe the damage is to compare the cross-sectional area of the material, A_0 with the effective area, A_r . A_c is the effective area due to voids and micro cracks of a certain area [1].

$$A_r = A_0 - A_c \quad (1)$$

The material has closed voids and micro cracks and due to this reason the effective area is usually considered to be even smaller than proposed in equation 1. The damage, D stated as equation 2 [1].

$$D = \frac{A_0 - A_c}{A_0} \quad (2)$$

Where, the value $D=0$ corresponds to the undamaged material and $D=1$ corresponds to failure/fracture and separation of the material into two parts. The values in between 0 to 1 displays the amount of damage occurred to the material [1].

The effective stress, σ_r may then be expressed as a function of nominal stress, σ_n [1]

$$\sigma_r = \frac{N}{A_r} = \frac{N}{A_0} * \frac{A_0}{A_r} = \frac{1}{1-D} \sigma_n \quad (3)$$

σ_r , can be expressed as a function of strain (J. Lemaitre, 1985)

$$\sigma_r = (1 - D)E\varepsilon \quad (4)$$

2.2 A generalized scalar Damage Model:

GISSMO is a combination of the proven features of failure description provided by damage models and also instability/localization description. With the help of phenomenological formulation of ductile damage the simple inputs of material parameters are achieved [5].

2.3 Stress and strain measures:

The usual way to treat instability/localization in sheet metal forming process is by comparing resulting strains in the final stage with a fixed curve of principal strain values. The forming limit curve considers only the final stage of deformation and doesn't consider the changes in the strain path [4].

The FLC from principal strain ($\varepsilon_1, \varepsilon_2$) space is transformed to a notation using the equivalent plastic strain ε_p . Which was initially proposed by Muschenborn and Sonne (1975), is a practical approach for a strain-path dependent forming limit determination [4].

$$\varepsilon_p = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_1 \varepsilon_2} \quad (5)$$

In isotropic material models, the usual notation for crashworthiness purposes is a characterization of load state using the invariants of the stress tensor. The invariant notation is independent of the respective material direction [5].

The strain increments are related to stress values by a 2D constitutive model considering plane stress case as a common assumption. The strain-based notation can be transformed into a notation in invariant of the stress tensor [5].

As a practice approach, the stress triaxiality is used to identify the state of stress and is defined as follows:

$$\eta = \frac{\sigma_m}{\sigma_v} \quad (6)$$

Where, σ_m (Mean stress) is the first invariant of stress tensor given for plane stress ($\sigma_3 = 0$).

$$\sigma_m = \frac{\sigma_1 + \sigma_2}{3} = -p, \quad (7)$$

σ_v is the equivalent stress or Von Mises stress:

$$\sigma_v = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2} \quad (8)$$

Usually, the actual value of accumulated equivalent plastic strain is compared to the limit value for a respective triaxiality. It can be expected that stress states will usually differ/change in a metal forming process compared to a following crash loading scenario [5].

2.4 Path-dependent failure criterion:

To allow the treatment of arbitrary strain paths to predict failure, an incremental formulation has been chosen to measure damage:

$$\Delta D = \frac{n}{\varepsilon_f(\eta)} D^{(1-\frac{1}{n})} \Delta \varepsilon_p \quad (9)$$

This equation represents linear accumulation rule for damage as proposed by Johnson and cook(1985).If GiSSMO is active, equation (9) is evaluated at every time step in LS-DYNA using the current values of damage(D), triaxiality(η) and increment of plastic strain($\Delta \varepsilon_p$) [5].

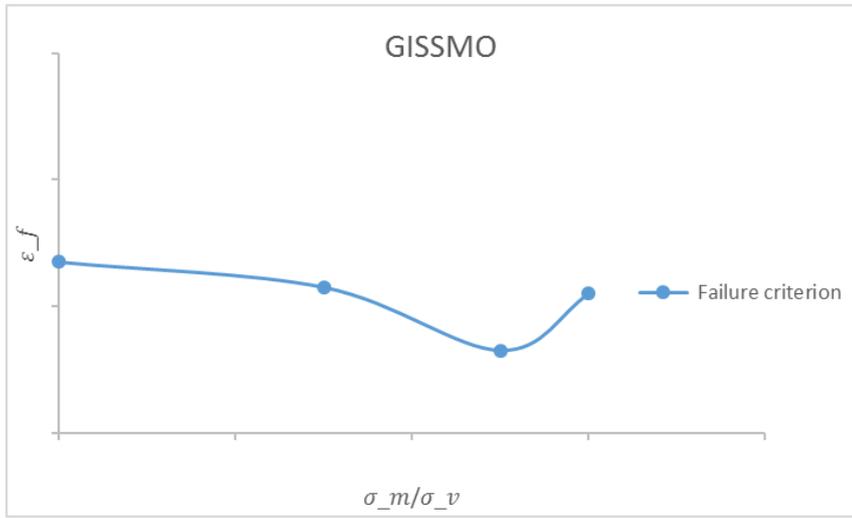


Figure 3: The failure criterion, ΔD plotted in failure strain vs. Triaxiality coordinates.

In equation 9, n is a damage exponent and allows for a non-linear accumulation of damage until failure and creates a possibility to fit the model to data of multi-stage material tests, and $\varepsilon_f(\eta)$ is the fracture strain as a function of triaxiality [5].

When the damage (D) reaches 1.0, it is assumed that fracture had taken place and the integration point can no longer be able to bear any external loadings. Equation (9) is important for accurate depiction of fracture when the triaxiality is not constant over deformation (i.e., non-proportional strain paths) [8].

Non-proportionality is an issue in the prediction of localization/instability and failure. FLC based approaches are popular and effective in forming analysis but have been struggling for years to find suitable methods for strain path independent forming limit diagrams(FLD). Damage accumulation like in equation (9) is simple and elegant way to deal with the problem. Equation (9) can provide results that are satisfactory in many practical applications Even though there are many issues regarding damage accumulation [8].

2.5 Path dependent localization:

In this section, the methods that are used in GISSMO for treating localized deformation/material instability are described. The strains are noted at the onset of localization from tests under constant stress state. The tests include tensile tests with various hole radii, notch radii, biaxial tests and shear tests which can result a forming limit curve. This curve is used as an input for the constitutive model and is also used as a weighting function for the path dependent accumulation of necking intensity up to the expected point of instability [5]. Similar to proposal of Bai and Wierzbicki method (2008).

Generally in numerical simulations, the localization behaviour of materials depends on yield locus and evolution of the flow/yield stress. Instability starts from the post critical range of deformation and the determination of yield curves from the specimen tests is not possible for this range, therefore stress extrapolation based on engineering assumptions or models is used. Due to the mesh size dependency of results in the post-critical range, the used parameters of an extrapolation would determine the material properties in the post-critical range, and lead to mesh dependent results and therefore, a damage-based regularization for the post-critical range is proposed in the present contribution [5].

One of the reasons for the treatment of localization is to determine the beginning of material softening which is used as a damage threshold for the coupling of damage to flow/yield stress in crashworthiness applications [4].

2.5.1 Linear accumulation of localization/instability criterion:

This criterion can be implemented in the GISSMO model by transforming the data from the FLC curve into the coordinates of equivalent plastic strain and triaxiality as a weighting function for the accumulation of “forming intensity”, here, is a measure of the remaining formability [4].

As proposed by Johnson and cook (1985), the Forming limit curve is introduced to the linear incremental formulation for the linear accumulation of damage to failure [4].

$$\Delta F = \left(\frac{\Delta \varepsilon_p}{\varepsilon_{p,loc}} \right) \quad (10)$$

Where, a function of triaxiality $\varepsilon_{p,loc}$ is the equivalent plastic strain to localization. The function of equivalent plastic strain to necking represents a triaxiality dependent weighting function. F is accumulated linearly and when F reaches unity, necking is expected to occur. For proportional loading case, the strain to necking will be the same as predicted by the standard FLC [4].

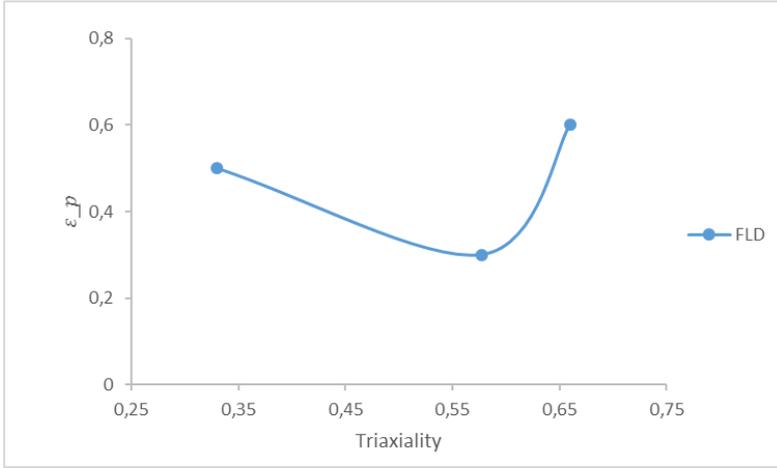


Figure 4: Forming limit curve plotted in equivalent strain vs. Triaxiality Coordinates. The strain values are not from the experiment.

2.5.2 Nonlinear accumulation of localization/instability criterion:

A nonlinear equation for accumulation is introduced to the GISSMO model by using the same relation as for the accumulation of ductile damage to failure. The parameters identification for this relation is difficult to obtain from direct tests and it is done rather by the means of reverse engineering simulations of multi-stage forming processes. The introduction of an additional parameter “n” should allow the fitting of the model to existing test data [5].

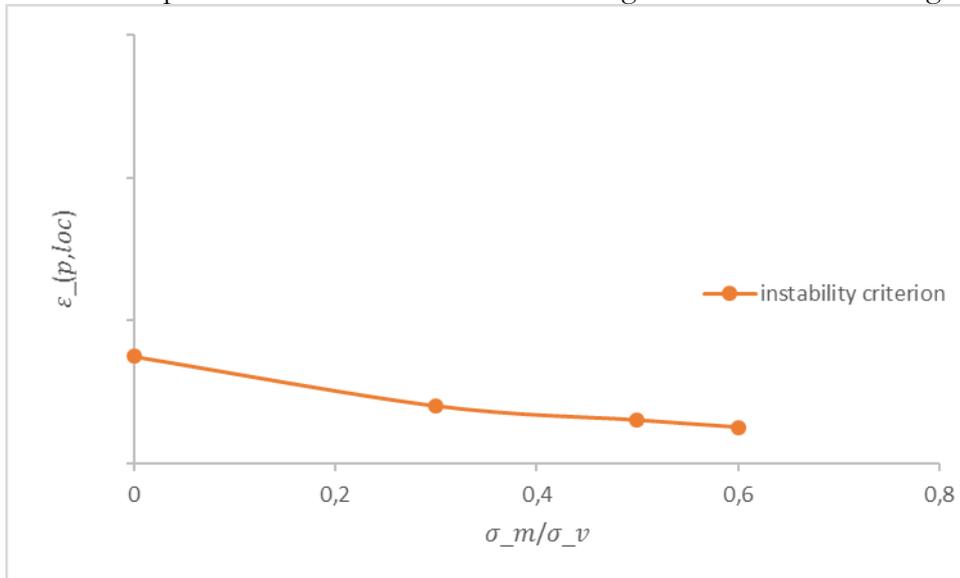


Figure 5: The instability criterion, ΔF plotted in localization strain vs. Triaxiality coordinates.

$$\Delta F = \frac{n}{\varepsilon_{p,loc}(n)} F^{(1-\frac{1}{n})} \Delta \varepsilon_p \quad n > 1 \quad (11)$$

Here, “n” is the accumulating exponent. If n=1, Equation 11 reduces to linear form (equation 10). For proportional loading ($\varepsilon_{p,loc} = \text{constant}$) the equation (11) can be integrated to yield a relation between the “forming intensity” F and the equivalent plastic strain [4]:

$$F = \left(\frac{\varepsilon_p}{\varepsilon_{p,loc}} \right)^n \quad \text{For } \varepsilon_{p,loc} = \text{constant}. \quad (12)$$

For n=1, the above equation is a linear relation of current equivalent plastic strain and equivalent plastic strain to failure [4].

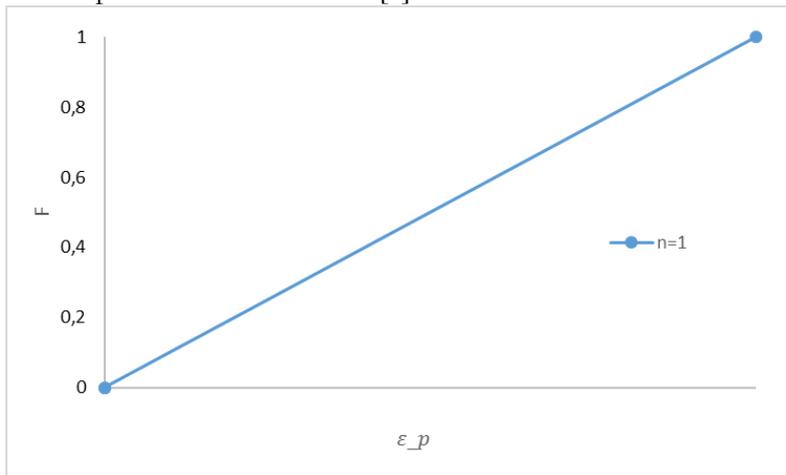


Figure 6: Graph showing linear accumulation.

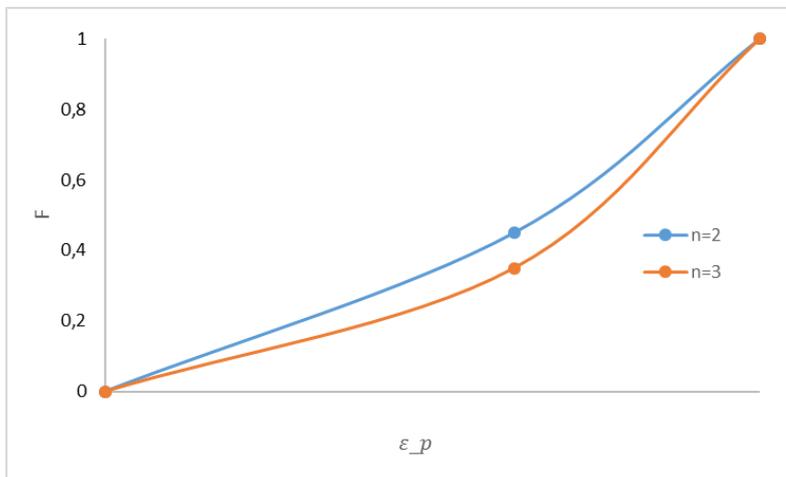


Figure 7: Graph showing nonlinear accumulation.

The same way as the damage parameter ‘D’, the forming intensity parameter ‘F’ is also accumulated, and the only difference is the use of different weighting function, which is defined as “a curve of limit strain depending on triaxiality for F”, and for the failure parameter D the fracture strain as a function of triaxiality is the input [5].

2.6 Post-critical behaviour

In the forming simulations the post critical range of deformation lacks interest because the formation of instability or necking is already considered as a failure. But in crash simulations it is important to collect the post critical behaviour because the maximum energy absorbed by the material can be found. Results based on the Mesh size dependency occurs while modelling of the post critical behaviour of metals using Finite Element Method [4].

When the forming intensity measure F reaches unity, i.e. $F=1$, a coupling of accumulated damage to the stress tensor using the effective stress concept (proposed by Lemaitre, 1985). A curve of material instability dependent on the triaxiality is used for the accumulation of forming intensity and this value represents the onset of material instability and ending of mesh-size convergence of results. For the practical application of the model to finite element simulations with limited mesh sizes requires regularization of different mesh sizes [4].

In the GISSMO model to regularize the amount of energy that is dissipated in the process of crack development and propagation the regularization treatment is combined with the damage model. For a finite element model this results in a variation of the rate of stress reduction through element fadeout [5].

Through a modification of Lemaitre's effective stress concept [4]:

$$\sigma^* = \sigma(1 - D) \quad (11)$$

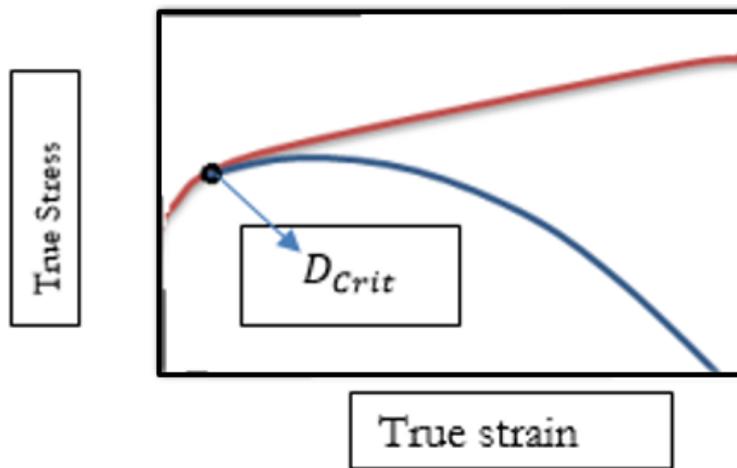


Figure 8: Graph showing coupling of damage to stress in True Stress vs. True Strain.

A damage threshold can be defined in combination with the treatment of material instability. Damage and flow stress will be coupled as soon as the damage parameter D reaches this value. This allows a possibility to enter a damage threshold as a fixed input parameter or to use the damage value corresponding to the instability point [5]. As the post-critical range of deformation is reached a value of critical damage D_{crit} is determined and used for the calculation of the effective stress tensor:

$$\sigma^* = \sigma \left[1 - \left(\frac{D - D_{crit}}{1 - D_{crit}} \right)^m \right] \quad \text{For } D \geq D_{crit} \quad (12)$$

Where, D_{crit} is the damage at the time step when F reaches 1.0 and m is called the fading exponent, which can be defined depending on the actual element size that governs the rate of stress fading and thus influences the amount of energy that is dissipated during element fadeout [5].

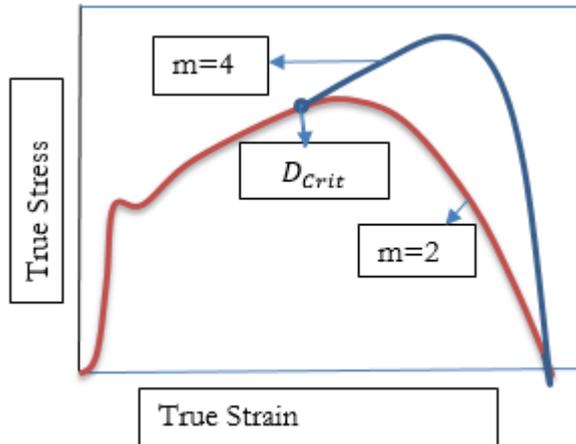


Figure 9: Graph showing coupling of damage to stress with influence of fading exponent in True Stress vs. True Strain.

This procedure allows regularizing the energy consumed during the post-critical deformation the fracture strains, and also regularizes the resulting engineering stress-strain curves in tensile tests with different mesh sizes [5].

3 Conclusion and discussion

In this paper, the GISSMO damage model has been described to capture the ductile damage and failure in different stress states for DOCOL 900M. The damage model is preferred based on the various LS-DYNA® conference proceeding papers which shows the potential of the model to predict the crashworthiness simulations. The damage model can be used for the simulation of shear, tensile and biaxial tests very effectively. This phenomenological damage model introduces many features suitable to describe ductile damage and failure in different stress states. The failure criterion and the instability criterion are both prescribed for DOCOL 900M. The major limitations for predictive performance occurs from the deficiencies in material modelling and coarse discretization of the test specimens. The mesh size dependency plays an important role in finding the energy absorbed through element fadeout so a fine mesh size is always preferred. The tests shall be performed on all the specimens along rolling direction and transverse direction to get better prediction of GISSMO.

3.1 Deep Discussion

For DOCOL 900M the test setup, material modelling and coarse discretization of the test specimens is being done by my thesis partner at NEVS, Yueyue Wang. We are going to have one combined thesis at NEVS and with the help of our thesis it is possible to do real tests and also CAE simulations in LS-DYNA.

3.2 Future Work and Research

Real tests are to be performed and also CAE simulations in LS-DYNA.

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