On the Prediction of Material Failure in LS-DYNA®: A Comparison Between GISSMO and DIEM

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Abstract

The accurate prediction of material damage and failure is an important aspect in forming and crash analysis. Experimental evidence shows that ductile fracture strongly depends on the stress state. Therefore, this effect has to be accounted for in FE simulations for accurate predictions. In this context, GISSMO and DIEM provide a framework within LS-DYNA where the user can define failure parameters which have to be calibrated to match experimental data. However, these models have been conceived following different interpretations of the failure phenomenon. In an attempt to shed some light on the differences between GISSMO and DIEM, this paper discusses their characteristics and compares both models in the calibration of a dual-phase steel. The results show that both models are able to reproduce experiments under different triaxialities and strain paths. Furthermore, both GISSMO and DIEM have incorporated features that deal with spurious mesh dependence where these features have also been compared in this contribution. The main conclusion is that both models can provide similar results, despite the contrasting differences in the formulation of each model.

1. Introduction

As a consequence of the worldwide tendency in reducing CO_2 emissions by producing lighter and more energy-efficient products, the demand for accurate predictions regarding material behavior and material failure has greatly increased in recent years. In particular in the automotive industry, there is also an increasing interest in effectively closing the gap between forming and crash analysis, since the forming operations may highly affect the crashworthiness of the produced parts. In this scenario, a correct depiction of material mechanical degradation and fracture seems indispensable.

Currently, there are several models implemented in LS-DYNA which have been developed to deal with material damage and failure. Many of them are complete constitutive models which consider elastoplasticity coupled with damage formulations as well as with embedded failure criteria (e.g., *MAT_015, *MAT_052, *MAT_081, *MAT_104, *MAT_120, *MAT_153, among others). Alternatively, LS-DYNA also allows the definition of failure and damage through the keyword *MAT_ADD_EROSION, where the user can choose different failure models and fracture criteria which are, in turn, coupled with the selected plasticity model in an ad-hoc fashion. In this context, GISSMO (Generalized Incremental Stress-State dependent Damage Model) and DIEM (Damage Initiation and Evolution Model) are good candidates for the task of predicting ductile failure using LS-DYNA. However, many users still seem to have difficulties in using these models, meanwhile other users, who already master either GISSMO or DIEM, feel somewhat insecure in employing the concurrent model.

These difficulties mainly arise because GISSMO and DIEM have been conceived following quite different interpretations of the phenomena that influence failure. For instance, in GISSMO the user has to input a failure curve as a function of the triaxiality (and also of the Lode parameter, in the case of solid elements) where this curve is used for the nonlinear accumulation of damage. This strategy intrinsically takes the strain path change into account, for which a numerical calibration based on experimental data is required. Furthermore, an instability curve may also be defined in GISSMO, where in this case, if instability achieves a critical value, the stresses are assumed to be coupled with damage, leading to a ductile dissipation of energy upon fracture. DIEM, on the other hand, allows the user to define multiple damage initiation indicators which evolve simultaneously. For example, the user can define a normal and a shear failure initiation criterion, the former as a function of triaxiality, the latter depending on the so called shear stress function. Additionally, a forming limit curve (FLC) can also be input in DIEM, where this criterion also evolves along the other two failure initiation criteria. The different damage initiation criteria can then be combined in a global damage evolution rule. Similarly to GISSMO, a certain number of experiments is required in order to properly fit the parameters necessary for DIEM.

This contribution is an attempt to compare and better understand the differences between GISSMO and DIEM where it is important to mention that the authors are much more familiar with the former than with the latter model. In this respect, the main differences between both models and how they are intended to predict failure are discussed. Additionally, the calibration of a dual-phase steel using GISSMO and DIEM is used to better highlight the differences between the models and how these are reflected in the final parameter fitting.

2. Preliminaries

Nowadays it is widely known that the stress state affects the fracture behavior of metallic alloys. Among the many important contributions in this field, we can cite the pioneering work of Bridgman [1] who collected experimental evidence showing that the fracture strain was related to the amount of pressure under which a tensile specimen was subjected. The stress tensor, $\boldsymbol{\sigma}$, can be split in two contributions, a hydrostatic (pressure, p) and a deviatoric part, $\mathbf{s}$:

$$\boldsymbol{\sigma} = \mathbf{s} + \frac{1}{3}\mathrm{tr}(\boldsymbol{\sigma})\mathbf{I} = \mathbf{s} - p\mathbf{I} \tag{1}$$

Bridgman also directly observed that the metallic alloys are isochoric under plastic flow, which means that they do not experience any changes in volume in the plastic regime. This account also has, to a larger extent, corroborated one basic assumption of already existing plastic yield criteria at the time, like von Mises and Tresca: plastic yielding does not depend on the pressure in metals. Fracture, on the other hand, is pressure-dependent.

The von Mises criterion, for instance, assumes that plastic yielding takes place when the equivalent stress, σ_{eq}, reaches a critical value, σ_y:

$$F = \sigma_{eq} - \sigma_y \leq 0 \tag{2}$$

where the equivalent stress is expressed, in terms of principal stresses, as

$$\sigma_{eq} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\right]} \tag{3}$$

In the late 1960’s and 1970’s, the contributions of Rice and Tracey [2], McClintock [3] and Mackenzie et. al. [4] further investigated the dependence of the stress state upon ductile fracture and observed that the fracture strain tended to decreased for tensile specimens when increasing the notch radius. These authors formalized this idea by proposing a stress state indicator that is nowadays widely known as “triaxiality” and is defined as the ratio between the pressure and the equivalent stress:

$$\eta = -\frac{p}{\sigma_{eq}} \tag{4}$$

The triaxiality is a very useful measure of the stress state if one aims to characterize the fracture behavior of a metallic alloy. For plane stress and isotropic materials, the triaxiality alone is enough to define any possible stress state in respect to fracture characterization. For three-dimensional stress states, also the so-called Lode angle is needed. However, we will restrict ourselves to plane stress states in this paper and therefore the consideration of the Lode angle is not necessary.

3. GISSMO – A short description

The Generalized Incremental Stress-State dependent Damage Model (a.k.a. GISSMO) has already been comprehensively presented elsewhere [5, 6] and the reader is referred to these contributions as well as to the LS-DYNA User’s Manual [7] for a more detailed description. Nevertheless, we will highlight some characteristics of this model that will be helpful in comparing it with DIEM.

One important aspect of GISSMO is the damage accumulation rule, which is given by

$$\Delta D = \frac{n}{\varepsilon_f(\eta)} D^{\left(1-1/n\right)} \Delta\varepsilon_p \tag{5}$$

If GISSMO is active, this equation is evaluated at every time step in LS-DYNA using the current values of damage (D), triaxiality (η) and increment of plastic strain ($\Delta\varepsilon_p$). In Equation (5), n is the damage exponent and $\varepsilon_f(\eta)$ is the fracture strain as a function of the triaxiality. When damage reaches 1.0, fracture is assumed to have taken place and the integration point is no longer able to bear any external loadings. An equation like (5) is very important for a more accurate depiction of fracture for non-proportional strain paths, that is, when the triaxiality is not constant over deformation. Because it is known from experimental evidence that the fracture strain is not the same for different triaxialities, it is important to take this influence into account.

Non-proportionality is a general issue in the prediction of localization, instability and failure. In fact, FLC-based approaches, which are very popular in forming analysis and proved quite effective in many practical applications, have been struggling for years to find suitable methods for strain path independent forming limit diagrams (FLD). On the other hand, damage accumulation like in Equation (5) is a simple and elegant way to deal with the problem. Although many issues regarding damage accumulation still remain open, Equation (5) can provide results that are very satisfactory in several practical applications.

Another interesting and useful aspect of GISSMO is the possibility of accumulating a measure of instability, denoted by the letter F, and written as

$$\Delta F = \frac{n}{\varepsilon_{crit}(\eta)} F^{\left(1-1/n\right)} \Delta\varepsilon_p \tag{6}$$

When $F = 1.0$, damage is assumed to affect the stresses through

$$\boldsymbol{\sigma} = \tilde{\boldsymbol{\sigma}}\left[1-\left(\frac{D-D_{crit}}{1-D_{crit}}\right)^m\right] \tag{7}$$

where D_{crit} is the damage at the time step when F reaches 1.0 and m is the so-called fading exponent, which has to be calibrated to match experiments. Equation (7) is in fact a generalization of Lemaitre's classical principle of effective stress where Lemaitre's formulation can be promptly recovered if one sets $m=1$ and $D_{crit}=0$.

The use of Equation (7) enforces a softening regime on the material level. Whether this is necessary or not, remains a point of debate among many engineers and researchers. Nevertheless, this feature can be very useful for relatively large shell elements. In general, large shells cannot depict localized necking accurately, which may be a disadvantage in crash analysis.

Finally, spurious mesh dependence is a known issue in finite element analysis. Especially in the case of ductile fracture prediction, this aspect plays a major role. Briefly speaking, different mesh sizes will lead to different strains in the simulation results if strain localization arises. Notice that this effect should not be confused with the inaccuracy of results caused by coarse meshes in calculations not involving localization. The issue of spurious mesh dependence has been subject of research since the 1980's and many solutions have been proposed in the literature. Among them, the nonlocal method, formulated either through integral or gradient-dependent strategies, seems to provide an effective solution to this issue [8, 9]. However, in order to be effective, this method requires very fine mesh sizes ($L_e < 0.5\,mm$) which are often prohibitive in forming and crash analysis.

Another way of dealing with spurious mesh dependence is by compensating its effects. In this respect, GISSMO allows the user to define element size-dependent factors which adjust the fracture curve to the corresponding element size. However, it is important to mention that this strategy does not solve the problem of spurious mesh dependence, but rather artificially compensate its effects in the calculation of damage. As a matter of fact, it seems that currently there is no other known method for large element sizes ($L_e > 0.5\,mm$). Nevertheless, practical experience by the authors has shown that this method is generally quite useful in crash analysis.

4. DIEM – Damage Initiation and Evolution Model

The Damage Initiation and Evolution Model (DIEM) [7, 10] is a relatively new damage/failure model available in LS-DYNA through the keyword *MAT_ADD_EROSION. Similar to GISSMO, it is intended to capture the behavior of metallic materials regarding damage and ductile fracture in a phenomenological fashion. However, its concepts are, to a larger extent, different from the ones of GISSMO. For example, in DIEM an arbitrary number of damage initiation and evolution criteria may be input and combined. The idea behind this approach is the hypothesis that fracture takes place due to different failure mechanisms, i.e., it is assumed that concurring mechanisms may evolve simultaneously and eventually lead to fracture. This is, to a general extent, in contrast with GISSMO, which assumes that a single instability and a single fracture curve are enough to characterize material failure.

One important aspect regarding DIEM is the differentiation between damage initiation and damage evolution. Within the framework of DIEM, damage initiation is regarded as an evolving variable which, when it reaches a maximum, defines the beginning of damage evolution. The beginning (or onset) of damage evolution is, in turn, understood as the moment when material degradation begins to macroscopically affect the overall load-carrying capacity of the material.

In DIEM, a ductile damage initiation indicator is accumulated following a linear law given by

$$\dot{\omega}_D = \frac{\dot{\varepsilon}^p}{\varepsilon_D^p} \tag{8}$$

In the equation above, $\varepsilon_D^p = \varepsilon_D^p(\eta, \dot{\varepsilon}^p)$ is a function of triaxiality and strain rate and represents the plastic strain at onset of damage. When ω_D reaches 1.0, damage is assumed to affect the material behavior by coupling damage and stress as it will be later discussed in this paper. This criterion is denoted in DIEM as ductile initiation and can be, in principle, regarded as the failure function related to the material degradation due to the nucleation, growth and coalescence of voids. At least, this is apparently the idea behind the ductile initiation criterion. In fact, one can actually define the ductile failure initiation curve for all triaxialities, which means that even shear and compression stress states (i.e., stress states that experimentally do not show failure mechanisms based on nucleation, growth and coalescence of voids) can be covered within the ductile initiation criterion.

In addiction to the ductile initiation criterion, DIEM also allows the definition of a shear damage initiation indicator, which is also accumulated following the linear law of Equation (8), but this time the plastic strain at onset of damage, i.e. $\varepsilon_D^p = \varepsilon_D^p(\theta, \dot{\varepsilon}^p)$, is a function of the so-called shear stress function, θ, defined as

$$\theta = \frac{2(\sigma_{eq} + k_s p)}{\sigma_{\text{major}} - \sigma_{\text{minor}}} \tag{9}$$

Apparently, the shear initiation indicator is intended to predict shear-like failure initiation. However, a contradiction seems to arise at this point. As stressed out above, it is possible to define an initiation curve for all triaxialities (including shear) within the ductile initiation criterion. Therefore, the use of an additional shear initiation indicator sounds somewhat redundant, since it is possible to write θ as a function of the triaxiality as well. This aspect will be discussed again in Section 6 when scrutinizing the results of the numerical calibration of a dual-phase steel.

In the special case of shell elements, DIEM also permits the definition of two FLD-like instability criteria: they are respectively called MSFLD and FLD damage initiation indicators. In this case, the plastic strain at onset of damage is a function of the in-plane deviatoric stress ratio, α, i.e. $\varepsilon_D^p = \varepsilon_D^p(\alpha, \dot{\varepsilon}^p)$, where α is given by

$$\alpha = \frac{s_{\text{minor}}}{s_{\text{major}}} \tag{10}$$

The only difference between MSFLD and FLD is that the latter has a damage initiation variable which evolves like Equation (8) while the former only considers damage initiation evolution for positive stress states. At this point, it is important to remark that the MSFLD and FLD initiation options are considered in the middle surface of the shell element only, which can be interpreted as an attempt to regard the shell cross-section as a whole; however, bending effects are inherently neglected. This deeply differs from the instability accumulation in GISSMO, which is carried out in all integration points of the shell element if it is activated.

Before further proceeding with the description of DIEM, it is important to remark that the i^{th} damage initiation evolution variable, ω_D^i, is independent of the other ones. That is, each initiation criterion evolves independently and each one of them is only considered if the user explicitly define it in the keyword *MAT_ADD_EROSION. Therefore, up to the onset of damage, the different initiation criteria do not influence each other, but rather evolve separately.

In this context, one could assume that, once damage onset or instability has been reached, the material has actually a very low load-carrying capacity and that fracture is about to take place shortly after damage initiation, which is, in turn, related to the appearance of localized necking (at least for tensile-like loads). In other words, one could consider that damage and localized necking onset mean imminent failure. This is, to a larger extent, the general approach of classical FLD's since localized necking is usually a synonym for inadequate product in forming analysis. Conversely, crash analysis often demands the modeling of the post-critical behavior experienced by the material due to two main reasons: (a) the energy dissipation upon fracture has a significant influence in the overall crash performance of the part; (b) since some components for crash are designed to absorb energy and eventually fail, it is important to know how the system will respond when the failed component is no longer able to resist further loadings. Therefore, modeling the damage evolution after the appearance of localized necking is an important feature of any damage/failure model if crash situations are to be considered.

To this end, DIEM adopts what is called the damage evolution criterion, which is active as soon as $\omega_D^i = 1.0$. From this point on, a global damage variable, D, affects the stresses following Lemaitre's concept of effective stress, that is,

$$\boldsymbol{\sigma} = (1 - D)\tilde{\boldsymbol{\sigma}} \tag{11}$$

where, in DIEM, if $D = 0.99$, failure is assumed to have taken place and the integration point has no longer load-carrying capacity. Equation (11) is less general than the GISSMO counterpart, given in Equation (7), and at first glance this may seem somewhat limiting in comparison to GISSMO but in fact it is not. The reason for that lies on the definition of damage evolution itself, which is expressed, in its generalized form, as

$$D = \frac{\dot{u}^p}{\dfrac{\partial u_f^p}{\partial D}} \tag{12}$$

In the equation above, u^p and u_f^p are the plastic displacement and the plastic displacement at failure, respectively. The latter can be defined as a function of triaxiality and damage, that is, $u_f^p = u_f^p(\eta, D)$. This means that, despite the simpler form of Equation (11), the damage evolution may be molded to better fit experimental data in the post-instability part. To some extent, this resembles the idea of the fading exponent of GISSMO, which is also intended to give more flexibility when calibrating post-critical material behavior.

The evolution of u^p is given by

$$\dot{u}^p = \begin{cases} 0 & \omega_D < 1 \\ l\dot{\varepsilon}^p & \omega_D > 1 \end{cases} \tag{13}$$

where l is the characteristic length of the element. Notice that the introduction of the concept of a "plastic displacement", which is element size dependent, is a direct attempt to correct the energy dissipation error due to spurious mesh dependence. Although this may seem physically sounder than the regularizing factors used in GISSMO, it essentially follows the same principle. After instability, plastic strain tends to spuriously depend on the mesh size and, both in DIEM and GISSMO, it is corrected by a factor for the evaluation of damage evolution. The difference is that, in DIEM, the factor is the element characteristic size itself, meanwhile in GISSMO the user may freely define the regularizing factor, which gives a little more flexibility. Nevertheless, none of both models resolves the problem of spurious mesh dependence, but rather compensates it numerically, as already discussed in Section 3.

The last aspect concerning DIEM is the possibility of combining the damage evolution variables where each criterion can be either set to maximum or multiplicative kind through the flag DCTYP [7]. If we define I_{max} to denote the set of evolution types of maximum-kind and I_{mult} representing the set of evolution types of multiplicative-kind, the global damage is given by

$$D = \max(D_{\text{max}}, D_{\text{mult}}) \tag{14}$$

where

$$D_{\text{max}} = \max_{i \in I_{\text{max}}} D^i \tag{15}$$

and

$$D_{\text{mult}} = 1 - \prod_{i \in I_{\text{mult}}} \left(1 - D^i\right) \tag{16}$$

As a matter of fact, the user has a lot of flexibility in DIEM by arbitrarily combining each damage evolution variable in different manners.

5. Numerical calibration of a dual-phase steel

In this section, the calibration of a dual-phase steel using both GISSMO and DIEM is presented. The experimental results of six different specimens have been used in the calibration procedure: two uniaxial tensile, two shear, one notched tensile and one biaxial test (see Figures 1 and 2). Notice that the idea behind the different tests is to achieve different triaxialities.

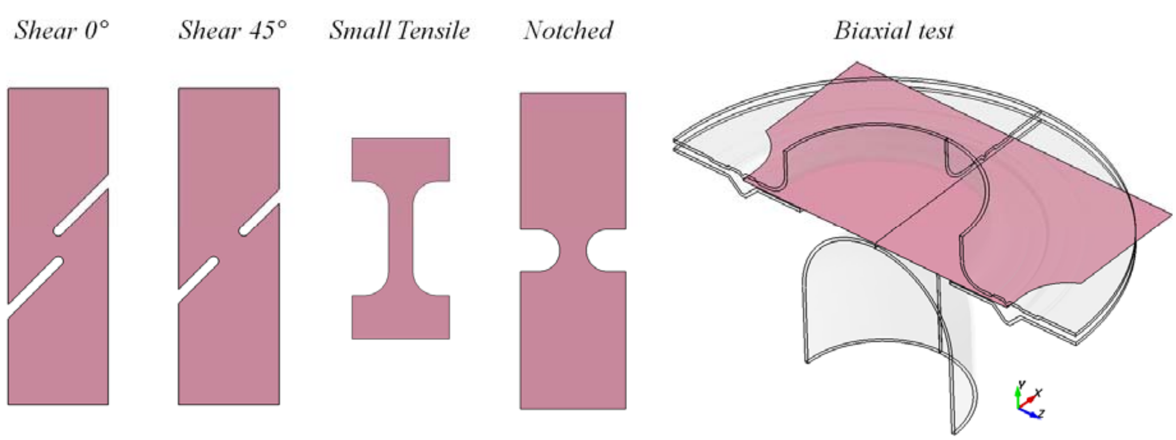

Figure 1: shear 0°, shear 45°, small tensile, notched tensile and biaxial specimens.

Ideally, each test would follow a constant triaxiality path so that the fracture curve could be directly measured from the experiments. However, in reality, the strain path and, consequently, the triaxiality are not constant in most specimen geometries. This strongly suggests that the calibration of GISSMO and DIEM has to be carried out numerically in order to identify the fracture curve. Furthermore, aspects like element formulation and plasticity model also influence the final calibration. In the present contribution, we will adopt fully integrated shell elements (ETYP=16) and the von Mises elasto-plastic model available in LS-DYNA through the keyword *MAT_PIECEWISE_LINEAR_PLASTICITY (*MAT_024). These choices are based on definitions that are very often used in car crash simulation for which the accurate prediction of material failure is very important. Notwithstanding their importance, the effects of strain rate have been disregarded in this paper and will be subject of further investigation in a future contribution.

The element size used in the discretization of the specimens was 0.5mm, which is in fact relatively small. In real car crash simulations, the element size is much larger, nowadays ranging from 2.5mm up to 10.0mm. For the calibration of mesh dependence, a large tensile specimen was used considering different mesh sizes as shown in Figure 2.

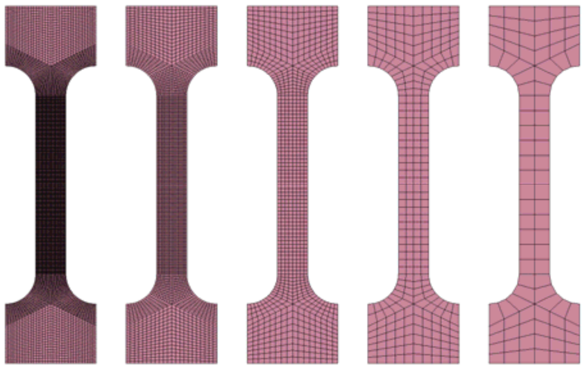

Figure 2: Large tensile specimen for different mesh sizes: 0.5, 1.0, 2.5, 5.0 and 10.0 mm.

Figure 3 shows the calibrated curves for both GISSMO and DIEM. In the case of GISSMO, a damage exponent $n = 2.0$ and a fading exponent $m = 2.5$ have been considered. Notice that the definition of the fading exponent only makes sense if an instability curve is defined, which is the case of the present calibration.

In the case of DIEM, only the ductile initiation and MSFLD criteria have been adopted, as shown in Figure 3. Despite the fact that the MSFLD initiation criterion has to be input in LS-DYNA as a function of the stress deviatoric ratio, it has been represented as a function of triaxiality for better comparison with GISSMO.

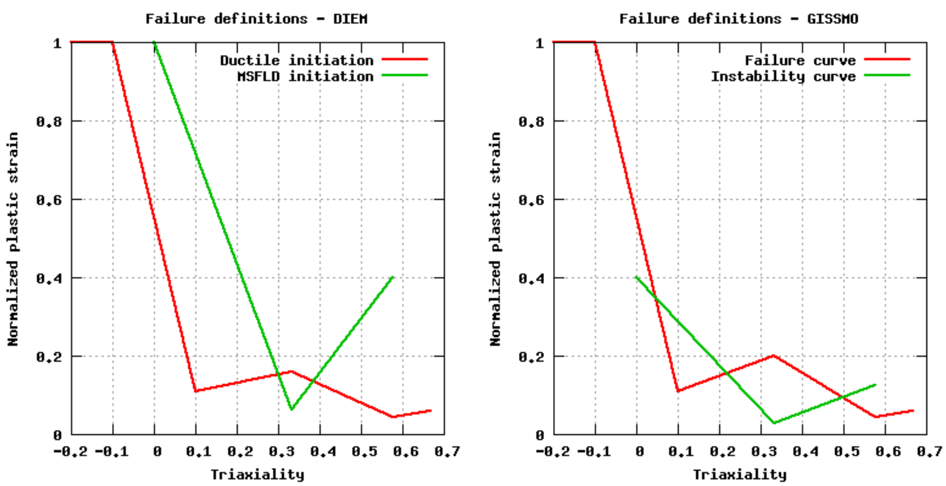

Figure 3: GISSMO and DIEM (normalized) calibrated curves for damage/failure.

6. Results and Discussion

Figure 4 shows the simulation results (normalized force-displacement diagrams) of the different specimens for both GISSMO and DIEM. The experimental curves are also given for reference. Close observation of these plots reveals that both calibrated models were able to reproduce the experimental data with similar accuracy.

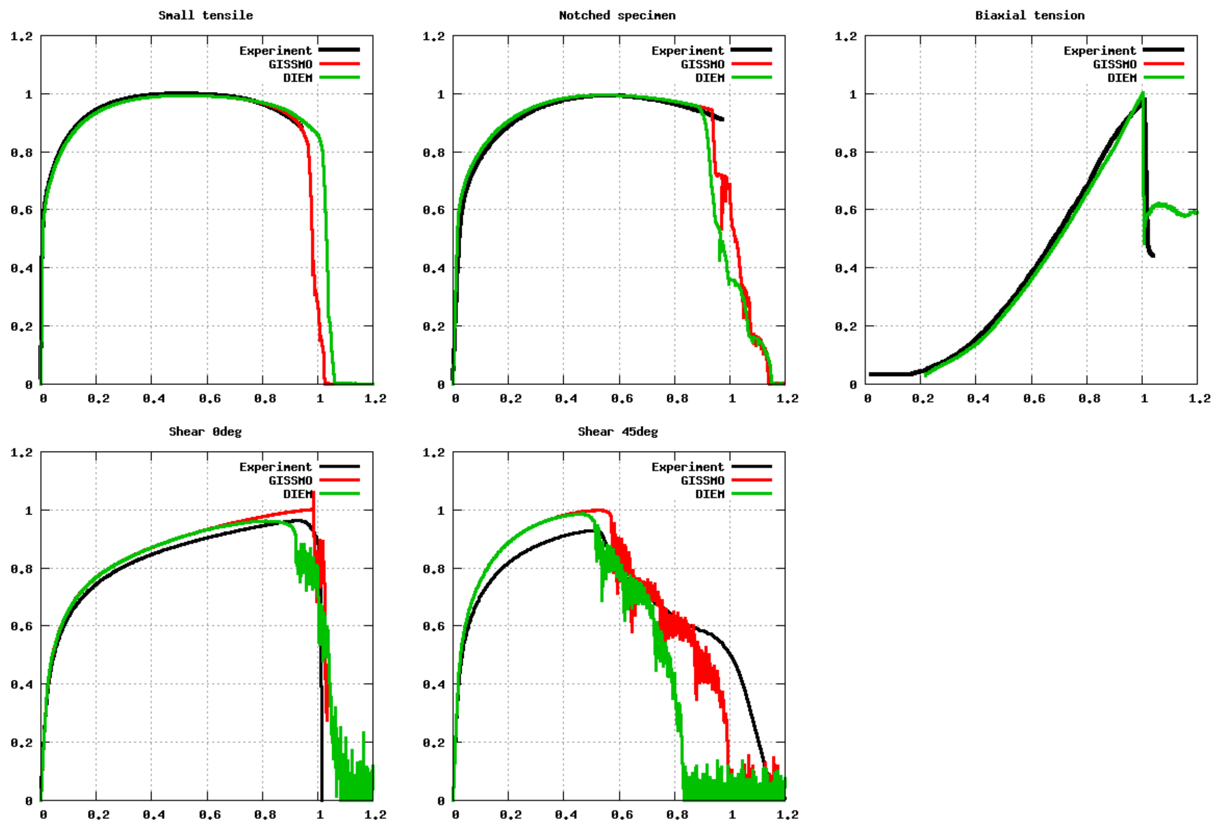

Figure 4: Simulation results with GISSMO (red) and DIEM (green).

Observing Figure 3, we see that GISSMO's calibrated failure curve is very similar to DIEM's ductile initiation criterion, where the main difference lies on the value of plastic strain at $\eta = \frac{1}{3}$. The two curves must not be necessarily similar, but in the present case we see that the similar curves provided a suitable final calibration in both cases. The difference in the value of plastic strain at $\eta = \frac{1}{3}$ has mainly to do with the fact that the instability criterion in the two models is different. In GISSMO, an instability curve has been defined where this curve dictates how the instability measure, F, evolves and, when $F = 1$, the coupling between damage and stress becomes active. In DIEM, damage initiation linearly evolves according to Equation (8), where this evolution is based on the curved defined in the MSFLD initiation criterion. In fact, the difference in the instability behavior in both models is quite noticeable.

Meanwhile GISSMO only has a single damage variable, D, and this is the damage that directly influences the stress through Equation (7), DIEM has two different variables that differentiate between damage initiation and damage evolution. That is, in DIEM, global damage D begins to evolve only when the damage initiation indicator, ω_D, has reached the critical value of 1.0. As a result, the coupling between damage and stress behaves differently in both models. In the case of GISSMO, instability has been conceived in an attempt to capture diffusive necking; in uniaxial tension, this corresponds to the initiation of necking or the maximum of the force-displacement diagram. In DIEM, the MSFLD criterion seems to follow the ideas normally associated with forming limit diagrams, where the interest lies on the determination of the point where localized necking begins. This is noticeably reflected in the calibration of GISSMO's instability curve and of the MSFLD criterion, where the former lies below the latter. This is in accordance to experimental evidence where diffusive necking occurs before localized necking. It is also interesting to report that the authors first tried to calibrate the MSFLD initiation criterion based on the instability curve of GISSMO, i.e., they attempted to define DIEM's instability criterion for diffusive necking. However, when this was done, failure always took place excessively early and the only way to achieve a good correlation with experiments was by defining the MSFLD initiation criterion to act as the trigger for localized necking.

Still in the case of DIEM, the authors have not seen the necessity of defining the shear initiation criterion as it seemed, to some extent, redundant for the present case. As discussed in Section 4, one can define a single fracture curve for all triaxialities, i.e., for all possible stress states within the assumption of plane stress, and it is, to some extent, difficult to contemplate a situation where two independent damage initiation evolution mechanisms would provide much better results than only using a single one. A possible motivation would be a finer calibration of the post-critical behavior under shear stress states. However, at least for the geometries, element type and mesh size adopted in this contribution, no significant gain has been observed when activating the shear initiation mechanism together with the ductile initiation one, despite the small deviation in the simulation curve for the shear 0° specimen (Figure 4, bottom left). Perhaps, some other specimen geometries under shear-dominated stress states, as well as finer meshes, would emphasize the need for such mechanism for a more correct identification of DIEM damage and failure parameters.

One important point that should be mentioned is that both GISSMO and DIEM seem to lack uniqueness of solution, i.e., distinct calibrations may lead to similar results. Nevertheless, the range of possible solutions tends to decrease by increasing the number of experiments upon which the parameter identification is based. Furthermore, the engineer's experience also plays a role in order to get accurate calibrations. This aspect may be seen as a big disadvantage, but it is just a natural consequence of the flexibility that GISSMO and DIEM provide. Especially in the case of newer and modern metallic alloys, the observed material behavior is often difficult to describe using analytical failure functions that are based on microstructural mechanisms. Therefore, phenomenological approaches like GISSMO and DIEM are quite convenient for treating practical problems using current technological resources.

Concerning the sensitivity to spurious mesh dependence, the simulation of a large tensile specimen was carried out with the calibrated curves for both models. In the case of GISSMO, one has to additionally calibrate the element size dependent regularizing factors that scale the fracture curve in order to get a similar failure pattern upon mesh refinement. In DIEM, this is done intrinsically because of the definition of the plastic displacement in Equation (13) which is inherently dependent on the element characteristic size and must not be numerically calibrated. Figure 5 shows the results for 5 different meshes: 0.5 mm, 1.0 mm, 2.5 mm, 5.0 mm and 10 mm. It becomes evident that, for this particular specimen, GISSMO provides a near perfect match for all element sizes meanwhile some deviations are observed in DIEM's results. Nevertheless, it is difficult to affirm that one model is more accurate than the other in regard to mesh sensitivity. This stems from the fact that, beyond spurious mesh dependence, the inherent inaccuracy arising from coarse geometrical discretization is also present in the case of larger elements. Thus, the regularizing factors of GISSMO inevitably end up correcting both effects. Unfortunately, it is very difficult to say how much is due to spurious mesh dependence and how much due to coarseness of geometrical discretization. As a matter of fact, material instability as well as spurious mesh dependence are still subject of intense research among scholars.

Another important point when working with GISSMO and DIEM in LS-DYNA is related to the post-processing of these models. Most material models in LS-DYNA have history variables that allow the user to post-process and control quantities of interest like plastic strain, strain rate, etc. In this respect, GISSMO is more flexible and complete than DIEM. The former allows the user to output up to 14 history variables while the latter provides only 2 histories in the output (see [7]). In the case of GISSMO, quantities like damage, triaxiality, instability measure, etc., facilitate the scrutiny of results. When working with DIEM, the user can only check the damage initiation and damage evolution variables. Nevertheless, many quantities of interest (e.g., triaxiality, Lode angle parameter) can also be obtained in LS-PrePost®.

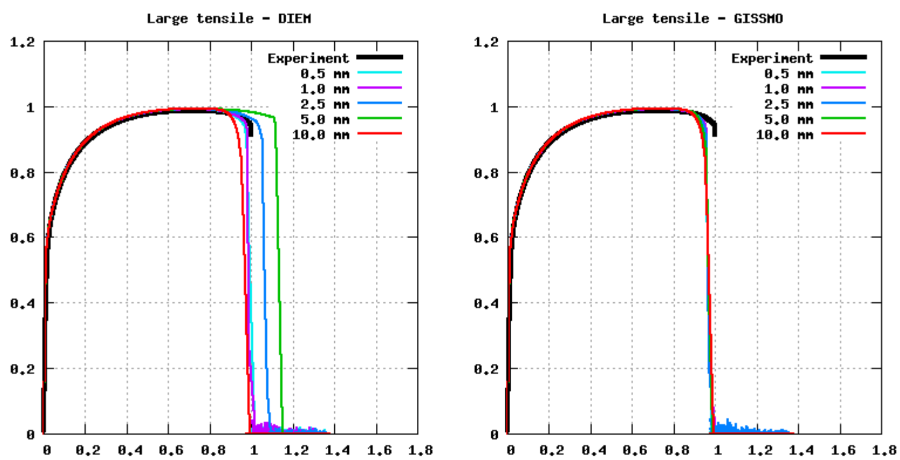

Figure 5: Results of the large tensile specimen with different mesh sizes.

7. Conclusions

Indeed, a more accurate modeling and prediction of fracture is essential for increasingly more efficient designs in the industrial scenario. In this respect, both GISSMO and DIEM seem to be useful options in order to predict ductile damage and fracture using current computational resources. In this paper, we discussed and compared both models in an attempt to better understand their differences. The calibration of a dual-phase steel has therefore been carried out and used as basis for the comparison.

As it has been shown throughout the paper, similar results can be achieved both with GISSMO and DIEM, despite contrasting differences in their formulation. For example, comparing the GISSMO equation for accumulation of damage with the equation for damage initiation of a single initiation criterion of DIEM, it is clear that GISSMO is more general due to the nonlinear damage accumulation. However, the lack of generality of a single initiation criterion in DIEM can be readily overcome if one defines multiple initiation criteria.

Concerning material post-critical behavior, both models provide alternatives to better match experimental data. GISSMO has a generalized coupling between damage and stress for which a fading exponent has to be calibrated to better capture the material behavior under strain localization. DIEM, on the other hand, assumes the less general coupling due to Lemaitre; however, it permits the definition of different damage evolution criteria that could also be used to model different post-critical behavior under different stress states. This is, in principle, an advantage over GISSMO, although in this work it did not help getting better results in the material calibration. However, it does not necessarily mean that the separate damage evolution criteria are not useful for the aforementioned purpose and further investigation is needed.

In view of the aforementioned differences, it is difficult to say that one model should be preferred over the other in forming and crash analysis. In the authors' opinion, it is more important to have representative experimental data for different stress states (upon which a consistent parameter identification has to be based) and to be aware of the capabilities and limitations of the damage/failure model adopted.

Finally, in the present work, strain rate effects have not been considered, despite their importance for the correct description of many metallic materials used in crash applications. In fact, this aspect is subject of current research by the authors whose results are to be presented in a future contribution.

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