SAE INTERNATIONAL

Application and Assessment of Bonora Damage Model for Geometry Transferability, Mesh Sensitivity and Plasticity Effects using MSC Marc

2014-28-0029

Published 04/28/2014

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CITATION: Srikanth, R., "Application and Assessment of Bonora Damage Model for Geometry Transferability, Mesh Sensitivity and Plasticity Effects using MSC Marc," SAE Technical Paper 2014-28-0029, 2014, doi:10.4271/2014-28-0029.

Abstract

A new damage model based on the Continuum Damage Model [Ref. 1] has been implemented in MSC Marc. It can simulate three process of damage evolution namely: void generation, growth and coalescence. By deactivating the element when a certain damage value is reached, users can now simulate a whole range of damage process; from micro crack to macro crack growth.

Micromechanical models like continuum damage mechanics (CDM) deal damage and failures as characteristics based on material and not as geometry configuration. These models are analyzed and validated only for simple geometrical configurations like uniaxial tensile bar, rotating beam specimen etc. A detailed assessment of the geometry transferability, mesh sensitivity and plasticity effects has been addressed only in a limited number of works.

In this paper, CDM approach, as proposed by Bonora is used to model and verify ductile damage processes for various stress states (triaxiality), and mesh sizes, thus validating its use across various models used in industries. Some preliminary results comparing MSC Marc results with experimental data are also discussed.

Introduction

New damage model has been implemented in MSC Marc based on Continuum Damage Model (CDM) developed by Bonora in Ref. [1]. This model has application in metal forming process where damage on the work piece has to be avoided. Typical applications of this model involve sheet metal forming, bulk forging and vehicle crashworthiness problems which require accurate prediction of damage accumulation in the material.

For other damage models available in Marc, the damage variable is calculated a posterior. This approach is useful as an indication when the material will fail, but it does not give a direct feedback so that the material quality is deteriorated and its load bearing capability is reduced. Gurson void damage currently available in Marc is effective only for certain class of materials (powder compaction processes) due to healing of voids. For metals under cyclic loading (in the plastic range), Gurson's model will not predict the experimentally observed continuous increase in damage, as the increase in voids ratio predicted in the tensile part of the cycle is reversed by the healing process predicted over the compressive part of the cycle.

Therefore a new Bonora damage model is implemented where the damage is coupled with the material stiffness.

Bonora damage model uses continuum damage mechanics (CDM) as the basis to derive the evolution of damage in the material. It takes the three processes of damage evolution in ductile metal (pore initiation, growth and coalescence) into account in a more explicit way as compared to other CDM damage models like Lemaitre.

Damage Models Available in MSC Marc

In ductile materials given the appropriate loading conditions, voids will form in the material, grow, and then coalesce, leading to crack formation and potential failure.

Damage models available in MSC Marc can be classified under

1. Abrupt failure Model:

Failure is predicted when a micromechanical variable, for instance the cavity volume fraction reaches a critical value characteristic of the material. (E.g. Principal stress model).

2. Porous metal plasticity Model:

Damage effects are accounted for into the plastic potential by a softening term, which is usually related to the void volume fraction ‘f’ in the material. (E.g. Gurson model).

In the modified Gurson model, the amount of damage is indicated with a scalar parameter called the void volume fraction ‘*f*’. Damage effects are accounted for into the plastic potential by a softening term, which is usually related to the void volume fraction in the material. The yield criterion for the macroscopic assembly of voids and matrix material is given by:

$$F = \left(\frac{\sigma}{\sigma_y}\right)^2 + 2 * q_1 * f^* \cosh\left(\frac{q_{2*}\sigma_{kk}}{2*\sigma_y}\right) - \left(1 + q_1 * f^*\right) \tag{1}$$

Where,

$$f^* = f \quad if \ f \leq f_c$$

$$f^* = f_c + (f_u^* - f_c)/(f_f - f_c) * (f - f_c) \quad if \ f > f_c$$

$$f_u^* = 1/q_1$$

The determination of parameters such as 1st yield surface multiplier (q_1), 2nd yield surface multiplier (q_2), critical void volume fraction (f_c), fracture void volume fraction (f_f) from experiments is extremely difficult. The modeling of the de-bonding process must itself be studied including the effect of differing particle sizes in a matrix. It is safe to say that such an experimental study is not possible. The above parameters must necessarily be obtained by intuition keeping in mind the meaning of the terms [Ref. 2].

3. Continuum Damage Mechanics Models:

Continuum Damage Mechanics Model features special internal variables representing, directly or indirectly, the density and/or distribution of the microscopic defects that characterize damage. In case of Lemaitre, it may be thermodynamic dissipation potential of the material during ductile damage (specific energy that is released when macroscopic fracture occurs) or in case of Banora damage model, reduction of stiffness is used as a basis for calculating damage.

Bonora damage model, like Lemaitre, uses continuum damage mechanics (CDM) as the basis to derive the evolution of damage in the material. It is also known as nonlinear CDM model. It takes the three processes of damage evolution in ductile metal (pore initiation, growth and coalescence) into account in a more explicit way. [Ref. 1]

The Bonora damage model utilizes the current state of the stress to determine the changes in Young's modulus with damage. In one dimension system, the damage is assumed to be completely closed under compression which means that the material temporarily recovers its virgin elasticity. The incremental damage is given as follows

$$dD = \frac{\propto * D_{cr}^{\frac{1}{\propto}}}{\ln \frac{\varepsilon_f}{\varepsilon_{th}}} * \left(D_{cr} - D\right)^{\frac{\propto - 1}{\propto * f(\eta)}} * \frac{1}{\varepsilon_p^+} * d\varepsilon_p^+ \tag{2}$$

Where ε_p^+ is the active equivalent plastic strain. The “active” equivalent plastic strain is the accumulated plastic strain during the tensile loading. This model has shown good correlation with experiments under cyclic compression-tension loading as discussed in the following sections [Ref. 3].
There are four materials parameters to be identified using experiments.

1. ε_{th} - Plastic strain threshold.
2. ε_f- Plastic strain at failure.
3. D_{cr} - Critical damage
4. ∝ - Damage exponent.

The damage starts to accumulate when the active equivalent plastic strain is greater than the threshold ε_{th} ε_f and D_{cr} - *are* the strain and damage at failure respectfully.

∝ is a factor to control how the damage evolution progresses. The procedure to identify these values is given in Ref. [1]. It also provides data for a number of materials.

Modelling Ductile Damage under Fully Reversed Cycling with Banora Damage Model in Marc

Analysis like sheet metal forming or bulk forging requires accurate prediction of damage accumulation in the material. Before the real structure is simulated, the engineer will need to validate the material models. These are normally done using the so-called round notch bar (RNB) tests.

Experiments are performed on RNB specimens of the SA 537 steel, whose dimensions and mechanical properties are reported in Figure. 1 and Figure. 2. [Ref. 3].

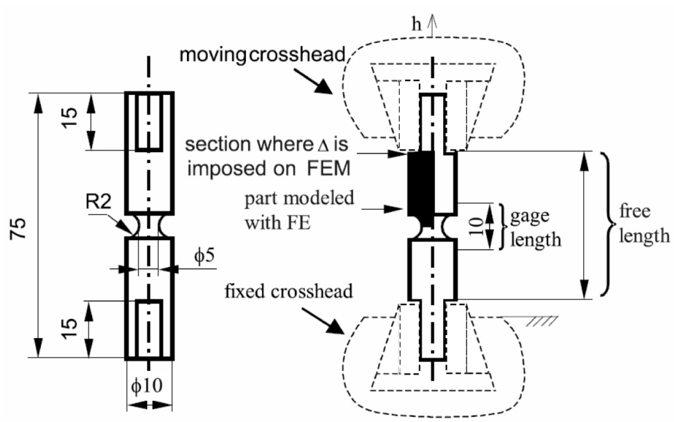


Figure. 1. An example of an RNB specimen. A finite element model is created to simulate this specimen and loading.

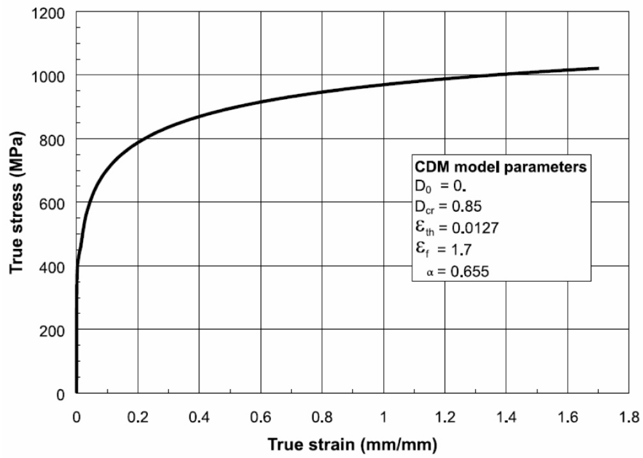


Figure.2. Material properties used for SA 537 steel

The loading cycle is characterized by an initial ramp to h = 0:25 mm at h* = 0:00625 mm/s followed by sinusoidal cycle between h = 0:375 mm and h = 0:125 mm at the frequency of 0.0125 Hz. A mesh size of 1 mm is used in FEA model at the damage locations.

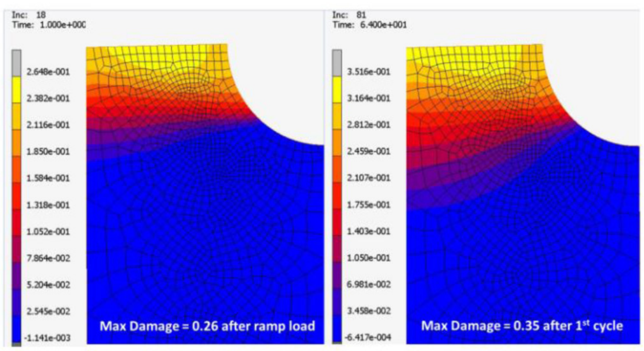


Figure. 3a. and Figure. 3b. Damage contours after ramp load and 1st cycle.

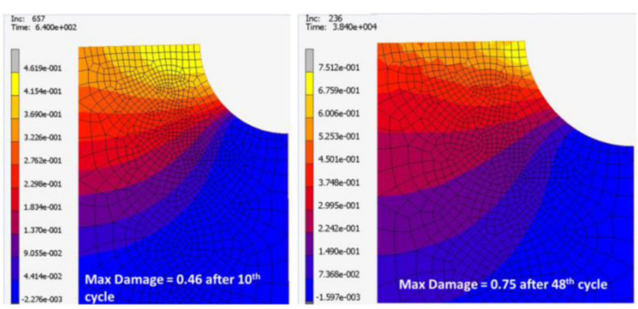


Figure. 3c and Figure. 3d. Damage contours after 10th and 48th cycle.

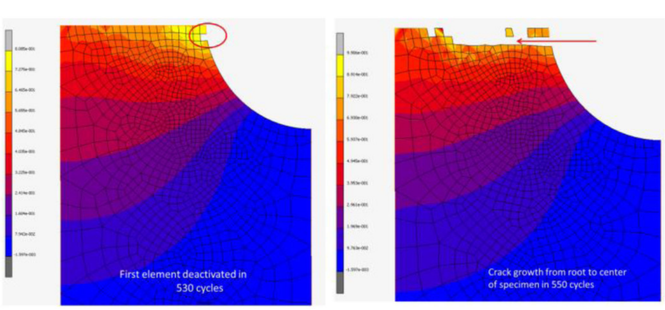


Figure. 3e and 3f. Damage contour showing element deactivation occurring from notch (530 cycles) to center (550 cycles) of specimen.

Table 1. Damage values and corresponding number of cycles.

Cycles	Damage
Ramp Load	0.26
1st cycle	0.35
10th cycle	0.48
48th cycle	0.75

In Figure. 3a-3d, the contour plot relative to damage distribution at the maximum load peak for different cycles is given showing the progressive transition of damage maximum location from the center to the notch tip.

Figure. 3e and 3f show the element deactivation occurring from root to center of specimen by activating element deactivation feature (when damage = D_{cr}) The damage values shown in Table.1 are in agreement with the experimental and FEA results given in Ref. [3]

Transferability of the Bonora Damage Model between Different Stress States (i.e. triaxialities)

Extensive work has been done in Ref.[4] with respect to Cyclic loading of different round notched bars (RNBs) in the plastic regime to study the evolution of plastic deformation and damage under multiaxial stress conditions. Two different mechanical situations are investigated by testing specimens with the same diameter of the notched section (8 mm) but notch radius of 2 mm (higher triaxiality) and 10 mm (lower triaxiality), respectively.

Damage properties used are given below

ε_{th} = 0.0213, ε_f = 1.2, D_{cr} = 1, α = 0.362

Elastic and Plastic properties for 20MnMoNi55 or A508 are given below

E = 204000 Mpa, μ = 0.29, Yield Stress = 472Mpa, R_0=429,

R_{inf} = 387.5, B = 0.1141, C = 11431, γ = 128.9

The tests were conducted under displacement-controlled (1 mm amplitude) condition with a ratio of minimum to maximum displacement of −1 and a frequency of 0.004 Hz for notch radius R = 2 mm and 0.008 Hz for notch radius R = 10 mm.

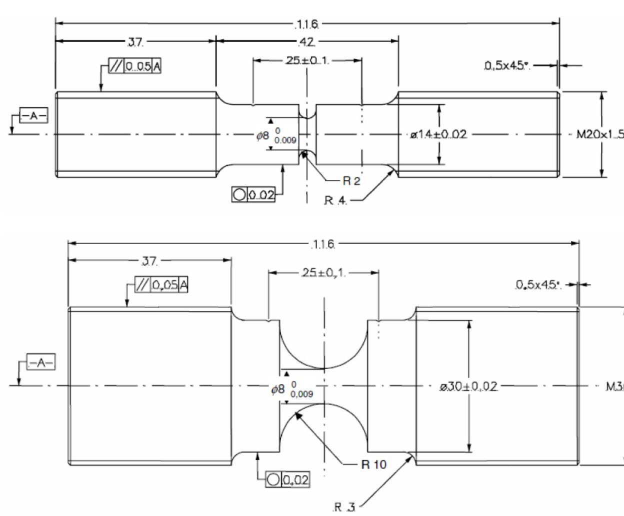
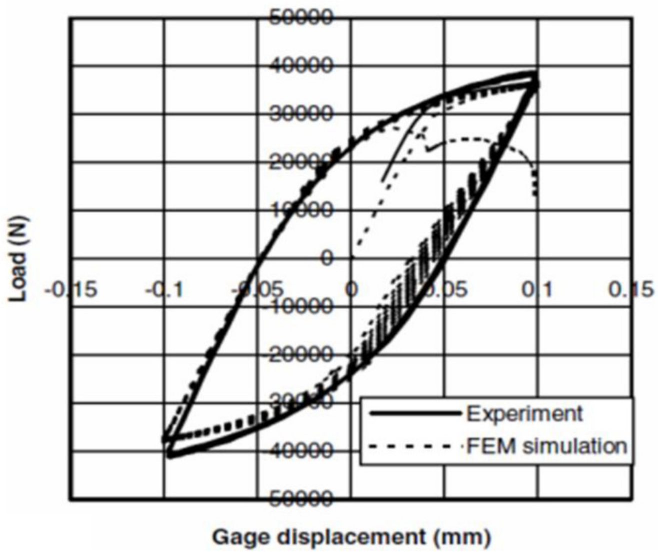


Figure. 4a and 4b. RNB Specimens (R2 and R10) used for testing.



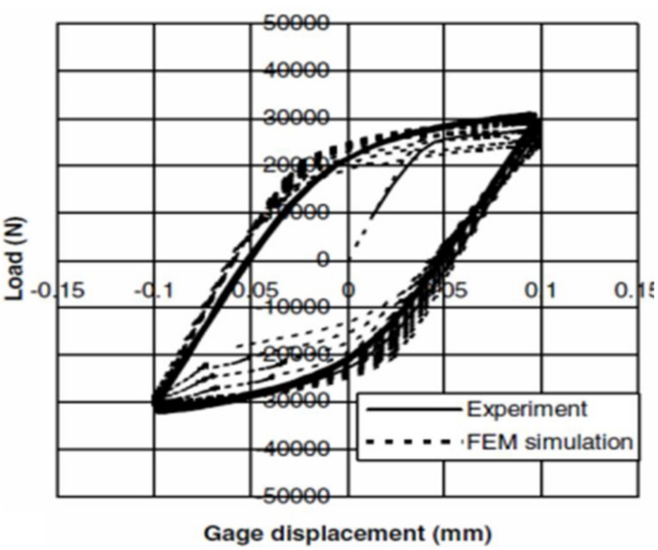


Figure. 4c and 4d. Cyclic Loading of RNB Specimens (R2 and R10) with 1mm amplitude during testing.

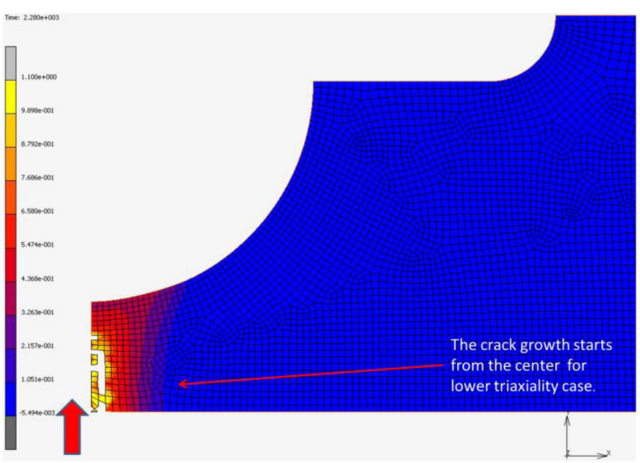


Figure. 4e and 4f.

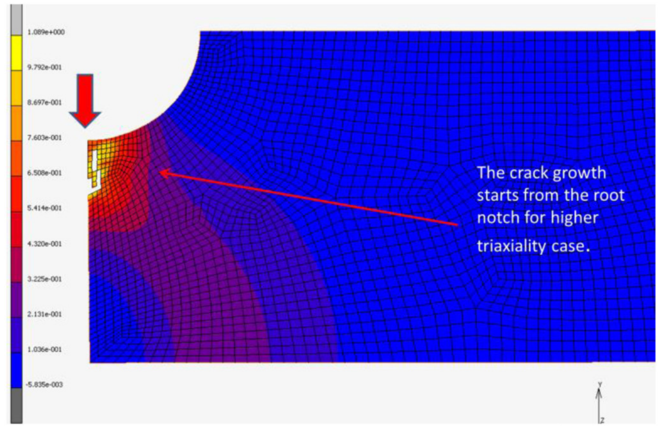


Figure. 4e and 4f. (cont.) Damage contour showing element deactivation for R10 and R2 specimen.

Figures above show that by activating element deactivation feature in Marc we see that, for lower triaxiality case (10 mm notch) we see that the crack growth starts from the center but for higher triaxiality case the crack growth starts from the root notch. This is in line with the experimental data in Ref. [4]

For lower triaxial case (10 mm root notch) the Marc results showed in Damage and failure at 23 cycles (i.e. the solution fails to converge) which matches with the FEA values in Ref. [4]. (22 cycles).

The fact that the experimental evidence suggests failure > 100 cycles for lower triaxiality geometry, can be explained by the fact that damage is always localized at the Centre, since plastic strain is fairly constant across the section. It seems therefore that the acceleration imparted by the triaxiality in the model is in this case too strong with respect to the experimental evidence (>100 cycles for failure.) Ref. [4].

For higher triaxial case (2mm root notch), the Marc results showed Damage and failure at 10 cycles which matches with the FEA and Experimental results in Ref. [4] (i.e. 12 cycles).

Bi-Axial Compression and Tension Test for Testing Softening Effect

In Bonora damage model, the coupling of the damage variable to the elastic properties of the material by using the effective Young's modulus, is derived using the strain equivalence hypothesis, the strain associated with a damage state under the applied stress is equivalent to the strain associated with the undamaged state under the effective stress. The effective Young's modulus is given as follows:

$E = E_0(1 - D)$, Where E_0 is the original Young's modulus.

The damage variable is not coupled directly to the plasticity potential as normally done (based on the strain equivalence hypothesis) in the CDM model. This is based on the proposition that the stress-strain plasticity data already contains implicitly the damage effect [Ref. 1]. This means that Bonora damage model does not generate additional material softening behavior.

To verify that two meshes with 15×30, 30×60, selectively integrated eight noded elements with (full integration) are analyzed as suggested in [Ref. 5]. To initiate a shear band an area in the bottom left-hand corner of the sample is assigned a slightly lower yield strength σyp (10% reduction) and the imperfect area is the same for each mesh (4×4 mm^2). A 1mm displacement is imposed at the top as shown in Figure. 5a

Young's modulus E =187GPa, Tensile strength =122.5 MPa the Poisson's ratio μ = 0.49 properties are used.

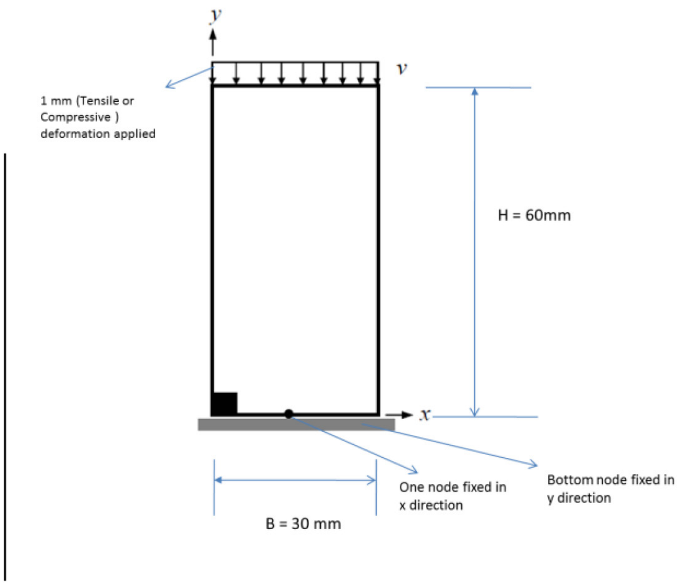


Figure. 5a. Model dimension for Bi-Axial tests.

Table. 2. Max equivalent plastic strain with and without damage

Test	***No. Of Elements***	***Max. Eq. Plastic Strain***		***Max.Damage***
		Without Bonora Damage	***With Bonora Damage***	
Biaxial compression test (course mesh)	15X30	2.40E-01	2.40E-01	1.227
Biaxial compression test (fine mesh)	30x60	3.60E-01	3.60E-01	1.29
Biaxial tension test(course mesh)	15X30	2.39E-01	2.40E-01	1
Biaxial tension test (fine mesh)	30x60	3.59E-01	3.60E-01	1.083

As the damage and plastic strain calculations are uncoupled, we see in Table-2 that the difference in plastic strains (with and without damage) is < 1%. This means that including Bonora damage model does not generate additional material softening behavior.

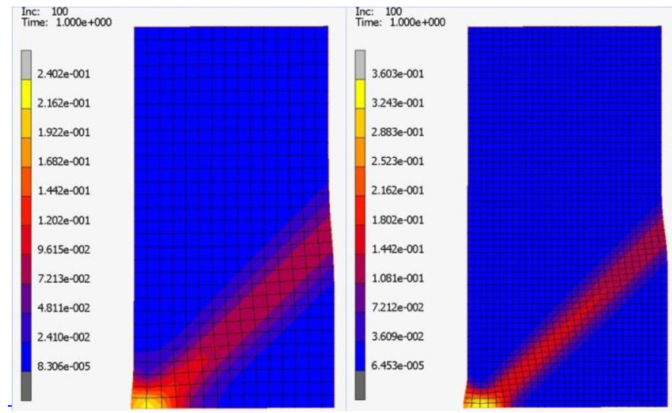


Figure. 5b and 5c. Compressoin test, total equivalent strain plot with damage value for course (15×30) and fine mesh (30×60) models.

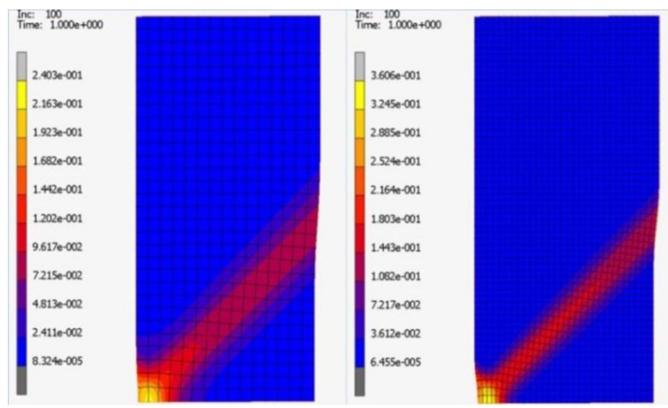


Figure. 5d and 5e. Tension test, total equivalent strain plot with damage value for course (15×30) and fine mesh (30×60) models.

We observe that the shear band has a finite width which is almost independent of the finite element size i.e. of 2 elements width in case of course mesh (15×30 elements) and of 4 elements width in case of fine mesh (30×60 elements) which confirms the mesh independency of results.

Bonora Damage Model Applied to Forming Models

Bonora damage accumulates its effect on material stiffness if and only if stress triaxiality is positive (the ratio of mean stress, to equivalent stress, $(\sigma_m/\sigma_{eqv}) > 0$), i.e. under compressive state of stress damage does not accumulate and its effects are inactive. [Ref. 4]

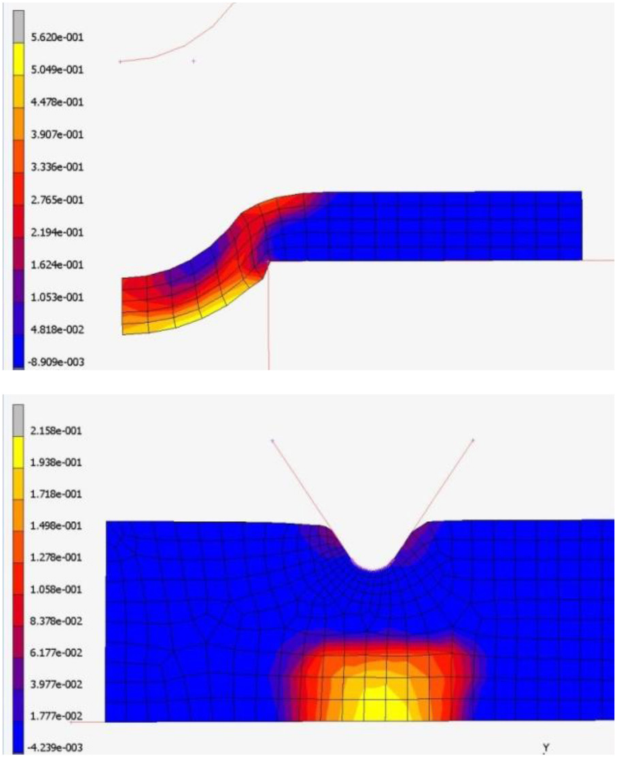


Figure. 6a and 6b. Damage contours for forming models showing max damage locations at regions where tensile stresses and strains are high.

This effect is seen in forming problems shown in Figure 6a and 6b. Max damage location is seen in locations where tensile stresses and strains are maximum. So it is advised to the user to be cautious while using Bonora damage model in cases where failure occurs due to compressive stresses and strains.

Conclusions

Three different micromechanical models were simulated with Bonora damage model in MSC Marc and it was found that the Marc results match with the experimental and FEA results given in [Ref. 3] and [Ref. 4].

In addition, the Bonora damage model in MSC Marc was tested and it was confirmed that additional material smoothing behavior was not generated due to Damage. This was done by inspection of plastic strain shear bands in two models with and without damage model. [Ref. 5].

Further by simulating actual forming problem, it was confirmed that under compressive state of stress, Bonora damage does not accumulate and its effects are inactive.

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Acknowledgments

Appreciation to the Automotive Research Association of India (ARAI) in association with Society of Automotive Engineers India (SAEINDIA) for organizing the International Conference on Automotive Materials & Manufacturing 2014 (AM&M).

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

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