

Calibration of the ductile damage model and comparison with the GTN model for high-toughness API X65 steel

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ABSTRACT

In this study, the material used was an API X65 sour steel. This steel exhibits high ductility, with a total fracture strain greater than 100% in a standard tensile test. Due to its high ductility and toughness, this steel is widely used in the oil and gas industry for pipeline applications. The Charpy V-Notch (CVN) test was selected for this study due to its wide applicability, low cost, and simplicity. In this test, the specimen is loaded under three-point bending. Several models for modeling ductile failure are available in the literature, the most commonly used being the Gurson-Tveergard-Needleman (GTN). In this work, the Ductile Damage (DD) model was applied to numerically reproduce the CVN test response for the X65 steel. This model is simpler than the GTN, requiring only two parameters: one describing the onset of damage and the other describing the damage evolution. This makes it an attractive choice for practical applications. The main issue of the DD model is determining the fracture onset to obtain its first parameter, particularly when used in tensile test, since fracture initiates at the center of the specimen. A methodology was proposed to calibrate the DD model using seven modified tensile geometries, with different stress triaxiality, to determine the first parameter. Subsequently, the second parameter was calibrated by varying its value until the curve was reproduced. The calibration using the GTN model was also performed to serve as a benchmark for comparison, since it is widely applied to ductile materials. The calibration results obtained with both models for the CVN geometry were compared. The reproduction of the CVN test curve was slightly better for the DD model than for the GTN. The maximum error for both models occurred around 10 mm of hammer displacement; for the GTN it was 13.7% and for the DD it was 7.7%. Additionally, the fracture morphology of the CVN specimen was also better described using the DD model than with the GTN model. In terms of fracture morphology, the remaining ligament exhibited the largest discrepancies. For the GTN, the smallest error was 11.95% and for the DD it was 7.86%. Considering the absorbed energy, the errors were smaller, 3% for the GTN and 1% for the DD. Overall, the results demonstrate the strong potential of the DD model and the proposed calibration methodology.

1. Introduction

The materials utilized in the oil and gas industry are characterized by high toughness. The Charpy V-Notch (CVN) energy for some API class steels exceeds 300 J, for example, the X80 used in [1] has 365 J of CVN energy. This value corresponds to the limit for the Leis correction of the Batelle Two-Curve Method [2], applied to predict failure in pipelines. This fact highlights the necessity for a more comprehensive approach to assess structural integrity, since experimental results alone may not be sufficient. The use of the finite element method to reproduce experimental data allows for the acquisition of additional

insights. The simulations should be nonlinear, including plastic properties and large displacements, together with a damage model capable of reproducing the failure of the analyzed specimens.

Several damage models have been reported in the literature. The Abaqus software library [3], employed in this study for numerical simulations, includes, among others, the XFEM (Extended Finite Element), GTN (Gurson-Tveergard-Needleman), and ductile damage (DD) models. The reproduction of CVN and DWTT (Drop Weight Tear Test) curves using different damage models has been widely reported by several authors [1,4–7].

For ductile materials, the GTN model is the most widely used damage model. For materials with higher ductility, some modifications

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of the GTN model have been proposed [8–10]. However, these modifications further complicate a model that already has several damage parameters to be calibrated, and require user-defined subroutines in Abaqus/Explicit [3]. In this context, the DD model is simpler than the GTN model. However, the available published data for the DD model is not as extensive as those available for the GTN model.

The advantage of the GTN is that its formulation is based on ductile fracture mechanics, modeling the fracture process. Furthermore, there is a large amount of published data using this model. The main disadvantage is the large number of parameters, which makes calibration challenging, especially for new materials. On the other hand, the DD model is computationally simpler, requiring only two parameters. However, the available data is limited, and additional experimental tests are necessary. In addition, the fracture onset parameters required for calibration are difficult to determine. In this context, this paper proposes a methodology for calibrating the DD model and to compare its results with those obtained using the GTN model, which is well established and widely applied in the literature.

This paper is organized into three parts. The first section describes the geometries and experimental results. The second section outlines the GTN model calibration methodology and its results. The third section introduces the DD model and compares it with the GTN.

2. Damage models

2.1. GTN model

The GTN model is based on ductile fracture, which models void nucleation, growth, and coalescence [11–13]. This model is widely used for ductile materials due to its effectiveness. The formulation of this model, Eq. (1), is based on the von Mises criterion, where σ_{vM} is the von Mises stress, σ_{LE} is the equivalent stress, σ_h is the hydrostatic stress, and q_1, q_2, q_3 are constitutive parameters [11,12]. The q_1 parameter accounts for the void interaction, q_2 the stress triaxiality effect, and q_3 the void volume fraction effect ($q_3 = q_2^2$) [13].

$$\frac{\sigma_{vM}^2}{\sigma_{LE}^2} + 2q_1 f^* \cosh\left(\frac{3q_2 \sigma_h}{2\sigma_{LE}}\right) - (1 + q_3 (f^*)^2) = 0 \quad (1)$$

The parameter f^* is defined as the effective void volume fraction and follows Eq. (2), where f is the instantaneous void volume fraction, f_c is the critical void volume fraction, and κ is a parameter that describes the acceleration of void growth. The variable f varies from the initial (f_0) to the void volume fraction at failure (f_F). κ is obtained from Eq. (3), whereas $\bar{f}$ is calculated using Eq.(4) [1].

$$f^* = f \text{ if } f \leq f_c \quad (2)$$

$$f^* = f_c + \kappa(f - f_c) \text{ if } f > f_c$$

$$\kappa = \frac{\bar{f} - f_c}{f_F - f_c} \quad (3)$$

$$\bar{f} = \frac{q_1 + \sqrt{q_1^2 - q_3}}{q_3} \quad (4)$$

Secondary nucleation is modeled using the parameter f_N , which represents the volume fraction of nucleating voids. New voids nucleate when the mean strain (ϵ_N) is reached, with a standard deviation (σ_N).

The main disadvantage of this model is the number of parameters that need to be calibrated. In addition to the parameters described above, this model depends on the mesh size (I_x), which can be considered another parameter. However, there are several studies in the literature for different materials, and the parameters can be found. Some of these studies for similar materials were conducted by [1, 4,6,7]. These studies served as the basis for the calibration performed in this paper.

2.2. Ductile damage model

The main advantage of the DD model is that it is simpler than the GTN. Only two parameters are required: one to describe the damage initiation criteria and a second to describe the damage evolution [3]. A third parameter could be the element size, since, like the GTN, this model is also mesh-dependent. Considering that this model has fewer parameters, it might be interesting for practical applications. One disadvantage is that the formulation is not based on void nucleation and growth as in the GTN model. In addition, there is also limited published data using this model.

The first parameter of the DD model is the plastic strain at the onset of damage $\bar{\epsilon}_D^{pl}$, which is a function of the stress triaxiality (η) and the plastic strain rate ($\dot{\epsilon}^{pl}$) [3,14–19]. The stress triaxiality is a key parameter in fracture mechanics [20–23], serving as one of the parameters in bi-parametric fracture [20]. The criterion for damage initiation is satisfied when the condition given in Eq. (5) is satisfied, where w_D is a state variable that increases monotonically with plastic deformation (ϵ^{pl}) [3].

$$w_D = \int \frac{d\epsilon^{pl}}{\bar{\epsilon}_D^{pl}(\eta, \dot{\epsilon}^{pl})} = 1 \quad (5)$$

After damage initiation in an element, the stiffness decreases according to a tensile separation law. For an elastic–plastic material with isotropic hardening, the damage causes the softening of the yield stress and the degradation of the elastic stiffness [3]. The damage evolution parameter (second parameter) describes the gradual degradation leading to failure [14]. This parameter can be either the equivalent plastic deformation at failure (when a finite element is deleted) or the energy dissipated at fracture, G_f [15]. This model is meshing-dependent, so these damage evolution parameters cannot be considered material-dependent [3]. This implies that the characteristic element length affects the calibration, and may also affect the results, as will be discussed in Section 5.2. For the DD model, the exponential form of the traction separation law may be used, and the damage evolution, d , is calculated using Eq. (6).

$$d = 1 - \exp\left(-\int_0^{\bar{u}_{pl}} \frac{\bar{\sigma}_y \cdot d\bar{u}_{pl}}{G_f}\right) \quad (6)$$

where $\bar{u}_{pl}$ is the plastic displacement and $\bar{\sigma}_y$ is the stress with damage. Fig. 1 illustrates the stress–strain behavior of a material undergoing damage. D is the total accumulated damage; when only the DD model is used, $D = d$. The yield stress and equivalent plastic strain at the onset of damage ($D = 0$) are σ_{y0} and $\bar{\epsilon}_0^{pl}$ [3]. While $D = 0$, $\bar{\sigma}_y$ is equal to the stress without damage ($\bar{\sigma}$). Beyond this point, $\bar{\sigma}_y$ decreases due to the damage, as a result of stiffness degradation (E), also illustrated in Fig. 1.

The main issue with this model is determining the point at which the damage initiates, in order to obtain the respective values of $\bar{\epsilon}_D^{pl}$ and η . This is particularly challenging when using the tensile test, as the crack nucleates at the center. The use of the maximum load point has been recommended in an Abaqus tutorial [16], being the instant when plastic instability begins, and is also used in [15]. For example, [24] considered the crack nucleates at the instant before strength begins to decrease. Nevertheless, for the GTN model, this corresponds to the instant of the onset of element deletion. Using the GTN model, the study presented in [25], also considered this instant. However, an element with an instantaneous void volume fraction equal to 0.1 was considered, instead of the center of the specimen. Therefore, this paper proposes an alternative methodology to find this point.

3. Experimental procedures

3.1. Methodology

The tensile and instrumented CVN tests were conducted at the Centro Universitário FEI and the Universidade Federal de Ponta Grossa,

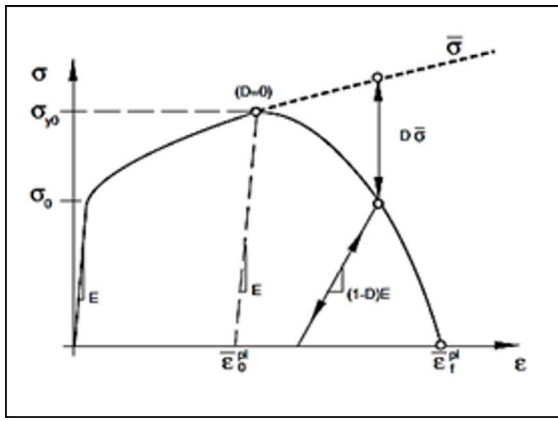


Fig. 1. Stress-strain curve considering progressive damage. The figure illustrates stiffness degradation as damage evolves.
Source: Adapted from [3].

respectively. For the tensile testing, the MTS 810 machine was used to obtain the load vs. displacement curve. Displacement was measured using an extensometer. In addition, two cameras were used to obtain the instantaneous diameter (minimum and maximum, due to anisotropy). A strain rate of 0.00025 s^{-1} was used for the tests. For the CVN, the instrumented Charpy pendulum, Zeick/Roel RKP 450 (450 J), was used to obtain the load vs. hammer displacement curve. These curves were numerically reproduced in Abaqus [3]. Additionally, the fracture morphology of the CVN specimens was also evaluated. For this purpose, the remaining ligament (RL), lateral expansion (LE), and lateral contraction (LC) were measured after the tests.

The material utilized is an steel class API X65 sour commonly employed in the oil and gas industry. The material's high toughness was demonstrated in Section 2.2. The Poisson ratio and density values were those recommended in the literature, mostly for the API 5L standard [26]. The adopted values were 0.33 and 7.85 g/cm^3 , respectively.

Seven different geometries were used in the tensile test, two following the standard ASTM E8 [27] and five modified geometries with notches. The standard geometries had minimum diameters of 12.3 and 10 mm, as illustrated in Fig. 2(a). The nomenclatures used for these specimens were S12 and S10, respectively. Two standard geometries were tested, one with the minimum diameter of the modified specimen and another with the maximum. This approach was adopted because it may be useful for future studies. The modified geometries were shown in Fig. 2(b). The radii of the notches were 10, 5, 3, 2, and 1 mm. The nomenclature employed was defined as N followed by the radius value. Three specimens of each geometry were tested, and average curves were obtained using MATLAB [28]. These curves were then used to calibrate the damage models.

The dimensions and tolerances for the CVN geometry can be found in ASTM E23 [29]. The procedure for the instrumented test is outlined in ASTM E2298 [30]. The twelve tests were performed at a temperature of 20°C , using a pendulum with a total mass of 32.85 kg and an initial speed of 5.234 m/s. Several parameters were recorded by the machine, including the displacement, the velocity of the hammer and, the force. This information was obtained from the hammer that is instrumented.

3.2. Tensile test results

The Young's modulus was obtained from the mean of the S12 and S10 tests and was approximately 205 GPa. The plastic properties were also obtained from the S12 and S10 tests. Due to the high ductility of this class of material, significant plastic strain develops after the ultimate tensile strength. Consequently, the entire true stress vs. plastic

strain curve was required. Therefore, image analysis was necessary to apply the Bridgman correction [31,32]. During the test, photos were acquired, and a MATLAB [28] routine developed by the group was used to analyze the images and obtain the minimum diameter of the section (a) and the radius of curvature (r) of the necking at several instants of the test, as shown in Fig. 3(a). These values were used to determine the true stress vs. plastic strain curve corrected using the Bridgman approach.

The average curve is shown in Fig. 3(b). The first point of the curve corresponds to the proportional limit. Using this limit, reproduction of the experimental curve was better than that obtained using the yielding stress limit. The proportional limit was defined as the point at which the correlation between stress and strain was less than 0.999. The points on this curve were used as input in numerical models.

The high ductility of this steel is observed in Fig. 4(a), where the minimum diameter for the specimen with low stress triaxiality (S10, N10 and N5) decreased considerably; however, the specimen did not fracture. The only specimens that separated in two parts were those with higher stress triaxiality (N2 and N1). One of the N1 samples is also shown in Fig. 4(a) to illustrate the fracture process.

3.3. CVN test results

None of the 12 specimens separated into two, so failure did not occur for the remaining ligament. This demonstrates the high strength and toughness of this steel. According to [29], this test is not suitable to evaluate the toughness. Therefore, actual value of CVN energy was not obtained; however, as the test was instrumented the curve force vs. displacement curve was also obtained. The average of the 12 curves can be numerically reproduced to better understand the test. The average curve was obtained using MATLAB [28]. In addition to the curve reproduction, the fracture morphology should also be reproduced in this case.

The values of the remaining ligament (LR), the lateral expansion (LE), and the lateral contraction (LC) for the 12 specimens were obtained using a measuring microscope. The average of these measurements was $LR = 5.797 \text{ mm}$, $LE = 11.975 \text{ mm}$, and $LC = 6.463 \text{ mm}$, respectively. The location of these measurements is shown in Fig. 4(b). They were measured on the surface of the specimens, i.e., tunneling in the remaining ligament is not considered. In an attempt to measure the equivalent LR, liquid nitrogen was used to complete the fracture of the specimen into two by brittle fracture. Two specimens were broken using the liquid nitrogen; however, as seen in Fig. 4(c), the fracture occurs in another direction. This happens because the region of the remaining ligament is too plastically deformed, causing strain hardening. Therefore, the crack propagation becomes more favorable along a different path than through the remaining ligament. For this reason, only the remaining ligament at the surface was measured.

4. GTN calibration

4.1. GTN methodology

The models were developed using Abaqus/Explicit [3] at Centro Universitário FEI.

The CVN geometry was modeled using the element C3D8R. This element is solid (3D), with eight nodes (8) and reduced integration (R). The reduced integration is required for the use the GTN model. Four minimum element sizes were selected: $0.2 \times 0.4 \times 1.0$, $0.1 \times 0.2 \times 1.0$, $0.05 \times 0.1 \times 1.0$, and $0.2 \times 0.4 \times 0.2 \text{ mm}$. The GTN model is mesh-dependent; therefore, the minimum element is applied to a region in the vicinity of the notch, approximately 2 mm from the X symmetry plane. This minimum element size was chosen based on values commonly adopted usually applied when the GTN model is used [1,4–7]. The mesh used for the GTN is the same as that the one used for the DD, so the number of nodes and elements is presented in Section 5.1.

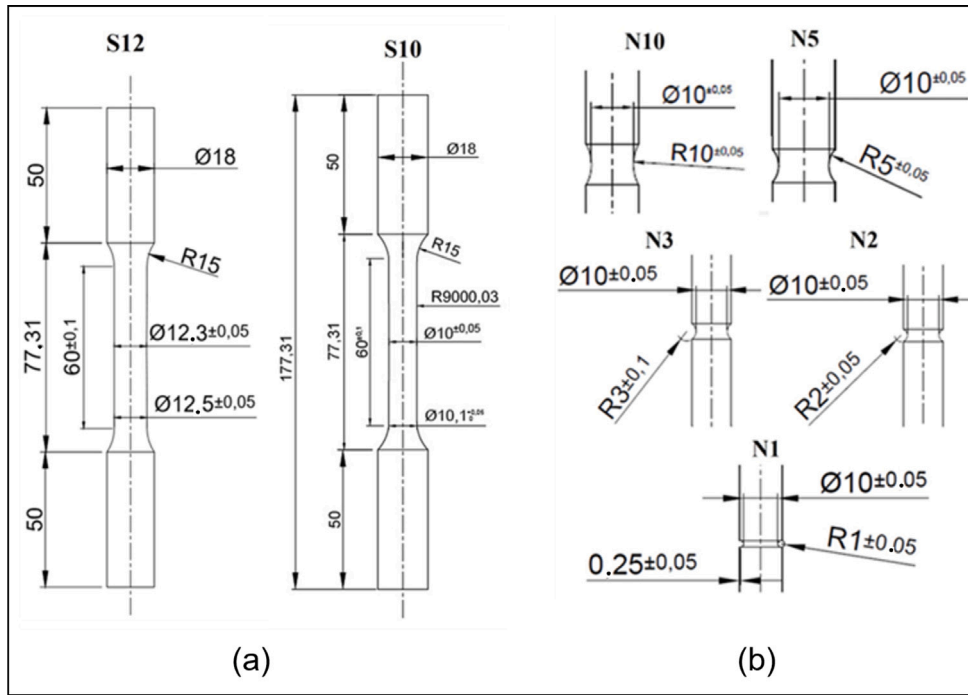


Fig. 2. Geometry of tensile test specimens: (a) Standard specimens; (b) Modified specimens. Dimensions in [mm].

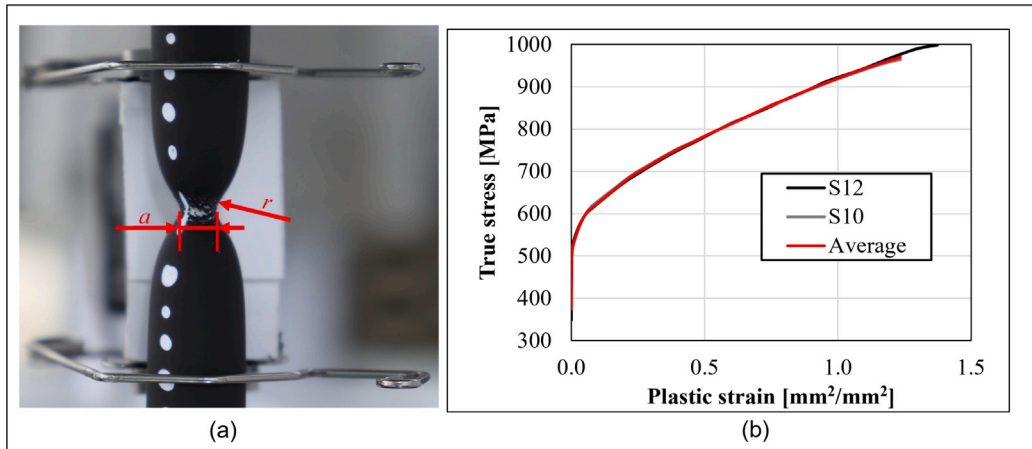


Fig. 3. (a) Experimental setup used for Bridgman correction, showing the necked region of the specimen, where a is the minimum radius and r is the curvature radius; (b) True stress vs. plastic strain curve obtained for specimens S10 and S12, along with the average response.

Symmetry boundary conditions were imposed in the X and Z directions, corresponding to the transverse and thickness directions of the specimen, respectively. The supports and the hammer were modeled as analytical rigid bodies. The supports were fixed, with all degrees of freedom set to zero. Only the displacement in the Y direction of the hammer was allowed, with an initial velocity of 5234 mm/s. This corresponds to the average initial velocity of the tests.

Contact interactions between the CVN and the rigid body (support and hammer) were also modeled, as this is an important source of non-linearity. The isotropic penalty method described in [3] was employed to model tangential behavior, and a coefficient of friction equal to 0.1 was incorporated. This value, derived from [5,6], is also suitable for the material studied.

To accurately simulate the dynamic nature of the CVN test, it is necessary to account for the strain rate effect. Abaqus [3] contains several models to simulate this effect. The Johnson-Cook model used in [5,6] was chosen, with the formulations presented in Eqs. (7) and

(8).

$$\dot{\epsilon}^{pl} = \dot{\epsilon}_0 e^{\left[\frac{1}{C} (R_t - 1) \right]} \quad (7)$$

$$\bar{\sigma} = 1 + C \ln \left(\frac{\dot{\epsilon}^{pl}}{\dot{\epsilon}_0} \right) \quad (8)$$

where $\bar{\sigma}$ is the yield stress, $\dot{\epsilon}^{pl}$ is the plastic strain considering the strain rate effect, $\dot{\epsilon}_0$ is the reference strain, C is a dimensionless quantity that depends on the material properties, and R_t is a dimensionless quantity representing the ratio between the apparent yield stress (with strain rate) to the yield stress without strain rate effects ($R(\dot{\epsilon}_0) = 1.0$).

In Abaqus [3], the strain-rate effect in the Johnson-Cook model requires only the parameters C and $\dot{\epsilon}_0$ are required, as shown in Eq. (8). The plastic properties used as input in the simulation were obtained from a tensile test with a velocity equal to 0.9 mm/min, with a gauge length of 60 mm, resulting in a strain rate ($\dot{\epsilon}_0$) of 0.00025 s⁻¹. With this value, based on [5,6] the value of C was calibrated for

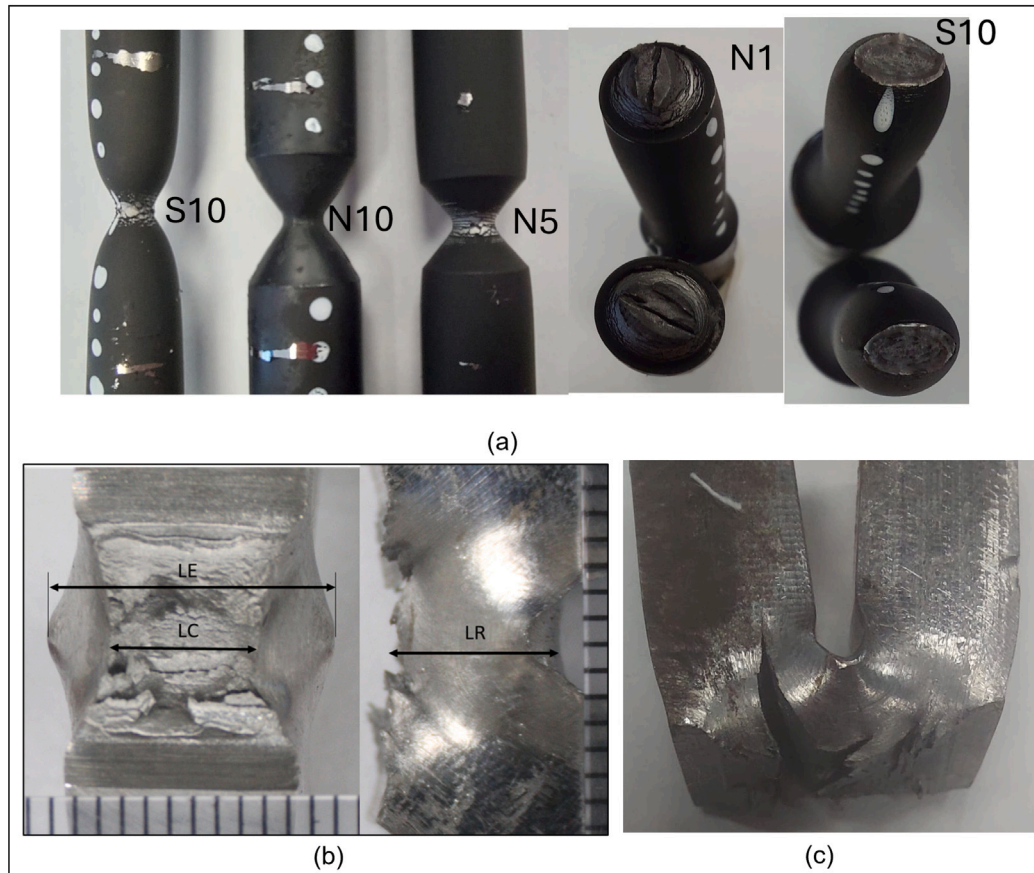


Fig. 4. Tested Specimens: (a) tensile specimens, showing different geometries (S10, N10, N5, and N1); (b) Charpy V-notch (CVN) specimen with indication of key geometric parameters (LE, LC, LR); (c) fractured CVN specimen after attempted splitting.

this material. Using the CVN geometry, without any damage model, only the material elastic and plastic properties and the calculated ϵ_0 were considered. Several simulations were performed by varying the C value. Then the initial portion of the curve (before the maximum force point) obtained from these simulation was compared with the experimental curve. The value that better described the initial portion of the experimental curve was 0.022.

The GTN properties were applied only at the refined region (with the minimum element size described above). This region was also used for the calibration of the DD model. The first mesh used was the one with the larger minimum element size ($0.2 \times 0.4 \times 1.0$ mm); several attempts were made to calibrate the CVN experimental curve using this mesh. This mesh was chosen first because the computational cost was smaller compared to the others. The variables that must be defined in Abaqus are: q_1 , q_2 , q_3 , r_0 ($r_0 = 1 - f_0$), f_c , f_F , f_N , ϵ_N and σ_N . The calibration process was manual; all variables but one were fixed, considering recommended values from the literature [1,4–7,13], and the value of the remaining variable was modified until the numerical curve approached the experimental curve. This process was performed for different variables. The variables q_3 and f_F are calculated, so they did not need to be calibrated. Among the secondary nucleation parameter (σ_N , ϵ_N and f_N), the parameter that most influenced the result is f_N , so this was the one chosen for calibration. Therefore, the calibrated parameters for this element size were: f_N , q_2 , f_c (consequently f_F), and q_1 (consequently q_3 and f_F). An additional approach to obtain results closer to the experimental data was to extrapolate the recommended limits for the variable; in this case the variable q_2 was calibrated. The process was repeated for the three remaining element sizes, using the combinations of fixed values that yielded the best results for the first mesh. The numerical curve is obtained using the linear displacement

on the Y direction of the hammer and the reaction force at the support. The force was multiplied by four due to symmetry.

The simulations were performed using Abaqus/Explicit with a time period of 0.01 s. This time period was sufficient for the specimen to pass through the supports. This is due to the fact that separation after contact was allowed when the contact properties were defined. When the specimen is no longer in contact with the support, the load decreases to zero; any further results after that can be neglected. Even though the specimens did not break completely into two parts during the test, they deformed enough to pass through the supports. This can be observed in the experimental curve, as the load decreases to zero at approximately 30 mm of hammer displacement.

4.2. GTN results

The calibrated parameters for the best calibration cases are shown in Table 1. The combination 1 to 10 used a minimum element size of $0.2 \times 0 \times 4 \times 1.0$ mm, for the combination 11 and 12, it was $0.1 \times 0.2 \times 1.0$ mm, for the 13 and 14, it was $0.05 \times 0.1 \times 1.0$ mm and the combinations 15 and 16, it was $0.2 \times 0.4 \times 0.2$ mm. The 17, 18 and 19 used an element size of $0.1 \times 0.2 \times 1.0$ mm that did not reproduce the experimental curve. Fig. 5(a) shows some of the calibrated curves for the element size $0.2 \times 0.1 \times 1.0$ mm. All curves coincide, and the same occurs with the others. The curves obtained numerically are close to the experimental curve. However, the difference between approximately 5 and 15 mm of hammer displacement is significant, and the numerical results overestimate the experimental load vs. displacement.

Fig. 5(b) shows the results for the more refined mesh, compared with the result of calibration 2. It is observed that refining the mesh in the thickness direction (from 1.0 to 0.2) does not affect the results

Table 1

Calibrated GTN model parameters obtained from different optimization runs. Each row corresponds to a parameter set evaluated during the calibration process. The parameters follow the standard GTN formulation.

	q_1	q_2	q_3	r_0	f_c	f_F	ϵ_N	σ_N	f_N
1	1.5	1.000	2.25	0.9997	0.030	0.1892	0.3	0.1	0.0018
2	1.5	1.025	2.25	0.9997	0.030	0.1892	0.3	0.1	0.0010
3	1.5	1.000	2.25	0.9997	0.021	0.1824	0.3	0.1	0.0010
4	1.6	1.000	2.56	0.9997	0.030	0.1788	0.3	0.1	0.0010
5	1.5	0.935	2.25	0.9990	0.030	0.1892	0.3	0.1	0.0010
6	1.5	1.065	2.25	0.9997	0.050	0.2042	0.3	0.1	0.0010
7	1.5	1.015	2.25	0.9997	0.050	0.1573	0.3	0.1	0.0010
8	1.5	1.055	2.25	0.9997	0.050	0.1528	0.3	0.1	0.0010
9	1.5	1.100	2.25	0.9997	0.100	0.1708	0.3	0.1	0.0010
10	1.5	0.940	2.25	0.9997	0.050	0.1528	0.3	0.1	0.0050
11	1.5	0.960	2.25	0.9997	0.030	0.1892	0.3	0.1	0.0010
12	1.5	1.000	2.25	0.9997	0.052	0.2057	0.3	0.1	0.0010
13	1.5	0.905	2.25	0.9997	0.030	0.1892	0.3	0.1	0.0010
14	1.5	1.000	2.25	0.9997	0.120	0.2567	0.3	0.1	0.0010
15	1.5	1.015	2.25	0.9997	0.030	0.2042	0.3	0.1	0.0010
16	1.5	1.000	2.25	0.9997	0.025	0.1854	0.3	0.1	0.0010
17	1.5	1.100	2.25	0.9997	0.030	0.1892	0.3	0.1	0.0010
18	1.5	1.050	2.25	0.9997	0.030	0.1892	0.3	0.1	0.0010
19	1.5	0.950	2.25	0.9997	0.030	0.1892	0.3	0.1	0.0010

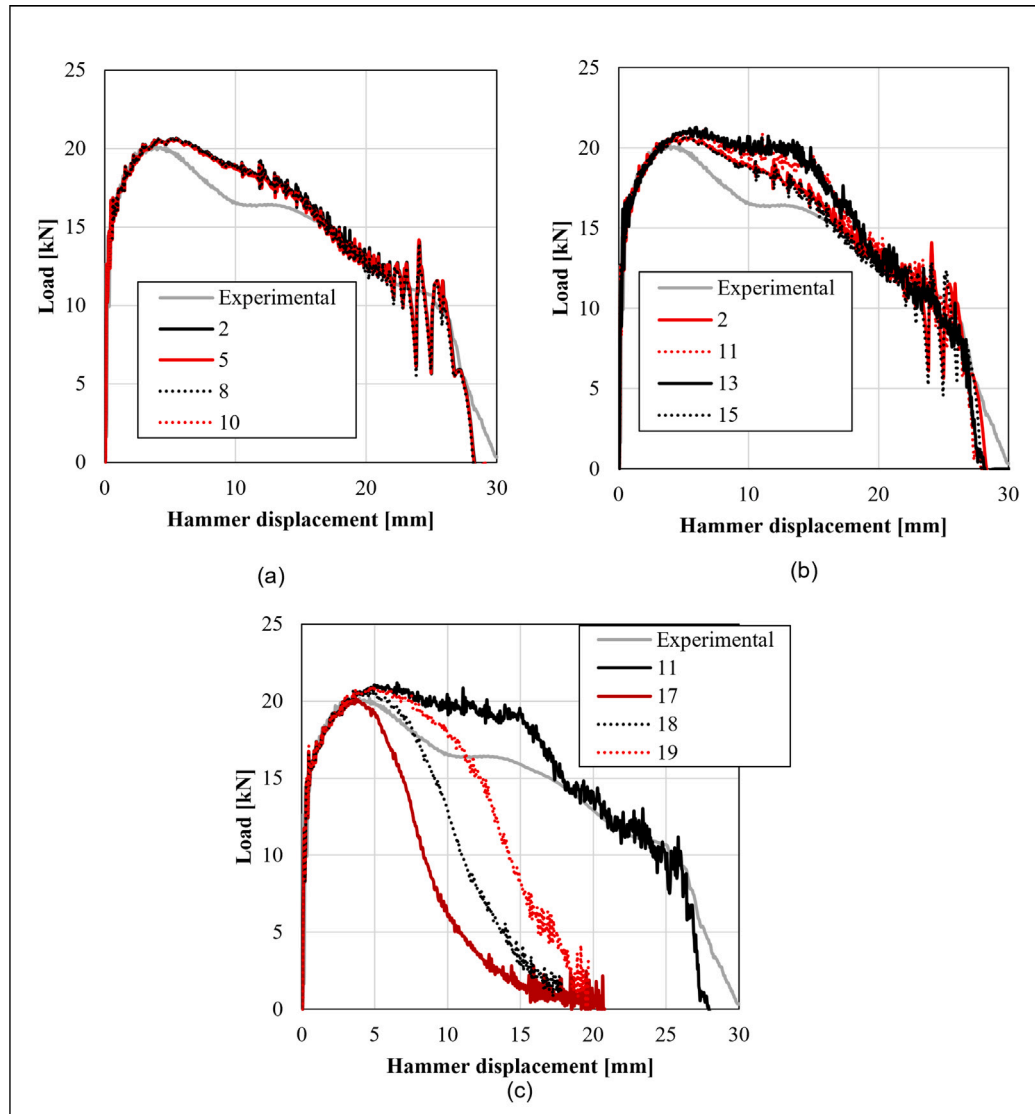


Fig. 5. Comparison between experimental and numerical load vs. hammer displacement curves using GTN model: (a) results for element size $0.2 \times 0.4 \times 1.0$ mm; (b) comparison with different element size; (c) results for element size $0.1 \times 0.2 \times 1.0$ mm.

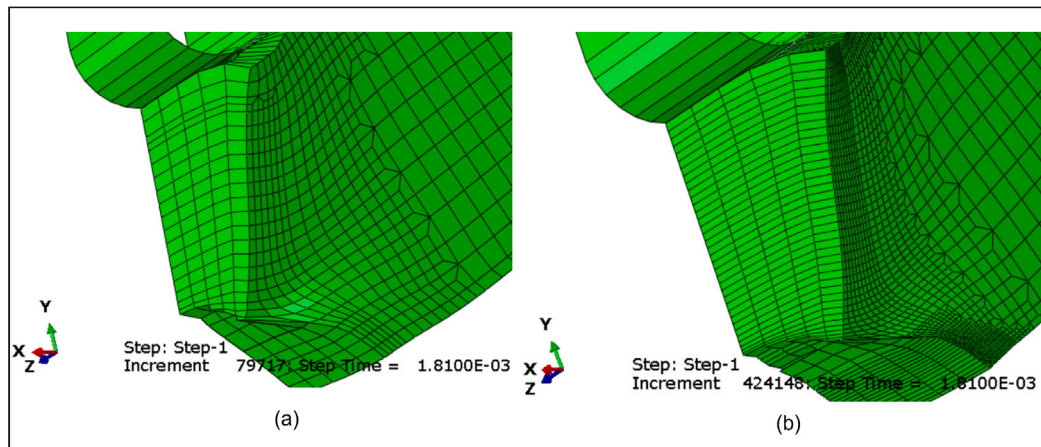


Fig. 6. Deformed configuration at approximately 10 mm of hammer displacement, the figure highlights the influence of mesh refinement on the deformation pattern: (a) mesh with element size $0.2 \times 0.4 \times 1.0$ mm (GTN2); (b) mesh with element size $0.1 \times 0.2 \times 1.0$ mm (GTN11).

(calibration 2 and 15). In contrast, the refinement in the two other directions affects the results. The best result was for an element size of $0.2 \times 0.4 \times 1.0$ mm, the coarsest mesh. This is approximately the value of element size used for some authors for CVN geometry [1,4,6,33]. This element size is more appropriate for the dimensions of this geometry. For a smaller geometry (e.g., punch test specimen), an minimum element size of 0.05 mm was used in [34].

In Fig. 5(b), it is also observed that, with a hammer displacement smaller than 10 mm, the curves for the minimum element size of $0.2 \times 0.4 \times 1.0$ mm are smoother than the other two curves. This may indicate that some dynamic effects introduce some noise in this region. That could be affecting the results, and making the calibration of this model more difficult. In Fig. 6, a comparison between the $0.2 \times 0.4 \times 1.0$ and $0.1 \times 0.2 \times 1.0$ mm minimum element size is shown, close to the notch, with approximately 10 mm of hammer displacement. The elements in this region deform in the Y direction, thereby decreasing their size. For the more refined mesh, the initial length in Y-direction is small, and when the deformation occurs, the size in this direction becomes even smaller. This means that the dynamic effects start earlier than for the less refined mesh. This highly deformed element may make it difficult for the GTN damage to occur within the element, and as a result, the element is not deleted. In Fig. 6, it is possible to observe that, at the same instant, the deleted elements correspond to a larger cross-sectional area for the coarse mesh than for the more refined mesh. After that point, the dynamic effects start to become significant for all minimum elements sizes due to the high deformation, and some elements start to lose element quality.

Fig. 5(c) shows three examples of curves for parameter combinations that did not reproduce the shape of the experimental curve (17, 18, and 19) using the minimum element size $0.1 \times 0.2 \times 1.0$ mm. This highlights a limitation where either the first 7 mm are well described (18) or the shape of the curve is described (11). Numerous combinations were tested, and the result was the same. Starting from a combination that causes the elements to fail faster (17) and changing the parameters to delay failure, the maximum load increases, while the difference between the experimental and numerical curves between approximately 7 and 17 mm also increases. None of the curves describe the results better than the minimum element size $0.2 \times 0.4 \times 1.0$ mm.

Considering the complexity of the model, the reproduction of the curve using the element size $0.2 \times 0.4 \times 1.0$ mm was considered satisfactory. The dimensions at the final instant of the simulation will be presented later in the paper.

Table 2

Mesh characteristics used in the numerical simulations of the CVN specimen, including minimum element size, number of elements, and number of nodes for each discretization level.

Minimum element size [mm]	N. of elements	N. of nodes
$0.2 \times 0.4 \times 1.0$	4470	5862
$0.2 \times 0.4 \times 0.2$	22,350	25,402
$0.1 \times 0.2 \times 1.0$	9410	12,303
$0.1 \times 0.2 \times 0.2$	47,050	52,130
$0.05 \times 0.10 \times 1.00$	17,895	22,251
$0.05 \times 0.10 \times 0.20$	89,475	96,411

5. DD simulations

5.1. DD methodology

The element type and size used for the DD model were the same as those adopted for the GTN methodology. A mesh discretization study was performed to evaluate the effect of the element size. Therefore, three minimum element sizes were selected: 0.2×0.4 , 0.1×0.2 , and 0.05×0.1 mm. As the elements used for the CVN geometry are three-dimensional, each mesh was generated with 5 (1.0 mm) and 25 (0.2 mm) elements along the thickness. Therefore, six different meshes were used for the calibration process. The total numbers of elements and nodes are presented in Table 2. For the CVN geometry, the symmetry, loads, and strain rate effect were the same as those described for the GTN model in Section 4.1.

The proposed calibration methodology for the DD aims to identify the onset of the damage. For this purpose, the seven tensile geometries were simulated, without any damage model, using Abaqus/Standard. The element used for tensile geometry is the CAX4R. This is a continuum element (C) with four nodes (4) and reduced integration (R). The minimum element size was 0.05×0.10 mm. The number of elements and nodes are shown in Table 3. These geometries were used only to determine the damage onset and to obtain the triaxiality and plastic strain at this point, to calibrate the CVN model. An axisymmetric model was employed to reduce the computational time for the tensile geometries. Furthermore, a Y-symmetry (specimen longitudinal direction) was also applied. At the top of the specimen, the only displacement that was not fixed was in the Y direction, where a 7 mm displacement was added.

The load vs. displacement curves were obtained numerically and compared with the experimental data. The load is computed as the sum of the reaction forces in the finite element model Y-symmetry nodes; the displacement is twice the average displacement in the finite element model Y-direction at the strain gauge set node. Four examples

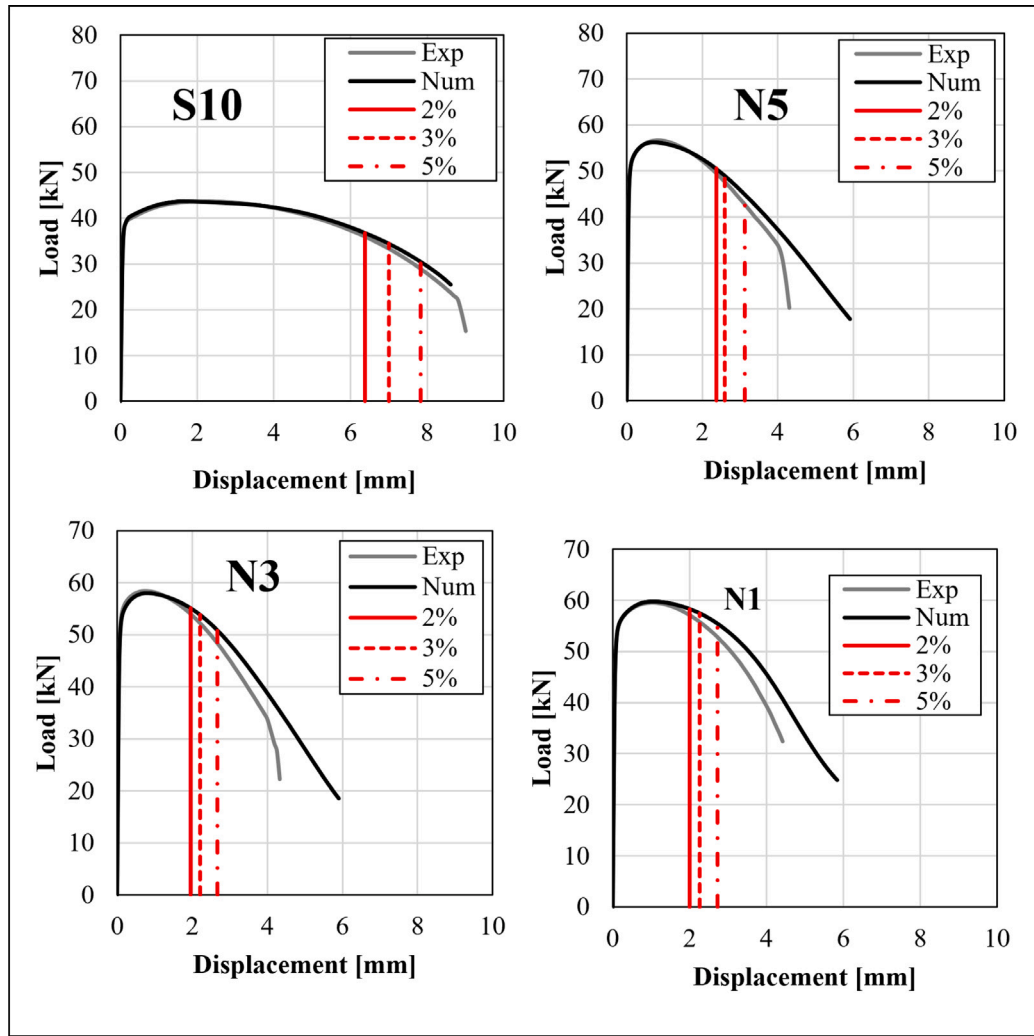


Fig. 7. Comparison between experimental (Exp) and numerical (Num) load vs. displacement curves for specimens S10, N5, N3, and N1. The vertical lines indicate displacement differences corresponding to 2%, 3%, and 5% deviation between the curves.

Table 3

Numbers of elements and nodes for the tensile specimen. S10 and S12 correspond to standard geometries, while N10, N5, N3, N2, and N1 correspond to notched geometries.

	N. of elements	N. of nodes
S10	6754	6988
S12	7312	7570
N10	11,019	11,314
N5	11,619	11,921
N3	6916	7162
N2	8006	8261
N1	10,906	11,900

are shown in Fig. 7, one standard (S10) and three notched (N5, N3, and N1). When the differences between the numerical and experimental curves are 2%, 3%, and 5%, this is defined the damage onset, as shown in Fig. 7. The nomenclatures used are DD2, DD3, and DD5, respectively. This instant is determined using a MATLAB [28] routine, and Fig. 8(a) shows a flowchart representing the logic behind the program. When the difference between the experimental and numeric curve is approximately 2%, 3% or 5%, depending on the input value, the routine identifies this instant in simulation as the damage onset and extracts the information at this point. The three instants lie between the maximum strength used in [22,23] and the crack onset used in [24,25].

The displacements shown in Fig. 7 correspond to the onset of damage. At the instant identified by the routine, the average stress triaxiality (η) and plastic strain (ϵ_{pl}) were obtained from the elements containing the nodes where Y-symmetry was applied, as shown in Fig. 8(b). This information was obtained using the same routine shown in Fig. 8(a). The routine extracts the plastic deformation using the variable PEEQ, as shown in Fig. 8(c); however, the stress triaxiality is obtained using the von Mises stress and hydrostatic stress. These values of each element in Y-symmetry are summed and then divided by the number of elements. The routine returns with the information of the hammer displacement at that instant, and the average values of η and ϵ_{pl} . This routine was used for each geometry and difference percentage. The points obtained were plotted as shown in Fig. 9 (red). Subsequently, these points were approximated by an exponential curve; the equations of the fitted exponential curves are also shown in Fig. 9.

Using the equations, with η varying between -0.5 and 2 , the values of ϵ_{pl} are calculated. These values were chosen because, for η lower than -0.5 , the ϵ_{pl} is significantly high and the damage will not begin. The value is so high that it was not shown in Fig. 9, due to scale limitation. On the other hand, close to 2 , the ϵ_{pl} approaches zero. These points (black) are used as the damage initiation parameters. The values of ϵ_{pl} for all three calibrations are shown in Table 4. The effect of the strain rate was not evaluated in this paper; however, it can be addressed in future studies.

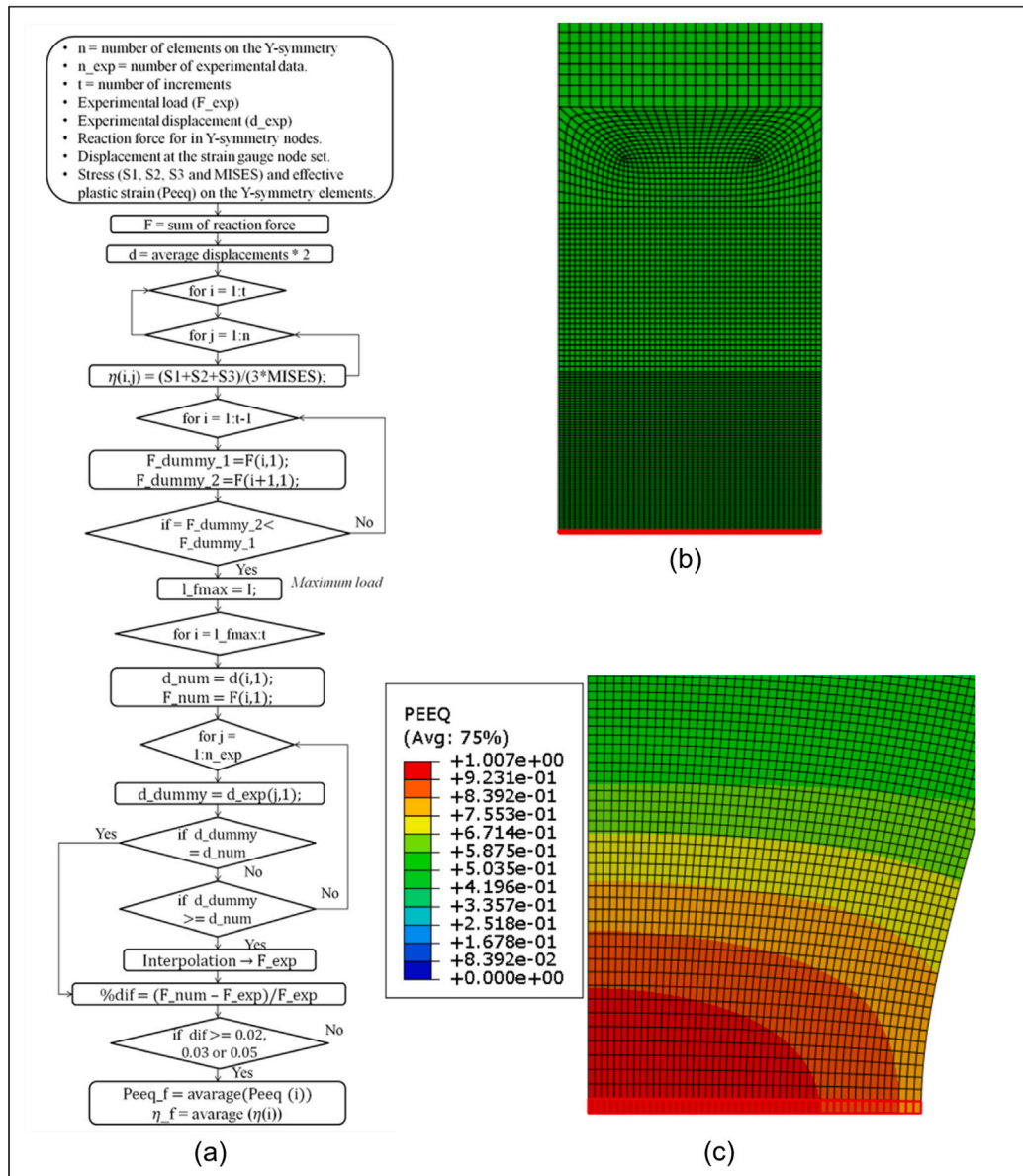


Fig. 8. Routine implemented in MATLAB: (a) flowchart of the algorithm used to compute the relevant parameters; (b) finite element mesh highlighting the elements considered in the analysis; (c) distribution of equivalent plastic strain (PEEQ) for specimen S10 at a selected deformation stage for the DD5 calibration.

Only part of the geometry was refined using the minimum element size described above. The damage properties were applied only in this region, as shown in Fig. 10. This region is the same size as the region used for the GTN calibration to enable comparison of the two models. The simulation was also done in Abaqus/Explicit using a time period of 0.01 s, the same as that used for the GTN, and data points after the load reached zero were also disregarded.

The damage evolution parameter, G_f , was calibrated until the description of the experimental curves. This means that, until the numerical curves matched the experimental curve, the value of this parameter is adjusted. For example, if the numerical curve lies above the experimental curve, the value of G_f must be reduced, since the energy required for element deletion must be smaller. The displacement corresponds to the Y-displacement of the hammer times -1, and the load is four times the reaction force at the support. The damage evolution formulation chosen is exponential, which implies that the stress decreases exponentially with the displacement. In Abaqus [3] the damage evolution needs to be defined in terms of energy with an exponential softening law.

5.2. DD results

The calibrated parameter (G_f) for the DD is shown in Table 5. As discussed earlier, a study of the mesh effect was made. Therefore, 18 calibrations were performed for this model. The results for different element sizes considering the DD3 calibration are shown in Fig. 11. The element size did not significantly affect the calibrated curve. To compare the different damage initiation parameters, the results for the mesh $0.1 \times 0.2 \times 0.2$ mm are shown in Fig. 11. After the calibration, it was observed that the shape of the curve for the different meshes and onset points was the same. The region around 10 mm was not well described, resulting in a slight overestimation of the load, as observed for the GTN model. The comparison with the GTN model and the best option for the DD will be discussed in the next section.

The calibrated parameter for DD2 is bigger than for the other DD calibrations. This indicates that, the sooner the damage initiates, the larger the G_f becomes. This occurs because the G_f is the energy absorbed after the damage starts; therefore, for the element deletion to

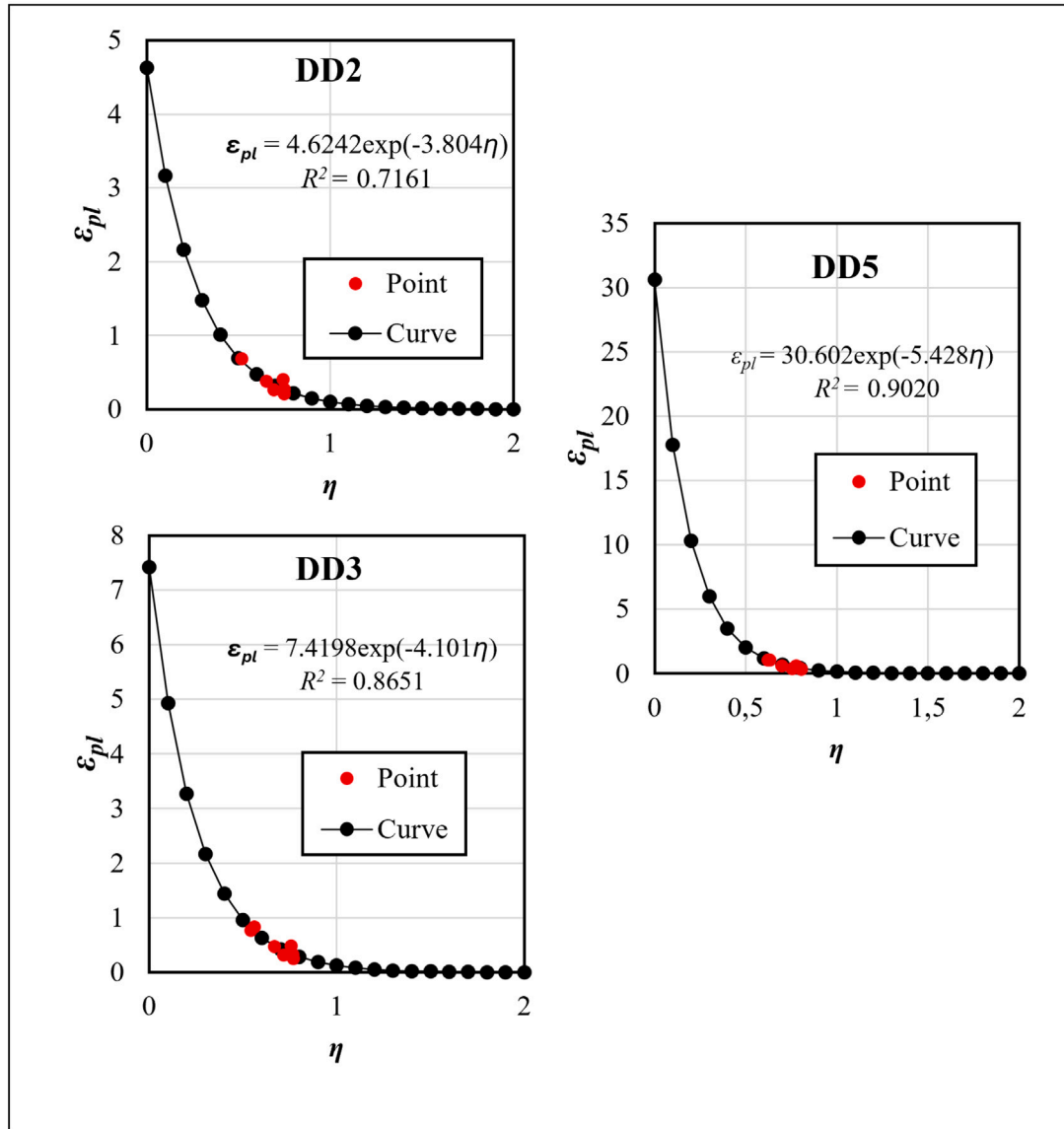


Fig. 9. Plastic strain at damage onset vs. stress triaxiality for different conditions. Experimental data points are shown together with the corresponding exponential fits used to describe the relationship between ϵ_{pl} and η .

occur at the same instant for the three calibrations, G_f must be higher when damage initiates at a lower strain (DD2).

The value of G_f varies depending on the minimum element size, if the mesh changes, the value must be recalibrated. To evaluate the effect of the mesh, Fig. 12 shows how the calibrated value of G_f varies with the element volume. As expected, the smaller the element volume, the smaller the G_f . Smaller elements represent a smaller volume in the geometry; therefore, to obtain the same result, the element must fail first. However, it is also possible to observe that, for smaller volumes, the change is greater than for the larger volume. For example, comparing the minimum element size of $0.2 \times 0.4 \times 1.0$ mm (0.08 mm³) with $0.1 \times 0.2 \times 1.0$ mm (0.02 mm³), besides the fact that the volume decreased to 1/4 of the larger volume, the change in G_f is negligible. However, for the minimum element size of $0.1 \times 0.2 \times 0.2$ mm (0.004 mm³) compared with $0.05 \times 0.1 \times 0.02$ (0.001 mm³), besides the decrease in volume is also being 1/4, the decrease in the G_f is greater. This indicates that the sensibility for this parameter is higher for more refined meshes.

The same procedure applied in Fig. 6 for the GTN was also applied to the DD and shown in Fig. 13. As the damage progresses, the element stiffness decreases; therefore, the deformation in the element is

greater than that observed for the GTN. The element stiffness decreases progressively as damage evolves until it reaches zero, at which point the element is deleted. This leads to two effects. First, the contribution of the element that has reached the damage initiation criterion to the global stiffness decreases as the simulation progresses. Therefore, elements in which the damage has begun contribute less, resulting in a reduction in the load. Another consequence of the decrease in element stiffness is that the deformation in the element is greater, as shown in Fig. 13, when compared with the GTN (Fig. 6). These more deformed elements no longer contribute significantly to the simulation because their stiffness is significantly reduced. The next section presents a comparison between the two models.

6. Results comparison

First, two of the best results of GTN and DD models were compared with the experimental curve (average of the 12 tested curves). This is shown in Fig. 14(a). The curves considered were the DD5 with an element size of $0.1 \times 0.2 \times 0.2$ mm, and the calibration 2 for the GTN. The DD model provides a better description of the experimental curve

Table 4

Plastic strain at damage onset (ϵ_{pl}) as a function of stress triaxiality (η) for different conditions, used as input parameters for the DD model calibration.

η	DD2	DD3	DD5
-0.5	30.9788	57.6651	461.7693
-0.4	21.1767	38.2656	268.3428
-0.3	14.4762	25.3925	155.9391
-0.2	9.8957	16.8500	90.6191
-0.1	6.7646	11.1814	52.6605
0.0	4.6242	7.4198	30.602
0.1	3.1610	4.9237	17.7834
0.2	2.1608	3.2672	10.3342
0.3	1.4771	2.1681	6.0054
0.4	1.0097	1.4387	3.4899
0.5	0.6903	0.9547	2.0280
0.6	0.4718	0.6335	1.1785
0.7	0.3226	0.4204	0.6849
0.8	0.2205	0.2790	0.3980
0.9	0.1507	0.1851	0.2313
1.0	0.1030	0.1228	0.344
1.1	0.0704	0.0815	0.0781
1.2	0.0481	0.0541	0.0454
1.3	0.0329	0.0359	0.0264
1.4	0.0225	0.0238	0.0153
1.5	0.0154	0.0158	0.0089
1.6	0.0105	0.0105	0.0052
1.7	0.0072	0.0070	0.0030
1.8	0.0049	0.0046	0.0017
1.9	0.0034	0.0030	0.0010
2.0	0.0022	0.0020	0.0006

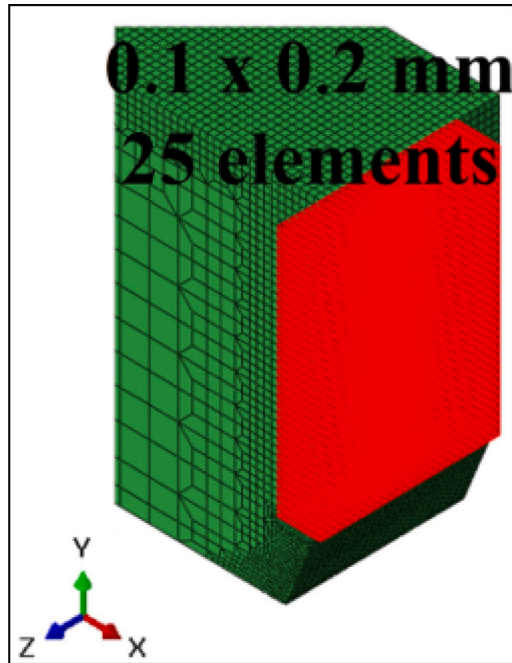


Fig. 10. Finite element model highlighting the region where the damage model parameters (DD and GTN) are applied.

Table 5

Calibrated fracture energy (G_f) values for the CVN specimens as a function of element sizes. Element sizes are given in the format length $\times$ width $\times$ thickness (in mm).

Size [mm]	0.2 $\times$ 0.4 $\times$ 1.0	0.2 $\times$ 0.4 $\times$ 0.2	0.1 $\times$ 0.2 $\times$ 1.0	0.1 $\times$ 0.2 $\times$ 0.2	0.05 $\times$ 0.10 $\times$ 1.0	0.05 $\times$ 0.1 $\times$ 0.2
DD2	630	510	600	365	410	270
DD3	600	490	570	350	380	220
DD5	570	470	520	335	350	220

than the GTN model; however, the difference is not so conclusive. Both models accurately captured the curve shape. The repeatability of this test was very good; in Fig. 14(a) the standard deviation for some points of the experimental curve is also shown. Between the peak point, at 3.95 mm, until approximately 12.5 mm, both numerical curves remain outside the standard deviation. However, for the GTN, the results fall within the standard deviation after 15 mm.

Another relevant evaluation concerns the peak load point. For the experimental curve, it happens at 3.95 mm of hammer displacement with a peak load of 20.17 kN. For the GTN, it occurs at 4.10 mm with 20.62 kN, and for the DD at 4.03 mm with 20.11 kN. Once more, the DD result is slightly closer to the experimental curve than the GTN. Another relevant aspect is the damage at the element. For the GTN the f_c at the element close to the notch at the center of the specimen occurs at 2.70 mm of hammer displacement. The f_F value for this element occurs at 3.96 mm, meaning that the first element is deleted before the load peak. On the other hand, the same element for the DD reaches 50% of damage at the same 2.70 mm; however, it is only deleted at 7.70 mm. As discussed earlier, even though the element is not deleted, the progress of damage causes the stress at the element to decrease for the DD model. Although it takes longer for the element to be deleted than for the GTN model, the damage at the element causes the drop in the load curve to start earlier for the DD model than for the GTN model.

In Fig. 14(b) the percentage error between experimental and numerical load is shown at selected instants of hammer displacement. The errors above the zero line indicate that the load obtained from simulation is greater than the experimental value. The closer the point is of that line, the better the agreement. The second instant corresponds to the peak point of the experimental curve (3.95 mm). The error is small at this point; however, it increases until reaching a maximum and then decreases again. The maximum error occurs around 10 mm, being approximately 13.7% for GTN model and 7.7% for the DD model. Observing Fig. 14(b), the error for the DD model is smaller than for the GTN model for almost all points, with the exception of 20 mm. However, at this point the element is so deformed that significant noise is observed in the curves, as shown in Fig. 14(a)).

Another way to quantify the results is by using the absorbed energy, defined as the area under the force vs. hammer displacement curve. Using numerical integration (trapezoidal method) to integrate the curves shown in Fig. 14(a), the obtained values were 421.35 J for the experimental curve, and 434.64 and 424.12 J for GTN and DD, respectively. The corresponding errors are 3% for the GTN model and 1% for the DD model.

The load vs. hammer displacement curve obtained using several combinations using GTN and DD models results in similar responses as shown in Fig. 5(a), Fig. 5(b), Fig. 11(a), and Fig. 11(b). Therefore, using geometrical measures after the test (RL, LE, and LC) may help to identify the combination that best describes the fractured specimen. In order to obtain these values from the numerical results, a routine in MATLAB [28] was implemented. This routine extracts the required values from the node coordinates. The remaining ligament (RL) was obtained considering the free surface of the specimen, similar to what was done for the broken specimen, as shown in Fig. 4(b). As explained in Section 3.2, it was not possible to measure the equivalent LR from the specimen.

The percentage error (%) in the experimental results are presented in Table 6. The percentage errors for lateral deformation (LE and LC) are relatively small. The main discrepancy is associated with the remaining ligament. The best results for the DD model were obtained with element sizes of 0.2 $\times$ 0.4 $\times$ 0.2 mm and 0.1 $\times$ 0.2 $\times$ 0.2 mm using DD5. Although the curves are similar, differences arise when the remaining ligament is considered.

The values for the GTN calibrations (2, 11, 13, and 15), are also shown in Table 6. The percentage errors for the RL are higher than those obtained for DD5 using the same element size. The smallest

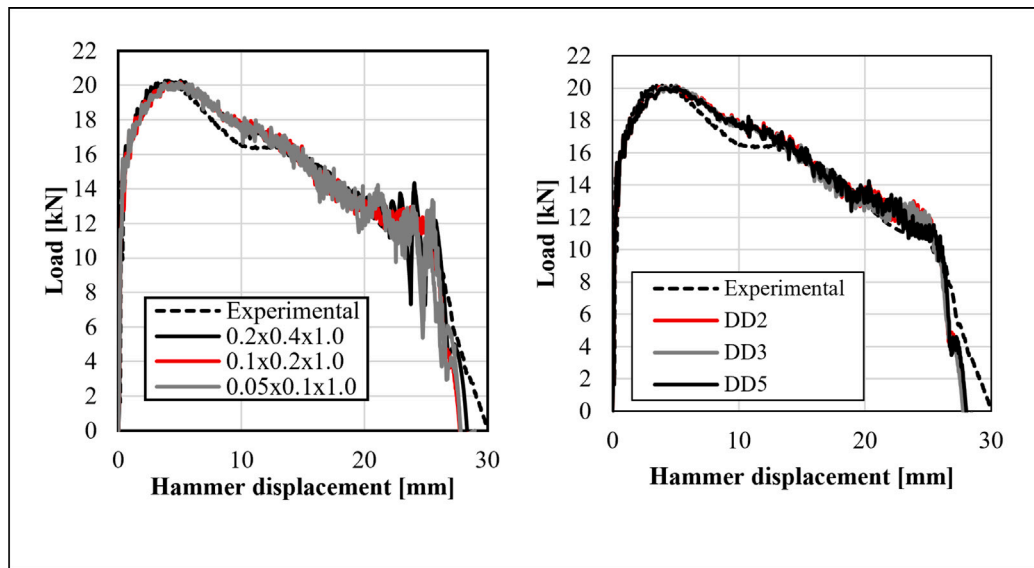


Fig. 11. Comparison between experimental and calibrated numerical load vs. hammer displacement curves for the CVN specimen.: (a) results obtained using calibration DD3 for different element sizes; (b) comparison between different calibration approaches for an element size $0.1 \times 0.2 \times 0.2$ mm.

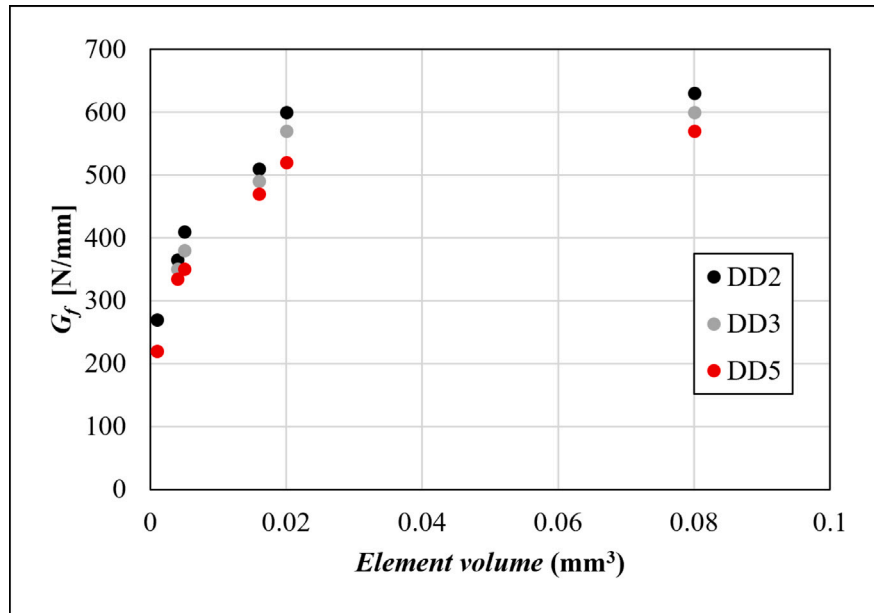


Fig. 12. Variation of the calibrated G_f as a function of element volume for different damage onset conditions (DD2, DD3, and DD5).

errors were obtained with the element size $0.2 \times 0.4 \times 0.2$ mm. It is noteworthy that, although the force vs. hammer displacement curves are very similar, significant differences are observed in LE, LC, and RL. This reflects a characteristic of damage models: different parameter combinations may result in comparable global structural responses (force vs. hammer displacement curves); however, the local response may differ significantly, highlighting the importance of validation using geometric measurements.

Another evaluation was performed to evaluate how the absorbed energy varies with the decreasing remaining ligament. For the DD model, calibration DD5 was used with an element size of $0.1 \times 0.2 \times 0.2$ mm, and the calibration 15 was used for GTN model. The results are shown in Fig. 15. The experimental data contain only two points: the initial point with zero energy and the final point corresponding to the total absorbed energy.

The remaining ligament measured on the surface of the curves closely matches the experimental curve for both models. However, the result for the DD model is slightly more accurate in terms of the equivalent remaining ligament. In Fig. 4, it is possible to observe that the tunneling at the specimen is relatively low; therefore the equivalent remaining ligament should be close to the surface measurement. As shown in Fig. 16, considering the tunneling effect, the result obtained using the DD model appears to be closer to the experimental result than that obtained with the GTN model. The color contours represent the distribution of equivalent plastic strain (PEEQ).

The tunneling is more pronounced for the GTN model than for the DD model, although the calibrated curves and the surface RL are similar. Damage initiates and progresses earlier in the elements located at the center of the specimen, where the stress triaxiality is higher, which explains the more pronounced tunneling observed for the GTN model. For DD, the damage also initiates at the elements in the central

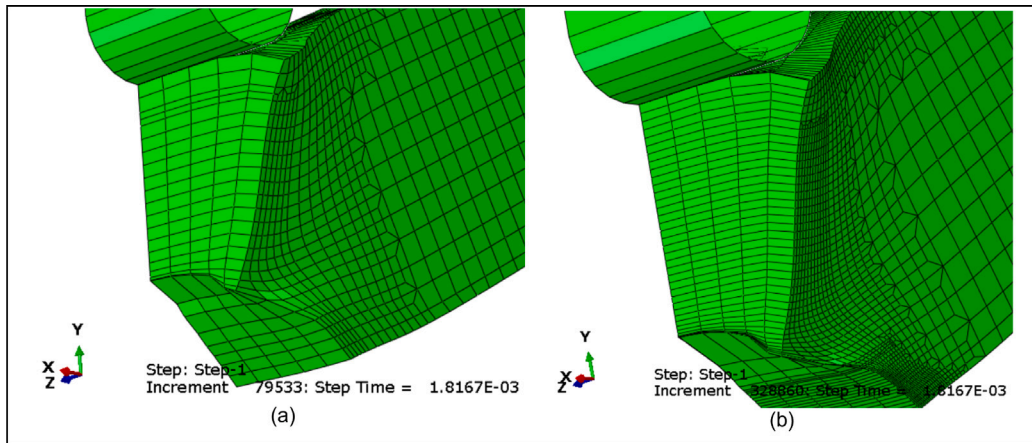


Fig. 13. Deformed configuration at approximately 10 mm of hammer displacement, using the calibration DD5. (a) Minimum element size of $0.2 \times 0.4 \times 1.0$ mm; (b) minimum element size of $0.1 \times 0.2 \times 1.0$ mm.

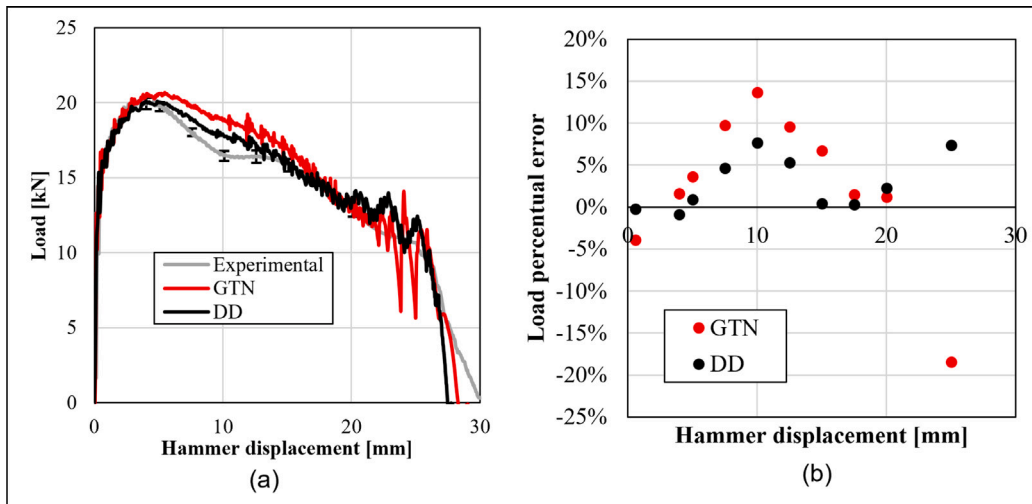


Fig. 14. Comparison between GTN and DD models: (a) load vs. hammer displacement curves; (b) load percentage error as a function of hammer displacement.

region. Fig. 17 shows the damage parameters and the corresponding tunneling for both models. For the GTN, the governing parameter is the VVF , which represents the instantaneous void volume fraction. The element is deleted when it reaches the critical value f_F , which for the GTN2 is equal to 0.1892 as shown in Table 1. For the DD, the governing parameter is $SDEG$, which represents the damage evolution parameter, and the element is deleted when it reaches 1.0. Damage using the DD initiates in a larger number of elements in the longitudinal direction compared to the GTN model. This indicates that the stress decreases over a larger area for the DD model. The GTN, on the other hand, exhibits more localized damage at the crack tip; therefore, a larger number of elements must be deleted to obtain a force vs. displacement curve similar to the DD model.

7. Conclusions

The material used in this study, API X65 sour, exhibits high toughness, as demonstrated by both the standard tensile and CVN tests. The total fracture strain in the standard tensile test exceeded 100%, and the CVN machine used had an energy capacity of 450 J, which was insufficient to break the specimens.

A key challenge of the DD model is identifying the damage onset point for calibration, a methodology was proposed to calibrate this model using modified tensile specimens, with different stress triaxiality.

For this purpose, differences between the experimental and numerical curves (without damage model) of 2%, 3%, and 5% (DD2, DD3, and DD5) were adopted. These results were used to define the first parameter of the damage model, after which the second parameter was calibrated until the experimental curve was accurately reproduced. The calibrated values vary depending on the mesh, indicating that recalibration is required for different meshes. The range studied was from $0.2 \times 0.4 \times 1.0$ mm to $0.05 \times 0.1 \times 0.2$ mm. For this geometry, the best results were obtained with a minimum element size of $0.1 \times 0.2 \times 0.2$ mm. Elements sizes larger than $0.2 \times 0.4 \times 1.0$ mm are too coarse to properly capture the failure of this geometry. However, smaller elements (less than $0.05 \times 0.1 \times 0.2$ mm), the computational cost is higher, and numerical instability may occur due of the dynamic effects within the element.

In addition to the calibration of the DD model, several calibration attempts were also performed for the GTN model to enable comparison between the two approaches. The numerical curve using the DD was closer to the experimental results than that obtained with the GTN model. The best result for the DD model corresponded to DD5 with a minimum element size of $0.1 \times 0.2 \times 0.2$ mm, and for the GTN model, it was obtained with a minimum element size of $0.2 \times 0.4 \times 1.0$ mm. When comparing both models with the experimental curve, the maximum error occurred at approximately 10 mm of hammer displacement for both models. The maximum error was 13.7% for GTN model

Table 6

Percentage error (%) between numerical and experimental results for different calibration approaches and element sizes.

Minimum element size	Calibration	LE	LC	RL
0.2 × 0.4 × 1.0 mm	GTN(2)	6.63	0.74	13.22
0.2 × 0.4 × 1.0 mm	DD2	7.07	19.13	17.24
0.2 × 0.4 × 1.0 mm	DD3	7.15	15.25	17.75
0.2 × 0.4 × 1.0 mm	DD5	7.19	11.22	11.01
0.2 × 0.4 × 0.2 mm	GTN(15)	5.23	1.27	11.95
0.2 × 0.4 × 0.2 mm	DD2	6.12	15.67	15.67
0.2 × 0.4 × 0.2 mm	DD3	6.09	10.84	17.22
0.2 × 0.4 × 0.2 mm	DD5	6.01	10.46	7.86
0.1 × 0.2 × 1.0 mm	GTN(11)	6.59	16.43	31.07
0.1 × 0.2 × 1.0 mm	DD2	7.71	7.73	16.41
0.1 × 0.2 × 1.0 mm	DD3	7.60	5.40	18.33
0.1 × 0.2 × 1.0 mm	DD5	7.79	6.78	10.74
0.1 × 0.2 × 0.2 mm	DD2	7.71	7.73	16.41
0.1 × 0.2 × 0.2 mm	DD3	7.60	5.70	18.33
0.1 × 0.2 × 0.2 mm	DD5	6.40	12.86	9.80
0.05 × 0.10 × 1.00 mm	GTN(13)	5.91	44.18	47.52
0.05 × 0.10 × 1.00 mm	DD2	7.64	8.74	17.54
0.05 × 0.10 × 1.00 mm	DD3	7.31	5.99	21.85
0.05 × 0.10 × 1.00 mm	DD5	7.48	5.22	17.73
0.05 × 0.10 × 0.20 mm	DD2	6.20	14.34	11.54
0.05 × 0.10 × 0.20 mm	DD3	7.31	11.13	16.99
0.05 × 0.10 × 0.00 mm	DD5	6.26	12.93	19.91

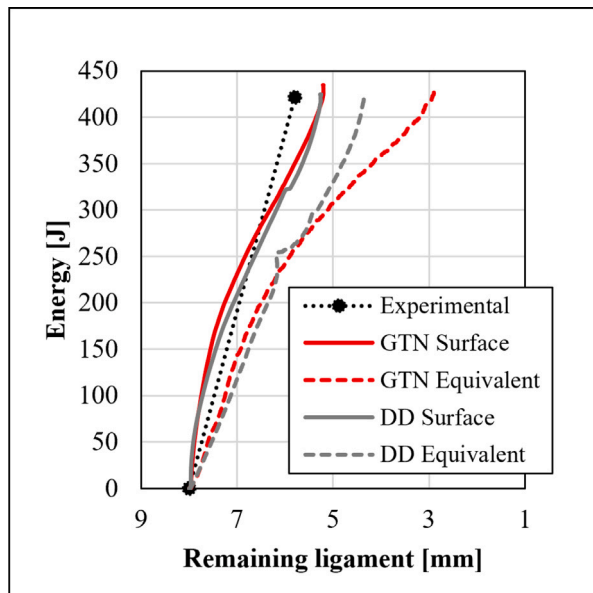


Fig. 15. Absorbed energy as a function of remaining ligament for experimental and numerical results, comparing GTN and DD models using surface and equivalent approaches.

and 7.7% for the DD model. Overall, the DD provided slightly better agreement with the experimental results than the GTN model.

The tested CVN specimens did not fracture completely; therefore, it was also verified whether the geometry after the tests was accurately reproduced. This was done by comparing the dimensions at the final simulation stage with those measured from the tested CVN specimens. The largest relative error was observed in the remaining ligament. In this case, the DD5 calibration yielded the smallest error among all simulations (7.86%), whereas for the GTN model, the smallest error was 11.95%.

The absorbed energy was also evaluated. In this case, the errors were even smaller: 3% for the GTN model and 1% for the DD model.

The results demonstrate the strong of the DD model for the studied API X65 sour steel and CVN geometry. This material exhibits high toughness and is widely used in pipeline applications. In addition, based on the different tensile geometries, the proposed calibration methodology proved to be simple and effective to apply. Further studies are recommended to incorporate strain rate and Load Angle effects at the damage initiation parameter to further enhance the predictive capability of the model.

8. Future work

Further complexity may be introduced into the DD calibration methodology. First, the strain-rate effect should be included in the calibration procedure; therefore, additional tensile tests at different strain rates are required. Subsequently, the Lode Angle effect may also be considered by testing different tensile geometries with different loading angle.

With the calibrated models, additional information can be extracted from the CVN test. For example, the instrumented test enables the evaluation of how the absorbed energy varies with the hammer displacement by integrating the load vs. hammer displacement curve. However, the model makes it possible to analyze how this energy varies with the remaining ligament. Furthermore, a deeper understanding of the energy involved in the fracture process may contribute to improved failure prediction in structural applications such as pipelines.

CRediT authorship contribution statement

L.d.S. Pereira: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **M. Mattar Neto:** Writing – review & editing, Supervision, Conceptualization. **G.H.B. Donato:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language editing and grammar improvement. The authors reviewed and edited the content as necessary and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Leticia dos Santos Pereira reports financial support was provided by National Council for Scientific and Technological Development. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

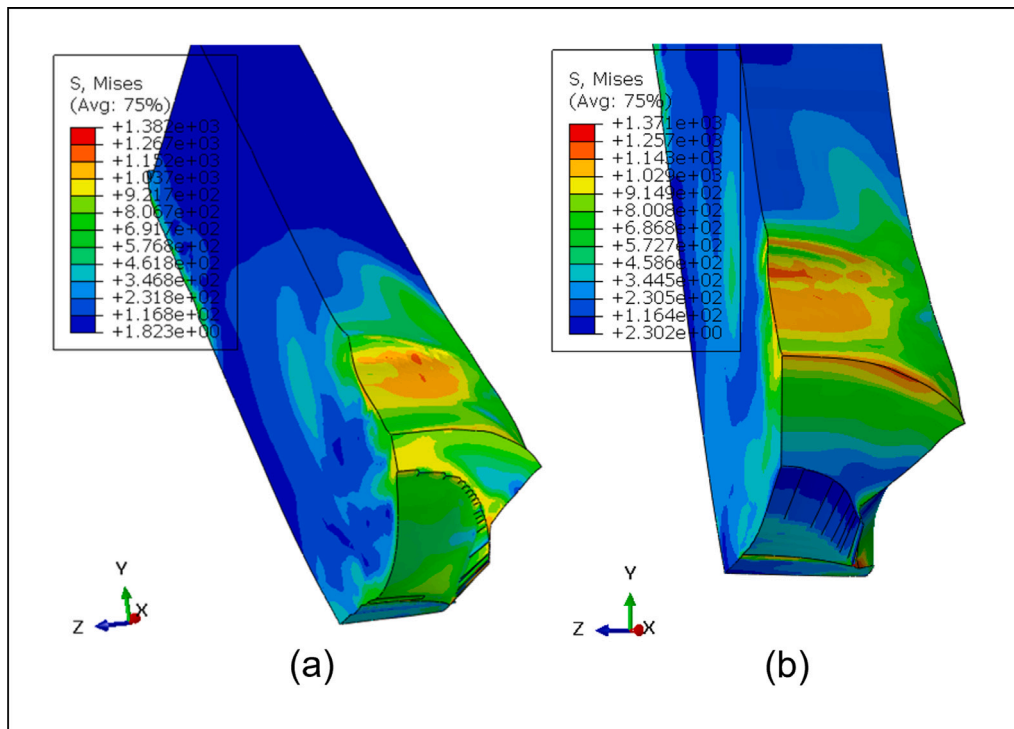


Fig. 16. Deformed configuration at the final stage using an element size $0.1 \times 0.2 \times 0.2$ mm comparing both models: (a) GTN model; (b) DD model.

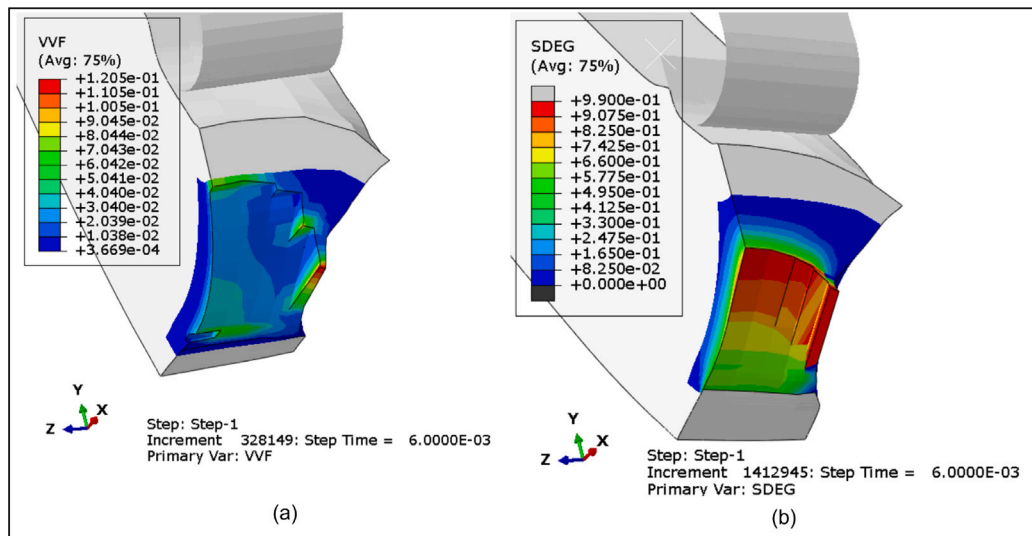


Fig. 17. Tunelling effect predicted by different models. (a) GTN2 showing void volume fraction (VVF); (b) DD5 showing damage variable (SDEG) for an element size of $0.1 \times 0.2 \times 1.0$ mm.

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