Sustainable Development of Civil, Urban and Transportation Engineering Conference

The Behavior of Ductile Damage Model on Steel Structure Failure

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Abstract

Damage of materials means the progressive or sudden deterioration of their mechanical strength due to loading, thermal or chemical effects. It could cover all related phenomena that occur from the virgin or reference state up to a mesocrack initiation. The continuum mechanical simulation of micro structural damage process is important in the study of ductile fracture mechanics. Material degradation has been widely modelled by continuum damage mechanics and it is accepted as a reliable methodology. In this paper, finite element simulation of damage evolution and fracture initiation in ductile solids will be investigated. Simulations are performed and the results are compared with the numerical and experimental ones addressed in the literature and good agreements were found between them. For this model, damage propagation and crack initiation, and ductile fracture behavior of notched specimens are predicted. The model can also quickly capture both deformation and damage behavior of the part by using 3D stress algorithm. Experiments are also carried out to validate the results. It is concluded that finite element analysis (FEA) in conjunction with continuum damage mechanics (CDM) can be used as a reliable tool to predict ductile damage. By means of examples, it has been demonstrated that the effect of softening cause by damage influences the global behavior of the structures and that the damage variable itself may give useful insights on failure analysis.

Keywords: Continuum Damage Mechanic (CDM); steel structures; mesocracks; 3D finite element; failure; elasto-plasticity; large deformation.

1. Introduction

Ductile materials undergo the large plastic deformation before damage and failure occurs. So, the prediction of the forming limits is one of the most important in this state. The accumulated plastic strain generated in a specimen

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is corresponding to changing of thermal dynamic such as nuclear, mesocracks, crack growth, coalescence of microvoids. The failure of micro-structure in alloy under the loading ultimately results in the damage components. Hence, improvement of the model and the material properties to ensure the ability and durability for micro-structure is forming processes. The alloying and the processing are responsible for making final properties of micro-structure including inside voids, gain size, homogeneities. The repeat loading like as the fatigue phenomena [1-5], operates on the structure until the limited level and then the material becomes brittle and weak. This is the necessary point to show that the micro-structure changing and reducing the energy by generating thermal. Thus, the Young’s modulus, micro-hardness are among important mechanical properties need to be considered. The indirect method for testing will deal with Leimaitre’s literature [6] and Vicker’s theory. It is well known that microvoids are one of the basic mechanisms for ductile failure process. [1] and [2] clarified the key role of the microvoids in ductile fracture. These studies were the first step for the development of a consistent constitutive model to predict the possible evolution of voids in a ductile matrix. Later, [3] proposed a porosity based model where the yield function for ductile materials is modified by the presence of voids. However, in most cases, these models were able to describe only damage evolution for particular metals. In this study, a nonlinear CDM model combined with the plasticity constitutive equation for ductile metals has been developed based on the FE method using a new damage dissipation potential formulation. The damage mechanics model pertains to the degradation of the material mechanical properties as a result of nucleation, growth, and coalescence of microcracks [7], and the damage growth law is based on the experimental observations reported in the literature [7]. Thus, the state variables including internal variables are expressed in effective terms as a function of the damage variable. Moreover, for simplicity, the isotropic damage evolution model is employed here. The validity of the proposed model has been confirmed by comparing the predicted damage variables for ductile metals with the experimental data available in the literature [11] and also duplex material steel. The fully couple elastic-plastic-damage model is developed and implemented into an implicit code, using three dimensional algorithm for sheet metals. Then, the model can quickly predict both damage behavior and deformation of the thin parts. Also, it is shown that the model can predict damage propagation, crack initiation and ductile fracture of duplex steel sheet metal under various loading conditions.

2. Constitutive nonlinear damage model

The damage variable defined by Kachanov [7] and Lemaitre [6] is given by for the isotropic damage case:

\[ D = 1 - \frac{A_D}{A_T} \]  

(1)

where \( A_D \) is the damaged surface area which takes into account the microcracks, the micro-stress concentration and the interaction between microcracks. \( A_T \) is the total cross-section area of the undamaged surface. The introduction of the damage variable leads to the concept of effective stress which means the stress calculated over the effectively resisting area. For the isotropic damage case, the effective stress for all stress components, \( \bar{\sigma} \), is expressed as [7]

\[ \bar{\sigma} = \frac{\sigma}{1 - D} \]  

(2)

The coefficient \((1 - D)\) is a reduction factor associated with the amount of damage in the material. \( D = 0 \) indicates the undamaged state and \( D = D_c \) defines the complete local rupture in which \( D_c \) is the critical damage amount at failure and \( D \in [0,1] \) means the partial damage state.

According to the observation, it is possible to separate the effects of elasticity with damage from those of plasticity and other internal variables. The damage strain energy release rate can then be derived from the framework of linear thermo-elasticity [7] and expressed as

\[ Y = \frac{-W_c}{(1 - D)} = \frac{\sigma_{eq}^2}{2E(1 - D)^2} f\left(\frac{\sigma_m}{\sigma_{eq}}\right) \]  

(3)
where
\[ \sigma_{eq} = \left( \frac{3}{2} s_{ij} s_{ij} \right)^{1/2}, \quad s_{ij} = \sigma_{ij} - \frac{1}{3} \sigma_{kk} \delta_{ij}, \quad \sigma_{eq} = \frac{1}{3} \sigma_{kk} \]
and
\[ f \left( \frac{\sigma_{m}}{\sigma_{eq}} \right) = \left[ \frac{2}{3} (1 + \nu) + 3(1 - 2\nu) \left( \frac{\sigma_{m}}{\sigma_{eq}} \right)^2 \right] \]

where \( W_e = \int \sigma_{ij} d\varepsilon_{ij}^{e} \) is the total elastic strain energy, \( \sigma_{eq} \) is the equivalent von Mises stress, \( s_{ij} \) and \( \sigma_{kk} \) are the deviatoric and trace of the stress tensor, respectively, and \( \delta_{ij} \) is the Kronecker delta. \( \sigma_{m} \) is the hydrostatic stress and \( \nu \) is Poisson's ratio. Moreover, the dissipation potential is formulated as a function of the associated variables using the Legendre-Fenchel transformation [8]:

\[ F = F_{plastic} (\bar{\sigma}, X, R, D) + F_{damage} (Y, D, p) \]  

where \( p \) is the effective accumulated plastic strain

\[ \dot{\bar{p}} = \left( \frac{2}{3} \dot{\varepsilon}_{ij}^{pl} \right)^{1/2} \]

(a) Elastic strain rate

\[ \dot{\varepsilon}_{ij}^{e} = \frac{1 + \nu}{E} \frac{\dot{\sigma}_{ij}}{1 - D} - \frac{\nu}{E} \frac{\dot{\sigma}_{kk}}{1 - D} \delta_{ij} \]

where \( \dot{\sigma}_{ij} \) is the rate of stress tensor.

(b) Plastic strain rate

\[ \dot{\varepsilon}_{ij}^{pl} = \dot{\lambda} \frac{\partial F_{p}}{\partial \sigma_{ij}} = \frac{3}{2} \frac{\dot{\lambda}}{1 - D} \left( \bar{\sigma}_{ij}^{eq} - X_{ij}^{eq} \right) \]

where \( \dot{\lambda} \) is the plastic multiplier.

(c) Damage evolution rate

\[ \dot{D} = -\dot{\lambda} \frac{\partial F_{D}}{\partial Y} = -\frac{\partial \phi^{p}}{\partial Y} = \dot{\lambda} \frac{1}{1 - D} \left( \frac{-Y}{r} \right) \]

The study problems involve both of the following nonlinear types of behavior, namely:

- Geometric nonlinearity associated with large deflection
- Material nonlinearity due to yielding or plastic deformation

In this work, the material nonlinearity is taken into account by the plasticity damage model and the geometric nonlinearity is accounted for by the large strain formulation. The large deformation implementation was done according to the procedure given in the literature [9]. The return mapping method introduced by Simo and Ortiz [10] was employed to numerically solve the elastic-plastic equations in the coupled plastic-damage analysis.
3. Verification analytical results

In order to validate the effectiveness of the proposed nonlinear damage model, the experiment and FEM results were conducted by Aboutalebi and Farzin [11] which described the load-displacement curves of St14 steel under tension were used. The monotonic results with and without incorporating CDM from the proposed model are directly compared experimental and the numerical FE data. The specific details of the material, the preparation of the specimen and the damage parameters are given in [11]. The geometry of specimen is presented with the thickness of 0.8mm, the length and width are of 120mm and 20mm, respectively. Fig.1 shows the axial load versus displacement curves for the FE model without considering damage (FEM) and another which takes into account damage (FEM+CDM). It is observed that the comparison between the experimental and the analytical results is very good agreement. The proposed damage mechanics model yields much closer corresponding to the experimental measurements and may better than the damage model which exhibited from the linear damage evolution and the large deformation effects [12]. The Fig. 2 illustrates the damaged model can well predict necking phenomenon as well as the analysis results. The coupled damage-plasticity causes the behavior of specimen reducing in load carrying capability. In the present model, the softening effect can be easily seen, however the phenomenon is taken placed in uniform distribution with undamaged model.

![Fig.1 Force and displacement curve in comparison](image1)

![Fig.2. Comparing the deformation and crack initiation: a) Virgin material b) Damage increasing c) Crack initiation d) Experimental deformation](image2)

In order to obtain more verifications for the damage model, the numerical calculations with the finite element method were carried out. The simulation for cylindrical smooth specimen meshed with eight-node axis-symmetric brick element was performed. The boundary condition was chosen with the nodes on the bottom are constrained in the three directions. The increasing displacement amplitude in the vertical direction was imposed on the nodes at the top of the model to allow displacement control within the procedure. The calculation automatically stops when the maximum value of the accumulated damage reaches to the critical value or until complete fracture. Following material properties of duplex stainless steel, and based on the ASTM, the material parameters are listed in Table 1 and Table 2.

Table 1. Mechanical properties of duplex stainless steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus E (GPa)</td>
<td>210</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>YP (MPa)</td>
<td>580</td>
</tr>
<tr>
<td>UTS (MPa)</td>
<td>810</td>
</tr>
<tr>
<td>% Elongation</td>
<td>30</td>
</tr>
<tr>
<td>Q (MPa)</td>
<td>140.0</td>
</tr>
</tbody>
</table>

Table 2. Damage characteristics of duplex stainless steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td>0.0</td>
</tr>
<tr>
<td>Dc</td>
<td>0.3</td>
</tr>
<tr>
<td>r</td>
<td>2.55</td>
</tr>
<tr>
<td>s</td>
<td>1.0</td>
</tr>
<tr>
<td>b</td>
<td>30.2</td>
</tr>
</tbody>
</table>

The coupled damage-plastic model indicates that the numerical analysis deformation is more reasonable then plastic model when the necking phenomenon takes place at ultimate plastic strain. Fig. 3 has shown the comparison of necking state for two models.

Fig. 3. Damage distribution and comparing necking phenomena between damage model and plastic model: a) Damage model b) Plastic model

It can be observed from the Fig. 4 that the load carrying capability drops to zero as soon as necking deformation almost terminates when the crack is formed. Consequently, either the reduction in area or the elongation of the gauge section at the point of fracture can be used as an indicator for the onset of a macroscopic crack in round bar tensile test. This justifies that a local effective plastic strain to fracture can be determined from numerical simulations using these experimental data.
The next analysis for a standard tensile test piece of duplex stainless steel with a side notch and the initial notch of 3mm length is considered. The comparison of the results as shown in Fig. 5 reveals that continuously increasing damage and crack propagation as well as the ductile fracture of the notch specimen can be predicted by the proposed model. The force-displacement prediction and the ultimate load plotted in Fig. 6 are also calculated. According to the coupled damage-plastic model, the diagrams of force-displacement are coincided to the testing results.

![Fig. 4. The loading carrying capability of specimen under loading condition](image)

![Fig. 5. Comparison FEM fracture and practical experiment observation: a) Notch b) Crack propagation c) Unstable crack d) Failure](image)
The load-displacement curves in Fig. 6a show the introduction of effective Young’s modulus as well as the damage coupling in constitutive plastic equation. These anticipated results with considerable loss in ductility are due to the strength loss of the material with damage deterioration. The resultant response can well obtained for the simulated local integration due to utilizing sufficient large number of loading steps has a stabilizing effect by improving the accuracy of the explicit damage integration steps.

Fig. 6b summarizes the global Force-displacement curves obtained with four various values of $r$ in the damage model. Clearly and expected, the higher $r$ indices, the later fracture occurrence. It can be showed that the Force-displacement curves are not smoothly decreased due to the strong dependence to the mesh size for the local/nonlocal model as well as the isotropic hardening effect. The refining mesh in finite element method can make these curves more properly. A damage-gradient elasto-plastic model with nonlinear isotropic hardening has been developed and implemented into FE code. This model will be implanted into a general proposed finite element program in order to show its ability to give a mesh independent solution for more complex structures as in metal forming.

5. Conclusion

This work aims to provide basic insight into the numerical simulation of damage within to concepts of continuum damage mechanics. Material parameters which included those used to describe damage evolution, are usually obtained from uniaxial experiments. The numerical analysis simulation is made to provide a simple step by step derivation of the consistent elasto-plastic modulus corresponding to FE algorithm. In standard tensile test, notched samples are investigated both numerically and experimentally. For these examples of ductile behavior, i.e. Crack initiation, propagation and ductile fracture of the specimens are well predicted between the FEM models and experiments. It is concluded that the finite element analysis (FEA) can practically predict ductile fracture for ductile materials. Knowledge about necking localization, direction and propagation crack is available to improve the analysis results for real structures.

References