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Finite element implementation of an orthotropic plasticity model for sheet metal in low velocity impact simulations

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ABSTRACT

A finite element (FE) implementation of an orthotropic plasticity model for sheet metal in impact simulations is performed. An accurate description of anisotropic plasticity model is presented for obtaining reliable predictions in FE simulations of low velocity impact processes. The elasto-plastic model includes isotropic elasticity, anisotropic yielding, associated plastic flow and mixed non-linear isotropic/kinematic hardening. The material model is implemented into a user-defined material (VUMAT) subroutine for the commercial finite element code ABAQUS/Explicit to predict the numerical response of circular aluminum plate subjected to low velocity impact. The impact energy was imposed by the definition of the impactor initial velocity. The numerical results of the impact force history and impact velocity are in good agreements with the LDA experimental data. The anisotropy effect of aluminum plate under low velocity impact is studied.

1. Introduction

Several questions can be posed by the designer when selecting materials: What material can be retained among the existing ranges? How and what is the structure size to obtain a good compromise between mechanical properties, protection of persons and environmental protection. Aluminum is one of the engineering materials that meet the requirements requested by the developer. Low density, strength and malleability of aluminum allow it to be used in applications of hydroforming metal. This metal ductility makes use of the complex shapes possible by hydroforming to produce lighter, stronger, and more rigid unibody structures. These reasons make the use of aluminum is ideal for construction of aircraft, sport equipments and lightweight vehicles. In many situations, these constructions are subjected to impact by foreign object, during operation or displacement. This phenomenon of impact has undesirable effects on the impacted parts for instance cracks; plastic deformation; rupture. The increasing demand on security and long-life of structures raised the need for the behavior prediction of parts subjected to the impact in order to take into account in structure designing. But the presence of anisotropy in aluminum alloy makes the simulation and prediction of impact loading more complicated, when taking into account the non-linear isotropic/kinematic hardening phenomenon during the impact process.

The literature on the subject of impact loading encompasses a variety of different materials, thicknesses and projectile geometries, as well as velocity ranges from low to the hypervelocity domain (see Johnson, Goldsmith and Stronge [1–3]). Investigations on elasto-plastic composite structures submitted to impact are presented by several authors [4–10]: to estimate the impact force between the punched bodies and to predict the response of the structures. Also, to facilitate elasto-plastic impact analysis of heterogeneous functionally graded (FG) circular plates under low-velocities, Gunes [11] used the homogenization method based on the Mori–Tanaka scheme to circumvent the heterogeneity of FG materials.

The study of the impact behavior of anisotropic ductile material has received much attention in recent years. In addition, the accurate constitutive models for ductile materials like aluminum alloys (AA) have been significant interest to the Aerospace and automotive industries, as the ability to predict inelastic materials behavior of the anisotropic AA, undergoing impact and dynamic loading. This anisotropy is an important aspect that should be taken into account when modeling inelastic materials impact behavior. For this reason, the constitutive equations governing the inelastic materials behavior are generally given in rate form, thus requiring numerical integration for implementation in finite element simulations.

Works covering low-velocity impacts on metal plates has been reported by [12–19]. The low velocity domain, often defined as the range between 0 and 50 m/s.

Grytten et al. [20] presented an experimental and numerical investigation on low velocity perforation of AA5083-H116 anisotropic aluminum circular plates. The non-quadratic Yld2004-18p yield

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criteria of Barlat et al. [21] with isotropic hardening model, to define the evolution of the flow stress, and the Johnson–Cook rupture model are adopted in the numerical simulation. The described material model was implemented in the commercial nonlinear finite element code LS-DYNA by means of a user-defined material subroutine. Grytten et al. [20] showed that low-velocity impacts can be reasonably well predicted without considering the effects of strain rate and temperature. However, in the case of medium or high velocity impacts, the strain rate effect appears to have a major effect on rupture initiation, Abdulhamid et al. [22]. Chen et al. [23] developed the theoretical contact-impact model to a thin aluminum circular target plate subjected to a traveling projectile collision. By adopting minimum principle of acceleration for elastic–plastic continue at finite deformation with the aid of finite difference method (FDM). The numerical analyses are compared with the experimental results obtained by LDA (Laser Doppler Anemometry) technique.

The present work aims at investigating the influence of anisotropy on low velocity impact on aluminum plates. A one-equation integration algorithm of a generalized quadratic yield criterion of Hill based on the mixed non-linear isotropic/kinematic hardening models of Chaboche is developed for computing elasto-plastic stress during impact process. The numerical simulation of the impact problem is carried out using the commercial software ABAQUS/Explicit. The material constitutive law is implemented in a user-defined subroutine VUMAT. The numerical results obtained by the present model are validated by experimental tests of [23] and numerical simulations obtained by ABAQUS software when the material anisotropy is assumed. The anisotropy effect on the low velocity impact of aluminum plate is investigated. Numerical results, including impact force, impact energy, velocity of impactor and dynamic response of plate are calculated.

2. Elasto-plastic constitutive equations

An extensive description for formulating constitutive rate equations in order to model anisotropic yielding, and mixed non-linear isotropic/kinematic hardening can be found elsewhere, and we will not elaborate on these details; see, for example, Lemaitre and Chaboche [24]. A summary of the resulting set of equations considered in this paper.

- Partition of the total strain

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p \tag{1}$$

- Hooke's law

$$\boldsymbol{\sigma} = D{:}\boldsymbol{\varepsilon}^e \tag{2}$$

- Yield function

$$f = \sqrt{\frac{3}{2}}\varphi(\boldsymbol{\xi}) - \sigma_p \le 0, \varphi(\boldsymbol{\xi}) = \sqrt{\boldsymbol{\xi}^t P \boldsymbol{\xi}} \tag{3}$$

$$\sigma_p = \sigma_Y + R, R = Q\left(1 - e^{-\beta\kappa}\right) \tag{4}$$

- Flow rule

$$\dot{\boldsymbol{\varepsilon}}^p = \dot{\gamma}\frac{\partial f}{\partial \boldsymbol{\sigma}} = \sqrt{\frac{3}{2}}\dot{\gamma}\boldsymbol{n}, \boldsymbol{n} = \frac{1}{\varphi}P\boldsymbol{\xi} \tag{5}$$

- Isotropic hardening

$$\dot{\kappa} = \dot{\gamma} \tag{6}$$

- Kinematic hardening

$$\dot{\mathbf{X}} = a\dot{\boldsymbol{\varepsilon}}^p - b\dot{\gamma}\mathbf{X} \tag{7}$$

$$\dot{\boldsymbol{X}} = \dot{\gamma}\mathbf{H}_X, \boldsymbol{H}_X = a\sqrt{\frac{3}{2}}\boldsymbol{n} - b\boldsymbol{X} \tag{8}$$

where $\boldsymbol{\varepsilon}^e$ denotes the elastic strain tensor and $\boldsymbol{\varepsilon}^p$ is the plastic strain tensor, $\boldsymbol{\sigma}$ is the stress tensor, $\boldsymbol{D}$ is the general elastic operator, where Q, β, a, and b are material parameters, $\dot{\gamma}$ is the plastic multiplier, $\mathbf{X}$ is the back-stress, and $\boldsymbol{P}$ is a fourth order tensor which define the yield criterion. This yield function includes the classical J_2 plasticity yield condition and the quadratic Hill criterion as special cases. The Hill yield criterion, in three-dimensional cases, is obtained by taking

$$\boldsymbol{P} = \frac{2}{3}\boldsymbol{H},\ [\boldsymbol{H}] = \begin{bmatrix} H+G & -H & -G & 0 & 0 & 0 \\ & H+F & -F & 0 & 0 & 0 \\ & & F+G & 0 & 0 & 0 \\ & & & 2N & 0 & 0 \\ & Sym & & & 2M & 0 \\ & & & & & 2L \end{bmatrix} \tag{9}$$

where F, G, H, N, M and L are material constants obtained by tests of the material in different orientations. The J_2 plasticity yield criterion is recovered using Eq. (9) and setting

$$F = G = H = 0.5, \quad N = M = L = 1.5 \tag{10}$$

In isotropic elastic material and Hill criterion with plane stress elements or Kirchhoff shell elements (exp. Dammak at al. [25] among others), $\boldsymbol{P}$ and $\boldsymbol{D}$ are simply

$$\boldsymbol{P} = \frac{2}{3}\begin{bmatrix} G+H & -H & 0 \\ -H & F+H & 0 \\ 0 & 0 & 2N \end{bmatrix}, \quad \boldsymbol{D} = \frac{E}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & (1-\nu)/2 \end{bmatrix} \tag{11}$$

2.1. One equation integration

The plastic strain $\boldsymbol{\varepsilon}^p_{n+1}$ and the back stress $\mathbf{X}_{n+1}$, are determined by integration of the flow and hardening laws over a time step. This may be written as

$$\begin{cases} \boldsymbol{\varepsilon}^p_{n+1} = \boldsymbol{\varepsilon}^p_n + \sqrt{3/2}\Delta\gamma\boldsymbol{n}_{n+1} \\ \boldsymbol{X}_{n+1} = \frac{1}{\omega}(\boldsymbol{X}_n + a\sqrt{3/2}\Delta\gamma\boldsymbol{n}_{n+1}) \end{cases} \tag{12}$$

where

$$\omega = 1 + b\Delta\gamma \quad \text{and} \quad \mathbf{n}_{n+1} = \frac{1}{\varphi_{n+1}}\boldsymbol{P}\boldsymbol{\xi}_{n+1} \tag{13}$$

Using Eqs. (1) and (12) into the stress–strain relation, Eq. (2), gives the stress tensor as

$$\boldsymbol{\sigma}_{n+1} = \boldsymbol{\sigma}^{TR} - \sqrt{\frac{3}{2}}\Delta\gamma\boldsymbol{D} \times \boldsymbol{n}_{n+1} \tag{14}$$

where $\boldsymbol{\sigma}^{TR}$ is the elastic trial stress

$$\boldsymbol{\sigma}^{TR} = \boldsymbol{D} \times \left(\boldsymbol{\varepsilon}_{n+1} - \boldsymbol{\varepsilon}^p_n\right), \quad \boldsymbol{\varepsilon}_{n+1} = \boldsymbol{\varepsilon}_n + \nabla^s\Delta\boldsymbol{u} \tag{15}$$

With Eqs. (14) and (15), the difference tensor, $\boldsymbol{\xi}_{n+1} = \boldsymbol{\sigma}_{n+1} - \boldsymbol{X}_{n+1}$, can then be computed as

$$\boldsymbol{\xi}_{n+1} = \boldsymbol{\xi}^{TR} - \sqrt{\frac{3}{2}}\Delta\gamma[\boldsymbol{D} + a_\omega\boldsymbol{I}]\boldsymbol{n}_{n+1}, \quad \boldsymbol{\xi}^{TR} = \boldsymbol{\sigma}^{TR} - \frac{1}{\omega}\boldsymbol{X}_n, \quad \in a_\omega = \frac{a}{\omega} \tag{16}$$

Or also,

$$\boldsymbol{\xi}_{n+1} = \boldsymbol{I}_c^{-1} \times \boldsymbol{\xi}^{TR}, \quad \mathbf{I}_c = \mathbf{I} + \sqrt{\frac{3}{2}}u[\boldsymbol{D} + a_\omega\boldsymbol{I}]\boldsymbol{P}, \quad u = \frac{\Delta\gamma}{\varphi_{n+1}} \tag{17}$$