

Fracture Prediction for Automotive Bodies Using a Ductile Fracture Criterion and a Strain-Dependent Anisotropy Model

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ABSTRACT

In order to reduce automobile body weight and improve crashworthiness, the use of high-strength steels has increased greatly in recent years. An optimal combination of both crash safety performance and lightweight structure has been a major challenge in automobile body engineering. In this study, the Cockcroft-Latham fracture criterion was applied to predict the fracture of high-strength steels. Marciniak-type biaxial stretching tests for high-strength steels were performed to measure the material constant of the Cockcroft-Latham fracture criterion. Furthermore, in order to improve the simulation accuracy, local anisotropic parameters based on the plastic strain (strain dependent model of anisotropy) were measured using the digital image grid method and were incorporated into Hill's anisotropic yield condition by the authors. In order to confirm the validity of the Cockcroft-Latham fracture criterion, uniaxial tensile tests were performed. It was found that the accuracy of the predicted rupture strain was improved if the local anisotropic r -value was used. To predict failure and force-stroke curve in collision phenomena, the Cockcroft-Latham fracture criterion, considering the local anisotropic r -value, was applied to three-point bending tests. The simulated results showed that the fracture locus of hat-shaped section and force-stroke curves were accurately predicted.

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INTRODUCTION

The use of high-strength steels in automobile body structures has been considered an efficient solution because of the lower cost of volume production in the automotive industry. With the improvement of the formability of high-strength steels by optimizing the metallic microstructure, the range of application of high-strength steels has been expanding in automobile body structures. Recently, advanced high-strength steels with strengths from 980MPa to 1500MPa used in automobile bodies have played a crucial role in crash safety performance. To design and manufacture automotive parts from high-strength steels, simulation has become an indispensable tool for the prediction of crack occurrence during metal forming and fracture behaviors under strong impact loading.

Over the past two decades, various approaches to the prediction of forming cracks have been made and several fracture criteria have been proposed. These fracture criteria include the plastic strain

criteria based on stress triaxiality, which were used in the fracture prediction of stamping parts by Bai and Wierzbicki[1] and by Sato et al [2]; the strain-based forming limit diagram proposed by Marciniak[3] and Nakajima [4]; the stress-based forming limit diagram proposed by Kuwabara [5]; the local necking theory proposed by Ito et al [6]; and the ductile damage criteria proposed by Cockcroft-Latham [7] and by Oyane [8]. Of these, it has been verified that the Cockcroft damage criterion, integrating maximum principal stress and plastic strain, can accurately predict crack occurrence during sheet metal forming as investigated by Takada et al [9,10] and Ma et al [11]; cracks due to tube forming presented by Ma [12]; and fractures under various loading conditions verified by Takada et al [13]. When ductile damage criteria are used to predict crack initiation and then to evaluate the strength of structures, the ductile damage limit of materials must be measured by experiments.

In this study, the Cockcroft-Latham fracture criterion based on ductile damage was used to predict the fracture of high-strength steels in crash tests. In order to obtain the material constants of the Cockcroft-Latham fracture criterion, Marciniak-type in-plane biaxial stretching tests were performed to measure the ductile fracture limits of high-strength steels. Furthermore, to reproduce local fracture behaviors, the local anisotropic r -value (ratio of local width strain to local thickness strain), which depends on the local plastic strain, was accurately measured using the digital image grid method. The strain dependency of the local anisotropic r -value was proposed in this study and it was incorporated into Hill's anisotropic yield condition.

In order to confirm the validity of the Cockcroft-Latham fracture criterion, uniaxial tensile tests based on a JIS No. 5 tensile specimen were performed. It was found that the accuracy of the predicted rupture strain was improved if the local anisotropic r -value was used. To predict the failure and force-stroke curve in collision phenomena, the Cockcroft-Latham fracture criterion taking into consideration the local anisotropic r -value was applied to three-point bending tests. The frame for the three-point bending tests, supposing an actual automobile structure, were assembled from a hat-shape stamped part and a plate of high-strength steels by spot welds. The simulated results showed that the fracture locus of the hat-shaped sections and force-stroke curves were accurately reproduced.

COCKCROFT-LATHAM FRACTURE CRITERION

The Cockcroft-Latham fracture criterion shown in [equation \(1\)](#) is the integral damage value using the maximum principle stress and equivalent strain. It needs only one material constant to express the amount of ductile damage. Therefore, the material constant can be determined through just one experiment.

$$\int_0^{\bar{\epsilon}_f} \sigma_{\max} d\bar{\epsilon} = C_1 \quad (1)$$

where $\sigma_{\max}$ is the maximum principle stress, $\bar{\epsilon}$ is the equivalent strain, $\bar{\epsilon}_f$ is the equivalent strain at which the fracture occurs, and C_1 is the material constant to express the limit of ductile damage. The integral I shown in [equation \(2\)](#) is the normalized damage value of [equation \(1\)](#). This integral I is calculated at each integration point (Gauss point), using the stresses and strains computed by finite element method. If the integral I at the Gauss point of an element becomes 1, its damage value in the element reaches the fracture criterion and the element is deleted.

$$I = \frac{1}{C_1} \int_0^{\bar{\epsilon}_f} \sigma_{\max} d\bar{\epsilon} \quad (2)$$

MARCINIAK-TYPE IN-PLANE BIAxIAL STRETCHING TEST

A Marciniak-type in-plane biaxial stretching test was performed in order to measure the material constant C_1 and rupture strain $\bar{\epsilon}_f$ shown in [equation \(2\)](#). The high-strength steels used in this study were 780MPa, 980MPa, 1180MPa and 1500MPa grade with a thickness of 1.6mm. In the test specimen, inscribed lattice lines with 2mm pitches were printed to measure the fracture strain. If the Cockcroft-Latham fracture criterion is expressed in the strain space, it is proven that the strain limit of the ductile fracture equals the straight line shown in [Figure 1](#) [9,10]. In other words, the strain limit of the ductile fracture can be determined through just one experiment. Therefore, in this study, Marciniak-type tests were performed only in the plane strain state in which the strain ratio ($\beta = \epsilon_2 / \epsilon_1$) is 0. To obtain the fracture strain at the plane strain state, the four kinds of tests with different widths were performed, which were 110mm, 120mm, 130mm and 140mm.

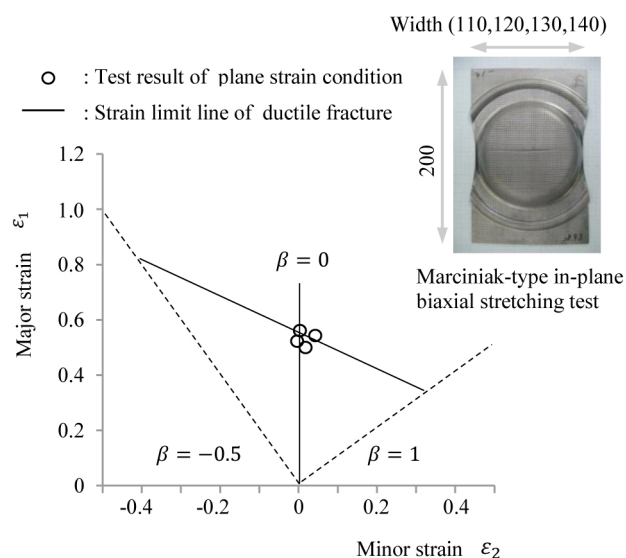


Figure 1. Example of limit strain for fracture in biaxial stretching tests

[Table 1](#) shows the material properties and material constant C_1 for four classes of high-strength steels.

Table 1. Material properties and material constant C_1

Material Grade	780MPa	980MPa	1180MPa	1500MPa
YS (MPa)	541.7	861.3	898.9	1049.1
TS (MPa)	845.8	1044.7	1256.2	1515.1
anisotropic r -value	0.62	0.75	0.79	0.67
Material constant C_1	556.8	690.2	553.5	562.4

[Figure 2](#) shows the true stress-strain curves for four classes of high-strength steels obtained from tests. In FEA, the swift equation shown in [equation \(3\)](#) is applied to express the stress-strain relation after uniform elongation (n -value).

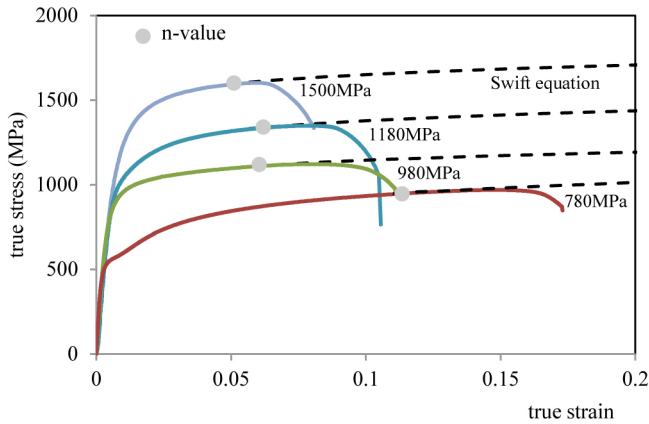


Figure 2. True stress-strain curves for high-strength steels

$$\sigma = \sigma_0 (\varepsilon_0 + \bar{\varepsilon}^p)^n \quad (3)$$

where σ_0 , ε_0 and n are the strength coefficient, yield strain and strain hardening exponent respectively.

DIGITAL IMAGE GRID METHOD

Ever since the digital image correlation method was developed by Peters et al [14], Chu et al [15], and Sutton et al [16], it has been possible to directly measure the displacement field and strain field. With the progress of the digital image correlation method as reviewed by Pan et al [17], it has been conveniently used to measure large strains in structure samples or local strains at a necking area of tensile test pieces presented by Coppieters et al [18]. However, there is measurement instability if the digital image correlation method is used to measure local strains with a large distortion in the measuring areas. This is because the digital image correlation method uses a random pattern painted on the surfaces of structure samples. In order to more accurately and reliably measure strain localization behaviors during the testing process, as well as local strain distribution before fracturing occurs, a digital image grid method was developed by Sato et al [2] using a regular pattern with grids etched electrochemically on the surface of a test piece.

In the digital image grid method, the deformation of the etched pattern on the specimen is analyzed using a computer vision algorithm. The computer vision algorithm is able to reconstruct a 3D shape from multiple 2D images. The relationship between a 3D-coordinate point, $M(x,y,z)$, in a global coordinate space and a 2D-coordinate point, $m(u,v)$, in the camera coordinate system is represented by equation (4).

$$\lambda \cdot m = A[R | T]M \quad (4)$$

where λ is a scale parameter, and A is a camera matrix including the focal length (a_u, a_v), the center of the image (u_0, v_0), and a share factor scale, s . The R and T matrixes are the transformation and rotation matrixes, respectively, shown in Figure 3. A , R , and T are described by the parameters defined by equation (5).

$$A = \begin{bmatrix} a_u & s & u_0 \\ 0 & a_v & v_0 \\ 0 & 0 & 1 \end{bmatrix}, R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}, T = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} \quad (5)$$

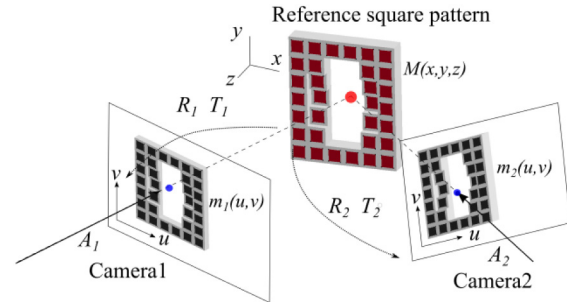


Figure 3. Rotation and translation of the stereo camera model

In equation (4), the part of $A [R | T]$ is condensed into a 3×4 matrix, P , shown in equation (6).

$$P = A[R | T] = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \end{bmatrix} \quad (6)$$

The parameters of the camera matrix P can be estimated using a pattern with known 3D coordinate points and the projected points in the camera coordinate system shown in Figure 4. Once P is determined, the transformation and rotation of the camera are calculated by the decomposition of matrix P . When the positions and rotations of all cameras are calculated, the 3D position of the object can be calculated from multiple images captured by the cameras. The calculation problem is a linear simultaneous equation with 3D-coordinate parameters x , y , and z . The equation can be solved using the inverse matrix of P as shown in equation (7).

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad (7)$$

The digital image grid method, which is used in uniaxial tensile tests, is schematically shown in Figure 4(a). It consists of a two-camera system for static tensile testing that is controlled by a computer. The specifications of the digital camera used in the experiments are shown in Figure 4(b). The grids, with a diameter of 0.25 mm or 0.5 mm, are printed at a certain pitch length, called the grid pitch length here, of 1.0 mm on specimens using the electrolytic etching method shown in Figure 4(c). The size of the grids and grid pitch length are designed by taking into consideration the limitations of the degree of etching precision and accuracy of the local strain measurement. The center of the grid is determined