

Numerical Fracture Analysis Considering Forming Effect and Element Size Regularization for Automotive Seat Structures

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ABSTRACT

The aim of this paper is to apply an advanced fracture model and to evaluate its applicability in automotive seat structures. A Generalized Incremental Stress-State dependent damage Model (GISSMO), which was one of the advanced fracture models implemented in LS-DYNA, was adopted as a fracture model. A description of the damage parameter identification process with material tests was introduced in this study. The GISSMO adopts most of the fracture factors, and was introduced in previous works. In order to evaluate the fracture strain in various stress states, uniaxial tension, simple shear-tension, notched-tension, and biaxial tension tests were carried out. The GISSMO damage parameters were calculated and identified using reverse analysis method and theoretical equations with some numerical fitting techniques. The results were compared with material test results, and it was evaluated that the values might be applicable to the seat frame model. In addition, it was found that the effects of element size and manufacturing (forming) are large with regard to fracture behavior. In particular, the seat rail has a residual stress owing to the bending process in the forming step. From these simulation results, the material parameters were applied to the full seat structure. Various models showed good agreement with the experimental fracture strength and crack propagation.

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INTRODUCTION

An automotive seat should guarantee the safety, convenience, and comfort of the passenger. In particular, for safety of the passenger during a collision, the roles of the seat frame and posture controllers (rail, recliner, and height adjuster) are important. Sufficient strength and rigidity should be ensured. To evaluate the structural safety of the seat, tests such as the seat belt anchorage and frontal/rear impact test are conducted. Companies that manufacture complete automobiles and seats apply regulations or self-developed criteria in their car designs. To reduce the weight of the seats, materials such as high-strength steel, magnesium, and aluminum have been applied. However, additional design techniques are required owing to changes of mechanical behavior in the materials. During evaluation of strength/fracture, complex load are applied to each unit product [1]. Depending on the design specifications, fracture shape and point can differ significantly. Therefore, in order to secure the structural safety of the product and to verify the design plan, an estimation of the strength and fracture should be conducted in advance. This means that the development of an advanced analysis model and method are required.

The strength estimation of the sheet metal using an analytical method generally adopts simple criteria, such as fracture elongation or maximum tensile strength measured from the uniaxial tension test. However, since these criteria only reflect partial aspects of the design, they are not suitable for a seat structure to which complex stress is applied [2, 3, 4]. In addition, there is a method that uses a forming limit diagram (FLD), which is often applied to a formability

evaluation. However, this is also known to be unsuitable for non-proportional and combined loading, and measurement of necking is not trivial [2, 3, 4]. Currently, various types of ductile fracture criteria, based on continuum mechanics and micromechanics, are being used. However, owing to the complex theories and difficulties in deriving the parameters, they have limitations in application fields. To approach to the fracture prediction efficiently and easily in an engineer's aspect, the utilization of commercial programs and advanced fracture model is needed. When doing so, the study of principles, and verification of data and parameters should be performed.

The purpose of this study is to verify the potential applicability of a damage model, which is enhanced for the reliable estimation of strength/fracture of seat parts applied to high-strength steel material. A GISSMO damage model included in the LS-DYNA, a commercial finite element analysis program, was selected. After conducting material tests on samples that represent the several stress states, damage parameters or data were calculated. Parameter verification was conducted by an inverse analysis method, and the reliability was evaluated for the single component model (seat rail assembly) and the full seat model. In the finite element analysis, the sensitivity regarding the element size hugely influences the analysis results. Therefore, a method of using it as a fracture model parameter was described, and its different result was explained. In addition, since the consideration of residual stress by forming is known to significantly influence the analysis results, the seat rail was evaluated to suggest an appropriate direction for the strength/fracture simulation of the seat model in future.

STRESS STATE AND FRACTURE BEHAVIOR

Generally, the metal fracture begin with a growth and coalescence of a void. The inside of metals, where external stresses are applied, is formed of voids around the inclusions. At a stress state that is higher than the yield stress, these processes lead to the cracks. The process can be explained by the damage, which is related with the material degradation and plasticity. Therefore, during the formulation of a fracture, the accuracy of estimation is determined by how the damage is defined and formulated. A general form of damage can be expressed by the fracture strain and equivalent plastic strain, as shown in equation (1). D is the damage, ε_{eq} is the local equivalent plastic strain, ε_f is the local fracture equivalent plastic strain, and n is the damage exponent.

$$D = \left(\frac{\varepsilon_{eq}}{\varepsilon_f} \right)^n \quad (1)$$

The fracture strain is known to be dependent on stress triaxiality. These are related to the void growth and Lode angle, which are related to the void coalescence. This dependency has been mentioned several times in various tests and stress/strain analyses [5, 6, 7, 8, 9]. The stress triaxiality in the principle stress space is defined by equation (2), using a ratio between the mean stress and equivalent plastic strain. The Lode angle is defined by deviatoric stress invariants as the parameters for quantifying the stress deviation state.

$$\eta = \frac{\sigma_m}{\sigma_{eq}} \quad (2)$$

$$\bar{\theta} = 1 - \frac{6\theta}{\pi} \quad (-1 \leq \bar{\theta} \leq 1), \quad \theta = \frac{1}{3} \cos^{-1} \left(\frac{3\sqrt{3}}{2} \frac{J_3}{J_2^{3/2}} \right) \quad (3)$$

where θ , $\bar{\theta}$, J_2 , and J_3 denote the Lode angle, Lode parameter, and second and third invariants of the deviatoric stress tensor, respectively. Therefore, to describe the ductile fracture as damage and define the fracture characteristics, most fracture models use quantified stress state parameters. Since stress triaxiality can express the two-dimensional stress state, and the Lode angle can express the three-dimensional stress state, the directions for adopting the quantified stress state parameters differ as depending on the fracture characteristics of the material. If the influence on the thickness direction is assumed to be insignificant and the characteristics are ignored, a sheet metal can be expressed in a two-dimensional stress state. Therefore, this can be defined as a function of the only stress triaxiality. The stress triaxiality can be idealized as shown in Figure. 1. By defining the fracture strain according to its respective idealized values, an evaluation of a fracture in a complex stress state becomes available.

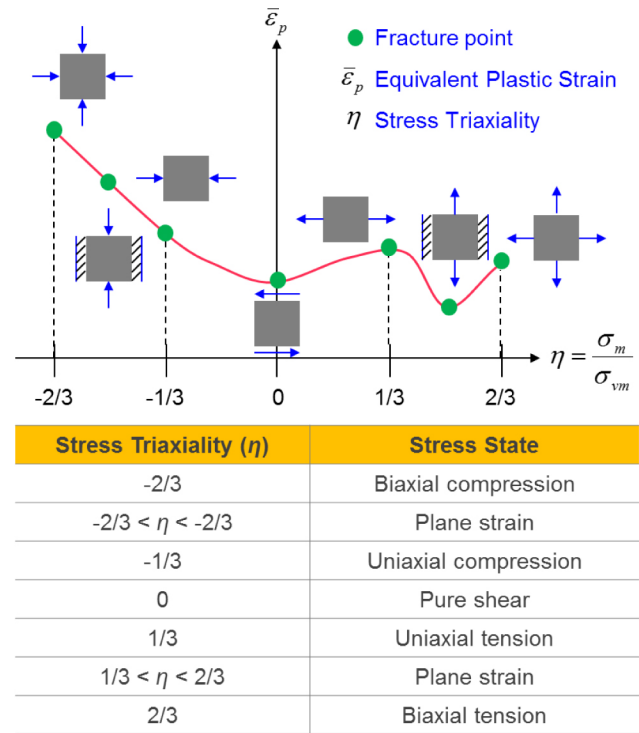


Figure 1. Stress triaxiality and stress state.

The fracture model selected in this study is GISSMO, a phenomenological damage model, which is becoming an issue in the field of structure/impact analysis. The model is being tested for its application to various automotive parts [10, 11, 12]. The model is one of the most advanced fracture models, and is a modular type that can be combined with various constitutive models. The model includes most fracture factors, such as stress triaxiality, Lode angle, element size sensitivity, and strain rate dependency. Equation (4) shows the damage increments of the GISSMO damage model. Accumulated damage is expressed by equation (5). In addition, the stress update, which is the plasticity-damage coupled model, is shown in equation (6) [13].

$$dD = \left(\frac{n'}{\varepsilon_f} \right) \left(\frac{\bar{\varepsilon}_p}{\varepsilon_f} \right)^{n'-1} d\bar{\varepsilon}_p = \frac{n'}{\varepsilon_f(\eta, \theta)} D^{\frac{n'-1}{n'}} d\bar{\varepsilon}_p \quad (4)$$

$$D_{\text{Total}} = \int \frac{n'}{\varepsilon_f(\eta, \theta)} D^{\frac{n'-1}{n'}} d\bar{\varepsilon}_p = \int f(D, \eta, \theta) d\bar{\varepsilon}_p \quad (5)$$

$$\sigma_{\text{Update}} = \tilde{\sigma} \left(1 - \left(\frac{D - D_{\text{crit.}}}{1 - D_{\text{crit.}}} \right)^{F_{\text{Exp}}} \right) \quad (6)$$

where D is the damage, ε_p is the equivalent plastic strain, ε_f is the fracture strain, n' is the damage exponent, D_{crit} is the critical damage value, F_{Exp} is the exponent for the damage-related stress fadeout, η is the stress triaxiality, and θ is the dimensionless Lode parameter.

MATERIAL TEST

For a sheet metal, it is known that it is difficult for a fracture to occur with negative stress triaxiality. This was proven experimentally [14]. Therefore, in this study, to determine the deformation modes at the area of positive stress triaxiality and to experimentally analyze the fracture characteristics, samples were considered as shown in Figure 2. The material of the seat frame used in this study can be classified into four classes: 440MPa, 590MPa, 790MPa, and 980MPa. Each material was tested with uniaxial tension, simple shear, notched type, and biaxial tension. All samples had a uniform velocity of 5 mm/min until the generation of a fracture.

A biaxial tension test was carried out using a punch and die, and the displacement at the punching part was measured. All other samples had their displacements traced by using a video extensometer at a gage length of 50 mm. The local fracture strain was evaluated by using the digital image correlation (DIC) method. As a result, a stress-displacement diagram and data regarding the fracture displacement, local fracture strain, etc., were obtained. The starting point of the fracture was determined as the point where the decreasing rate in the stress-strain curve becomes more than 60%.

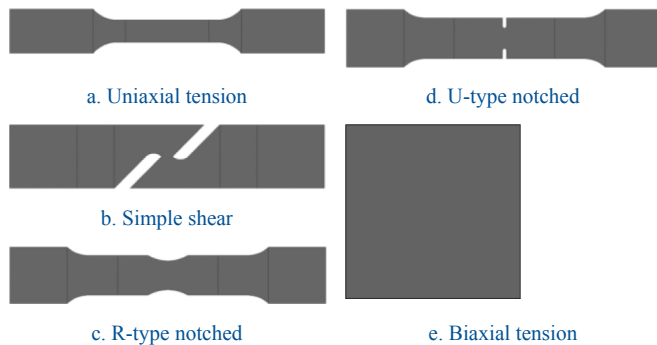


Figure 2. Specimens for evaluation of fracture behavior.

IDENTIFICATION OF MATERIAL DATA

To determine the behavior of the high-strength steel in this study, a piecewise linear plasticity model, which applies isotropic yield conditions and isotropic hardening rules, was adopted. The stress-strain relationship, as shown in Fig. 3, was defined from the uniaxial tension test and was expanded to the data zone past the maximum stress. The parameter verification shown in this paper refers only to the 980MPa class. To apply a GISSMO damage model, an inverse analysis method [2, 3, 4] was used.

The relationship between fracture strain and stress triaxiality plays the most important role in defining the material fracture characteristics of the GISSMO damage model. The local fracture strains were measured from the uniaxial tension, simple shear, notched type tension, and biaxial tension tests. Measurement errors in these strains can occur depending on the devices employed or on the measurer's skill. In addition, the material behaviors is different as depending on the constitutive model. Experimentally determining the fracture strain and using it in the analysis is not an easy approach. Therefore, in this study, after conducting a strength analysis on the

simple specimens, an inverse analysis [2, 3, 4] was used to obtain the fracture strain and the stress triaxiality relation by comparing the values with the actual experiment.

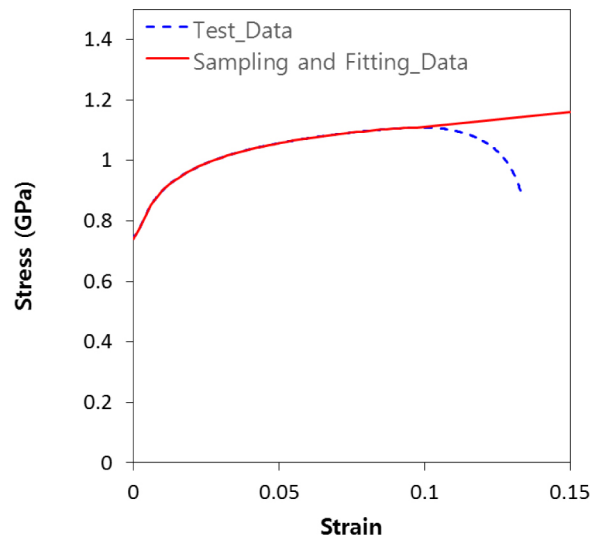


Figure 3. Relation of plastic stress and strain.

After the deformation analysis of simple specimen models (tension, shear, notched, biaxial), the data for defining the damage parameter was traced. The FE models were constructed with shell elements and the fracture criterion was not considered to calculate the damage parameter from stress and strain data. Figure 4 shows the analysis results without the fracture criterion and the contour shows the equivalent plastic strain. On the shell element where shows severe deformation, the plastic strain, mean stress, and equivalent plastic stress were traced. The data used for calculating the GISSMO damage and the calculated fracture displacement was compared with the fracture displacement measured in the actual tests to find the corresponding fracture point.

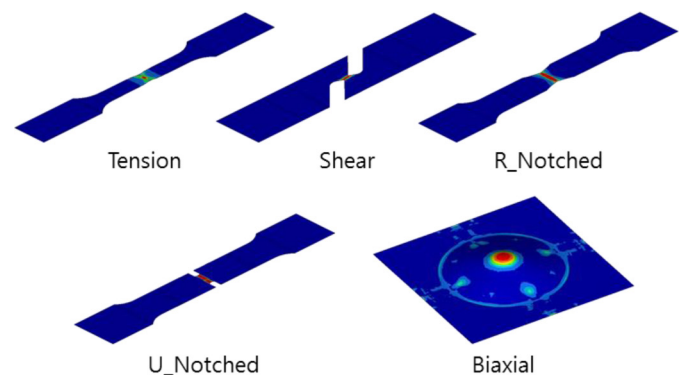


Figure 4. Critical point predicted in specimen models (simulation without fracture criterion).

To generate a continuous fracture curve from the fracture strain data of five samples, the relationship between stress triaxiality and fracture strain is shown in Figure 5. In addition, since a plasticity-damage coupling is applied during the stress update, a material constant for the stress update is required. This was arranged using Table 1, along with the damage exponent. The defined material model and the parameters of the fracture model were applied to the previous sample model to