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Calculation of J-Integral by CMOD at Impact Behavior of 3-Point Bend Specimen

Jae-Ung Cho[1*]

삼점 굽힘 시험편의 충격 거동에 있어서의 CMOD에 의한 J-적분의 계산

조재웅[1*]

Abstract The J-integral used as a ductile crack initiation criterion has been discussed for the impact loaded elastic-plastic 3PB specimens. The experimental method to measure or estimate the J-integral history has been investigated and its result has been compared to the obtained elastic-plastic values by the finite element model of this study. These numerical results and the experimental curves are found to agree closely. J-integral can be calculated by only numerical analysis with the finite element model. It is proved that simple calculation can be made in order to find the possible value of J-integral by crack mouth opening displacement(CMOD) in the dynamic nonlinear fracture experiment of 3-point bend(3PB) specimen. The property of elastic-plastic material is considered at different impact velocities. The J-integral may be estimated from the crack mouth opening displacement which can be measured directly from photographs taken during impact experiments.

Key Words : Dynamic nonlinear fracture, 3-point bend specimen, Crack mouth opening displacement, J-integral

요 약 연성 크랙의 발생 평가를 위한 J-적분이 충격 하중을 받는 탄소성 3점 굽힘 시험편들에 대하여 연구 한다. J-적분을 측정하고 평가하는 실험적인 방법이 연구되었으며 이 결과가 유한 요소법을 이용한 탄소성 이론 해석을 한 값들과 비교하여 거의 일치함을 보였다. 이론적인 수치 해석으로서도 본 연구의 유한 요소 모델로서 J-적분값을 계산할 수 있으며 삼점 굽힘 시험편의 동적 비선형 파괴 실험에 있어서 크랙 입구 개구 변위 (CMOD)에 의하여 J-적분값의 단순 계산이 가능함을 입증하였다. 탄소성 재료의 특성이 여러 가지의 충격 속도들에서 고려된다. J-적분은 충격 실험 동안 얻어진 사진들로부터 직접적으로 측정된 크랙 입구 개구 변위로부터 예측될 수 있다.

1. Introduction

During the development of dynamic fracture mechanics, many investigations have been made on the dynamic behavior of the impact loaded 3PB specimen and the influence of the boundary conditions at the impact points[1][2][3]. Nowadays, the dynamic analysis is also applied by the area of automobile[4][5]. The J-integral used as a ductile crack initiation criterion has been discussed for the dynamically loaded elastic-plastic 3PB specimens[6][7]. Some experimental methods to measure or estimate the J-integral history have been investigated and compared to the theoretically obtained values. For example, a caustic method has been successfully applied[6]. Another method is to use the multiple strain gauge measurements and then to estimate the J-integral value near the crack tip [7]. It is well known that a correlation between the J-integral and CMOD exists under the static and small scale yielding condition[8]. In this paper, numerical calculations are performed in order to find a correlation between the J-integral and CMOD for the dynamic nonlinear stationary crack. And then, the dynamical J-integral history has been estimated at different impact velocities(Vo=15, 30, 45, 60 m/s) from

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[1] Mechanical & Automotive Engineering, Kongju University
[*] Corresponding author: Jae-Ung Cho(jucho@kongju.ac.kr)

the relation between CMOD and J-integral. The property of elastic-plastic materials are considered. Numerical simulations are made by using the FEM code, ABAQUS[8]. These results can be utilized by the basic design in the impact analysis of automobile. The purpose of this study is to evaluate the safety parameter of the nonlinear plastic specimen by impact.

2. Finite element model

The geometry and the finite element model of the specimen are shown in Fig. 1 and Fig. 2

respectively. The dimensions of this specimen are given as shown in Fig. 2.

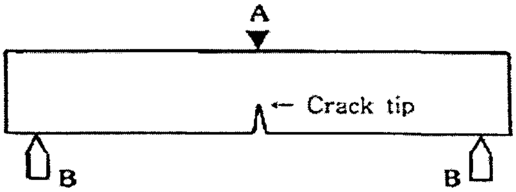

Fig 1. Geometry of the specimen.

Due to the symmetry, only half a specimen is modeled. A two-dimensional mesh including 92 eight node plane stress elements with 2*2 Gauss points, i. e. with reduced integration, is chosen.

The mesh near the crack tip is concentrated by using the degenerated eight node elements. In order to model a possible loss of contact at the load point A and at the support points B which had been discussed[2], gap elements with one degree of freedom are introduced. Furthermore, a lumped mass element is used to model the impact head in Fig. 2. No crack propagation is taken into account in the calculations. The dynamical J-integral and CMOD are calculated using the commercial finite element method code, ABAQUS[9]. In this code, the virtual crack extension method is successfully used to evaluate the J-integral in the dynamic case[10]. The dynamically loaded 3-point bending ductile steel specimens are made to compare with numerical simulation.

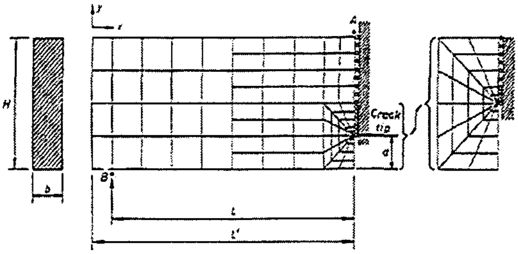

Fig 2. Finite element model for 3PB specimen with a quarter notch (L=300mm, L′ =320mm, H=75mm, b=18mm, a=H/4=18.75mm).

In order to investigate the accuracy of the present numerical method, its predictions are compared with the experimental results of Zehnder et al.[6]. In this experiment, a three point bend specimen was impact loaded at the middle point A with the velocity 5 m/s. the dimensions of the specimen were taken as (cf. Fig. 2):

L=305 mm, L'=319 mm, H=76 mm, b=10 mm, a=34 mm

The material used in the experiments[6] was a 4340 carbon steel. The material parameters were given as elastic modulus E= 200 GPa, Poisson's ratio υ= 0.3, mass density ρ= 7800 kg/m^3, yield stress σY =1030 MPa and the hardening exponent n= 22.5 for a large strain elstic-plastic von Mises model with power isotropic hardening. The impact head weight M= 195 Kg. The material in [6] is assumed to be relatively rate insensitive. With these parameters, a simulation was performed by using the finite element model described in Fig. 2 and the dynamical J-integral history was calculated numerically. A comparison with the experimental J-integral history in [6] was performed from impact up to 400μs at about which tunneling(thumb-nail effect) was observed in this experiment. This condition is no crack propagation or tunneling. The comparison between theoretical and experimental results is shown in Fig. 3. The theoretical predictions were obtained with both an elastic-plastic material as well as elastic-viscoplastic material. The elastic-plastic results and the experimental curve is found to agree closely. The elastic-viscoplastic results differ only slightly from experimental results. This means that the assumption of rate insensitivity of the material is reasonable for the low impact velocity. Therefore, the inspection of this specimen model in this presented paper is sufficient for the numerical simulation.

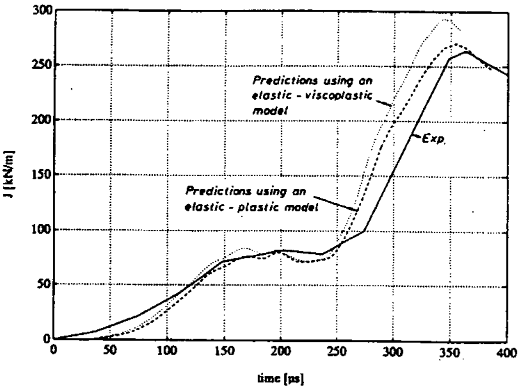

Fig 3. Comparison of numerical and experimental J -integral history.
The velocity of impact is V_0= 5 m/s.
Solid line shows the experimetal results of [6].
Dashed line shows the theoretical results using an elastic- plastic model.
Dotted line shows the theoretical results using an elastic- viscoplastic model.

3. Results from elastic-plastic analysis with 3PB specimen

Plane stress in FEM simulation is made under the assumption of no crack growth. An isotropic elastic-plastic hardening von Mises material is modeled with Young's modulus E= 206 GPa, Poisson's ratio υ= 0.3, Density ρ= 7800 kg/m^3, and yielding stress σ_Y= 360 MPa. The static stress to strain curve is shown in Fig. 4. The possible effects of rate dependent material properties are ignored.

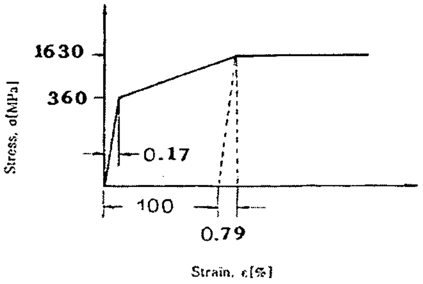

Fig 4. Static stress-strain curve of the material.

The specimen in this study is loaded at the middle point A by an impact head with a weight of 1.96 KN as shown in Fig. 1. Four different impact velocities are chosen for the simulations. These calculations are run up to 600μs after impact. The J-integral and CMOD history can also be found at every time step.

And then, it is found that the formula between J= J(V_o,t) and CMOD= δ_M(V_o,t) can be written as:

$$J(V_o,t) = \beta(V_0)\sigma_Y\delta_M(V_0,t) \tag{1}$$

where β(V_o) is estimated by the least square method. The following β(V_o) values are found as:

$$\beta(15)=0.72 \ \beta(30)=0.78 \tag{2}$$
$$\beta(45)=0.79 \ \beta(60)=0.76$$

These results suggest that β(V_o) is insensitive to the impact velocity V_o and so, we may take β= β(V_o)= 0.76, i. e. the mean value of the above results.

Indeed, the maximum error using this -value is less than 5% when compared with the use of -values given by (2). Figs. 5 to 8 show the J-integral and $\beta \cdot \sigma_Y \cdot$ CMOD history at the four different impact velocities of 15, 30, 45, and 60m/s with β=0.76 in case of elastic-plastic material.

It can be shown that the value of J-integral becomes more than that of $\beta \cdot \sigma_Y \cdot$ CMOD history at more than time of 400μs after impact in Figs. 5 to 8. As the impact velocity increases, the stress around crack tip increases. The value of J-integral becomes higher and so, this value tends to become higher than that of $\beta \cdot \sigma_Y \cdot$ CMOD history.

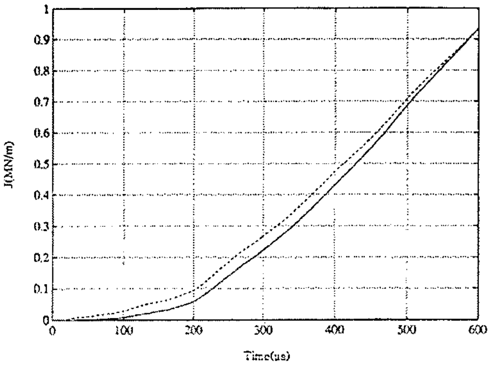

Fig. 5 J-integral(solid line) and β (V_o)$\sigma_Y \delta_M$(dashed line) history at the impact velocity of 15 m/s (β is chosen as 0.76).

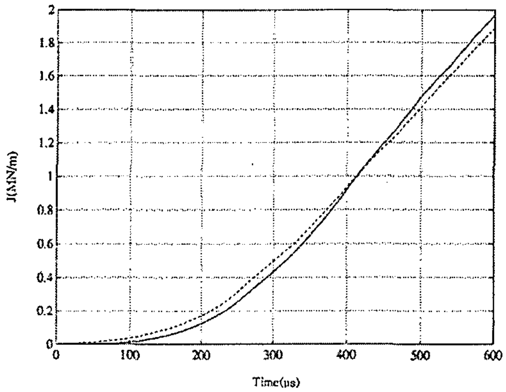

Fig 6. J-integral(solid line) and $\beta(V_o)\sigma_Y\delta_M$(dashed line) history at the impact velocity of 30 m/s(β is chosen as 0.76).

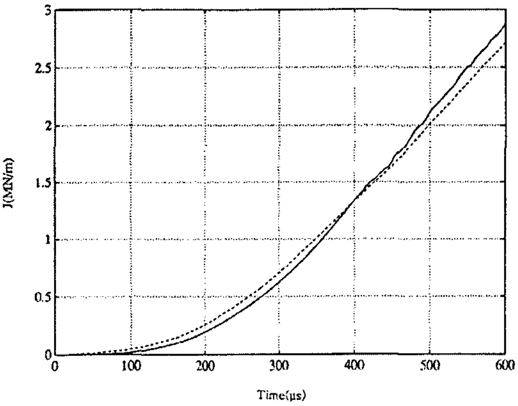

Fig 7. J-integral(solid line) and $\beta(V_o)\sigma_Y\delta_M$(dashed line) history at the impact velocity of 45 m/s (β is chosen as 0.76).

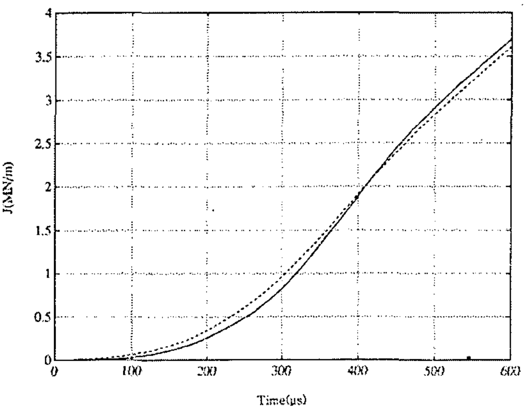

Fig 8. J-integral(solid line) and $\beta(V_o)\sigma_Y\delta_M$(dashed line) history at the impact velocity of 60 m/s (β is chosen as 0.76).

In Figs. 5 to 8, the J-integral and $\beta \cdot \sigma_Y \cdot$ CMOD history are found to be in a good agreement. It is found that the parameter $\beta(V_o)$ is independent on any impact velocity V_o in the studied range of impact velocity. By this result, as soon as the CMOD history $\delta_M(V_o,t)$ is measured from experiments at a specific impact velocity in case of elastic-plastic material, the J-integral can be calculated according to the relation $J(V_o,t)=\beta(V_o)\sigma_Y\delta_M(V_o,t)$.

4. Conclusions

From the impact analysis for the nonlinear plastic behavior with the dynamically loaded 3PB specimens, the results are obtained as follows;

1. The possibility relating the J-integral and the crack mouth opening displacement at the dynamically loaded 3PB specimens has been investigated. The J-integral can be the yielding stress multiplied by crack mouth opening displacement times $\beta(V_o)$.
2. In the calculations of this study, the impact velocities are varied from 15m/s up to 60m/s. The material with elastic-plastic property has been considered.
3. In case of elastic-plastic material, it is found that the parameter $\beta(V_o)$ is independent on any impact velocity, V_o in the studied range of impact velocity. Thus, once is determined by a finite element calculation for a specific material and geometry, the J-integral can be calculated from CMOD experiments.

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Jae-Ung Cho [Regular member]

- Feb. 1980 : Inha University, B. S. in Mechanical Engineering
- Feb. 1982 : Inha University, M. S. in Mechanical Engineering
- Aug. 1986 : Inha University, Ph. D in Mechanical Engineering
- Mar. 1988 ~ Present : Professor, Div. of Mechanical & Automotive Engineering, Kongju University

<Research Interest>
Design of mechanical & automotive parts, Assessment of durability, Dynamic analysis at fatigue or impact