1. Introduction
Carbon nanotube (CNT)-based polymer composites are candidate materials in numerous engineering applications, and a study on the fracture behavior of the nanocomposites is important. It is known that the crack response of polymeric materials is susceptible to loading rates. In general, high loading rates lead to decreased ductility. This can significantly influence the performance of the CNT-based polymer composites as structural materials. The purpose of this work is to investigate the loading rate-dependent fracture and electrical resistance responses of cracked CNT-based polymer composites under tension.

2. Experimental Procedure
The multi-walled nanotube (MWNT)/polycarbonate composites (Takiron Co., Ltd., Japan) were used in this study. The nanocomposites contained 2.5 wt.% MWNT. Neat polycarbonate samples were also studied for comparative purposes. Single-edge cracked specimens, shown schematically in Fig. 1, were cut from the MWNT/polycarbonate composite and polycarbonate plates. The specimen dimensions were 180 mm (length L) × 18 mm (width W) with a notch of depth 9 mm and width 1 mm. The as-received thicknesses of the plates were measured to be about 2.7 and 2.9 mm for the MWNT/polycarbonate composite and neat polycarbonate samples, respectively. The notch front was extended by tapping a razor blade resulting in a sharp crack front. Conductive silver paint was applied on one surface of the composite specimens to be used as electrodes. The distance between the electrodes was 40 mm and the electrode width was 4 mm. End tabs of length \( L_g = 22 \) mm were attached in order to electrically isolate the specimen from the metallic test fixture.

Fracture tests were conducted at ambient temperature in displacement control with displacement rates of 0.6, 60, 600 and 1200 mm/min using a servo-hydraulic testing machine. In order to determine the crack length, crack propagation was monitored using a high-speed microscope until the maximum load was achieved. Electrical resistance measurements were performed on the MWNT/polycarbonate composite during the fracture tests. The number of specimens was limited to two for each material and condition. Fracture surfaces after testing were examined using scanning electron microscopy (SEM).

3. Finite Element Analysis
A two-dimensional elastic-plastic finite element analysis was performed to calculate the J-integral at the onset of crack propagation, \( J \). The analysis was carried out using the incremental plasticity theory and the von Mises yield criterion. The following equations were used to describe the uniaxial stress (\( \sigma \))-strain (\( \varepsilon \)) behaviors of the polycarbonate and the 2.5 wt.% MWNT/polycarbonate composite:

\[
\sigma = \begin{cases} 
E\varepsilon, & \text{for } \varepsilon \leq \varepsilon_{YS}, \\
\alpha \varepsilon^A, & \text{for } \varepsilon_{YS} < \varepsilon \leq \varepsilon_T, \\
\beta \exp \left( \beta \varepsilon \right), & \text{for } \varepsilon_T < \varepsilon,
\end{cases}
\]  

where \( E \) is the Young's modulus, \( A \) is the strain hardening exponent, \( \varepsilon_{YS} \) is the yield strain, \( \varepsilon_T \) is the transition strain, and \( \alpha, \beta \) and \( B \) are constants. \( E, A, \varepsilon_{YS} \) and \( \varepsilon_T \) were considered as the independent material constants and we impose continuity of the stress \( \sigma \) at \( \varepsilon = \varepsilon_{YS} \) and \( \varepsilon = \varepsilon_T \), as well as continuity of the tangent modulus \( d\sigma/d\varepsilon \) at \( \varepsilon = \varepsilon_T \). The resulting equations are: \( \alpha = E/\varepsilon_{YS}^A, \beta = \alpha \varepsilon_T^A/\exp \left( A/2 \right) \) and \( B = A/2\alpha^2 \).

For the neat polycarbonate and the 2.5 wt.% MWNT/polycarbonate composite, \( E, A, \varepsilon_{YS} \) were determined based on the experimental tensile stress-strain curves. It should be noted that the transition strain \( \varepsilon_T \) was taken to be 0.5.

The model consisted of four-noded plane stress elements. Due to symmetry, only a half of the specimen was modeled. The gripped portion was not included in the model. The finite element model and the boundary conditions are shown in Fig. 2, where O-xyz is the Cartesian coordinate system. The crack surface was traction free. The loading was simulated by applying the constant prescribed displacement in the y-direction \( u^* \) at \( y = L/2 - L_g \) \((0 \leq x \leq W)\). The summation of nodal forces at \( y = L/2 - L_g \) \((0 \leq x \leq W)\) corresponds to the experimental load at the onset of crack propagation. The J-integral is given by

\[
J = \int_{r_0} \left\{ \frac{w\varepsilon_x}{2} - \left( \sigma_{xx}\frac{\partial u_x}{\partial x} + \sigma_{xy}\frac{\partial u_y}{\partial x} + \sigma_{yx}\frac{\partial u_x}{\partial y} + \sigma_{yy}\frac{\partial u_y}{\partial y} \right) n_x \right\} d\Gamma,
\]  

where \( w \) is the width of the specimen.
allows responding identified circles at error wt.% displacement the change results crack traction are, at 4.6, shown as crack propagation was proposed. The resistance change due to crack propagation is given as

\[ \frac{\Delta R}{R_0} = \frac{\Delta \alpha}{W - \alpha_0 - \Delta \alpha}, \]

where \( \Delta \alpha \) is the crack extension amount, and \( \alpha_0 \) is the initial crack length. Fig. 4 shows the experimental and predicted results for the relationship between the normalized resistance change \( \Delta R/R_0 \) and the crack extension amount \( \Delta \alpha \) of the 2.5 wt.% MWNT/polycarbonate composite at 0.6 and 60 mm/min displacement rates. Fig. 5 shows the variation of the J-integral at the onset of crack propagation, \( J_i \), with the displacement rate for the neat polycarbonate and the 2.5 wt.% MWNT/polycarbonate composite. In the figure, the error bars indicate the maximum and minimum J-integrals at each displacement rate and material, and open and solid circles are average values. For the specimens which failed in a ductile manner, the onset of crack propagation was identified from the visual crack extension observations and corresponding load was utilized to evaluate \( J_i \). In the case of brittle fracture, the catastrophic onset of crack propagation allows the peak load to be used for the calculation of \( J_i \). Fig. 6 shows the SEM images of the fracture surfaces for the 2.5 wt.% MWNT/polycarbonate composite at the displacement rates of 0.6, 60, 600 and 1200 mm/min.

In concluding, we studied the fracture and electrical resistance behaviors of cracked MWNT/polycarbonate composites subjected to high-rate tensile loading. The findings of this study may be useful for commercial applications of CNT-based polymer composites.