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Technical Note

# Effect of crack-tip plasticity on crack length estimation methods for SENB sample

S. Xu *, G. Shen, W.R. Tyson

*CANMET-Materials Technology Laboratory, 568 Booth Street, Natural Resources Canada, Ottawa, Ont., Canada K1A 0G1*

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**Abstract**

This note is a discussion of "Crack length calculation for bend specimens under static and dynamic loading" by Jiang FC, Rohatgi A, Vecchio KS, Adharapurapu RR [Engineering Fracture Mechanics 2004;71:1971–85]. Crack-tip plasticity of SENB samples were evaluated and its effect on unloading compliance and crack length estimation were assessed by the FEA method.


*Keywords:* Compliance method; Finite element method; Toughness testing; Plasticity; SENB sample

Crack-length measurement techniques are very important in many fracture toughness tests, such as those to determine $J$-integral ($J$) and crack-tip opening displacement (CTOD) resistance curves, since these require determination of crack lengths during testing. A widely accepted method of crack-length measurement, the crack-mouth opening displacement (CMOD) compliance method, uses the unloading compliance of CMOD vs. load to estimate crack length. The advantages of this method are (i) no additional measurements need are required since load and CMOD are used to evaluate $J$ and CTOD; (ii) no correction is required for machine compliance since this has no effect on CMOD; and (iii) the relationship between unloading compliance and crack length can be easily established by elastic numerical calculation. The CMOD unloading compliance method has been used in some standards, such as ASTM E 1820 and BS 7448 (Part 4). Alternatively, the unloading compliance of load–line displacement (deflection) rather than CMOD vs. load can also be used to evaluate crack length although, in this case, consideration must be given to machine compliance. The unloading compliance method requires frequent unloading during

* Corresponding author. Tel.: +1 613 992 1960; fax: +1 613 992 8735.
*E-mail address:* sxu@nrcan.gc.ca (S. Xu).

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testing which is not always possible, e.g. in dynamic testing such as Charpy impact and drop-weight tear testing (DWTT). Other methods have been developed to estimate crack length in these cases, e.g. the key-curve method [1].

In a recent paper by Jiang et al. [2], interesting experimental data have been reported for single-edge-notch-bend (SENB) samples of a high-strength steel and 6061-T6 aluminum alloy. These authors suggest that the crack length can be estimated using the ratio of deflection to load ($\delta/P$) (referred to here as the apparent compliance) as an approximation to the true unloading compliance $\Delta\delta/\Delta P$. This method will be referred to here as the ''elastic method''. They report that values obtained using this method were in good agreement with results from a crack propagation gauge in a dynamic test. They also report measurements from quasi-static tests, but do not compare the estimated crack lengths with measurements on the fracture surface. The elastic method [2] neglects the effect of crack-tip plasticity. This is obviously appropriate in the elastic loading regime, and could provide an acceptable approximation in cases of confined plasticity. The crack length estimated by this method is the ''effective'' crack length as described in ASTM E 561 [3]. As pointed out by Anderson [4], the ASTM E 561 standard is appropriate only when the plastic zone is small compared with the in-plane dimensions of the test specimen, and the practice of using the effective crack extension is inconsistent with the $J_{Ic}$ and $J$–$R$ resistance curve approach where $J$ is plotted against the physical crack extension. Indeed, Jiang et al. state that their method should only be used in cases of small-scale yielding (SSY) [2], although they do not state the criteria defining SSY conditions. While it is generally accepted that in SSY the plastic zone is well contained, there does not seem to be a universally accepted quantitative statement of the requirements that must be met for this to be the case. This will be discussed further below.

In the present study, the difference between unloading compliance ($\Delta\delta/\Delta P$) and apparent compliance ($\delta/P$) under increasing load and its effect on crack length estimation have been investigated using finite-element analysis (FEA). For simplicity, only quasi-static loading has been studied.

The quasi-static mechanical properties of the high-strength steel and the 6061-T6 aluminum [2] are listed in Table 1. The uniaxial stress–strain behavior of these materials is described by the following Ramberg–Osgood relation:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n, \tag{1}$$

where $\sigma_0$ is a reference stress that is usually set equal to the yield strength, and $\varepsilon_0 = \sigma_0/E$ ($E_{steel} = 207 \times 10^9$ MPa and $E_{Al} = 69 \times 10^9$ MPa). The parameter $\alpha$ is assumed to be 1 and the exponent $n$ is estimated using the following equation [5]:

$$\frac{\left(\frac{1}{0.002n}\right)^{1/n}}{\exp\left(\frac{1}{n}\right)} = \frac{\sigma_{YS}}{\sigma_{UTS}}. \tag{2}$$

The values of $n$ for these two materials are also listed in Table 1.

As implied by Jiang et al. [2], quasi-elastic methods apply only to situations of well-contained yielding. In other words, the plastic zone size must be small compared with the dimensions of the sample. The plastic

Table 1
Mechanical properties and $n$ values

| Materials | YS (MPa) | UTS (MPa) | $n$ |
|---|---|---|---|
| High-strength steel | 1053 | 1249 | 14.8 |
| 6061-T6 aluminum | 282 | 310 | 22.3 |