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Evaluation Method for Fracture Mechanics-Based Material Toughness from Charpy Impact Test

Yasuhito Takashima[1, a], Mitsuru Ohata[1, b] and Fumiyoshi Minami[1, c]

[1]Department of Manufacturing Science, Graduate School of Engineering, Osaka University, 2-1, Yamada-Oka, Suita, Osaka, 565-0871, JAPAN

[a]takasima@mapse.eng.osaka-u.ac.jp, [b]ohata@mapse.eng.osaka-u.ac.jp, [c]minami@mapse.eng.osaka-u.ac.jp

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Abstract. The V-notch Charpy impact test, which has been widely used as a pre-qualification test of material toughness, is also used for estimating "fracture mechanics-based toughness of materials". However, there have not been any theoretical estimation methods to correlate Charpy test results with CTOD fracture toughness, whereas many empirical correlations between these testing results have been suggested. In this research work, we suggest a method for evaluating fracture mechanics based material toughness, which is measured with three-point bend or compact specimens with fatigue pre-cracks, from the Charpy impact test. This method is based on the Weibull stress criterion, in which the Weibull stress at brittle fracture could provide materials constants independent of differences in loading rate and specimen geometry. The applicability of this method is discussed by conducting instrumented Charpy impact tests and CTOD fracture toughness tests in the lower fracture transition-temperature range for two structural steels of the 780-MPa strength class with different work-hardening properties. It is shown that this method makes it possible to transfer the Charpy impact test results to the fracture mechanics-based toughness for two steels with different work-hardening properties.

Introduction

The fracture mechanics approach is used to assess a structural steels fitness for service. In the fracture mechanics assessment of crack-like defects, it is necessary to measure the material fracture toughness as the plane strain toughness K_{Ic}, J_{cr} or critical CTOD δ_{cr}. The material fracture toughness is evaluated by K_{Ic}, CTOD and Charpy impact tests. But, Charpy impact test results can not be applied directly to the fracture mechanics assessment. However, the Charpy impact test is easier and less expensive to conduct than the fracture toughness test. Therefore, there are industrial needs to estimate critical CTOD from correlations with the Charpy impact test.

A number of empirical correlations between the Charpy absorbed energy vE and fracture toughness have been proposed. However, there have not been any theoretical estimation methods to correlate Charpy and CTOD fracture mechanics testing results, whereas many empirical correlations between these testing results have been suggested. This is due to not only the impossibility of direct application of the fracture mechanics approach to Charpy test specimens with V-notches, but also an incomplete understanding of what material properties can influence the correlation between them.

The aim of this work is to establish a correlation method between Charpy absorbed energy, vE, and the fracture toughness value, CTOD. In this research work, we suggest an evaluation method for fracture mechanics-based material toughness from the Charpy impact test, considering the effect of material properties on stress fields near the notch or crack tip. This method is based on the Weibull stress criterion, in which the Weibull stress that is influenced by the mechanical and toughness properties of materials is assumed to provide materials constants. The applicability of this method is discussed by conducting instrumented Charpy impact tests and CTOD fracture toughness tests in the lower fracture transition temperature range for two structural steels of the 780-MPa strength class with different work hardening properties. The stress fields of Charpy and compact specimens are analyzed by 3D-FEM considering strain-rate effects on flow stress and temperature rise during dynamic loading.

Experiments

Two high-strength structural steels of the 780-MPa class, HT780HYR and HT780LYR, were used in the experiments. Table 1 shows the chemical composition and mechanical properties of these steels. The materials were selected in terms of the yield-to-tensile ratio YR, which exerts a strong influence on crack-tip stress fields.

Table 1 Chemical composition and mechanical properties of structural steels used.

	Chemical composition [mass%]					Mechanical properties			
	C	Si	Mn	S	C_{eq}	σ_Y [MPa]	σ_T [MPa]	ε_T [%]	YR= σ_Y / σ_T
HT780HYR	0.10	0.23	0.95	0.001	0.53	837	864	6.8	0.97
HT780LYR						720	934	4.8	0.77

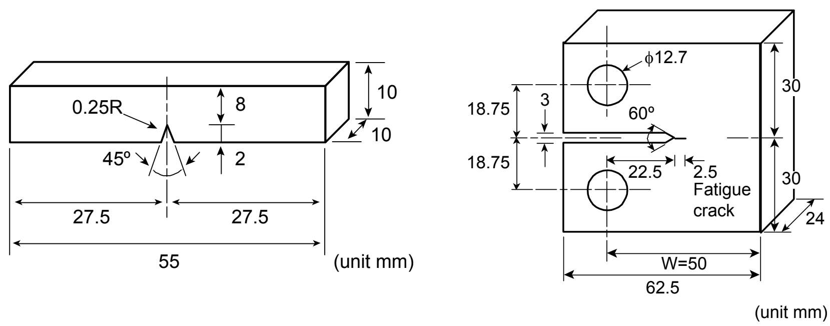
C_{eq}=C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14

σ_Y: Yield stress, σ_T: Tensile strength, ε_T: Uniform elongation, YR: yield-to-tensile ratio

The present experiments include instrumented Charpy tests and fracture toughness tests. Figure 1 shows the configuration of the specimens used. The crack length in the compact specimen including a fatigue pre-crack was 25 mm, which was equal to the plate thickness.

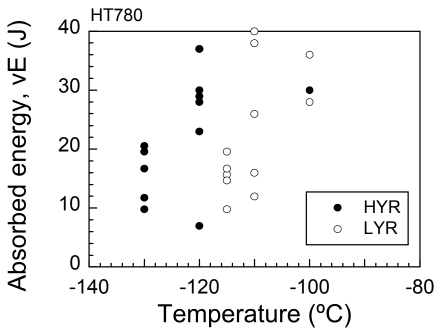
The Charpy impact test was conducted in a temperature range from -130ºC to -100ºC for HT780HYR steel and from -115ºC to -100ºC for HT780LYR steel. The test temperatures were selected to induce brittleness over a large portion of the notch section. The impact test machine featured a pendulum striker of 447 N with an arm length of 850 mm, which produced an initial potential energy of 490 J. Elastic strain gauges of a semiconductor type were pasted onto both sides of the pendulum striker edge to measure the impact load. The position of the striker during impact loading was measured with an angular displacement transducer, and the output signals from the strain gauge and displacement transducer were recorded with a digital data logger through a high- frequency amplifier. The sampling interval time was 0.5 μs for each signal, which was short enough to record the dynamic fracture phenomena in impact tests. The specimens were cooled in a cryogenic bath filled with liquid nitrogen and alcohol, with each specimen held in the bath at the test temperature within ±1ºC for at least 15 minutes prior to impact testing. The specimen was broken within 1 sec. after removal from the cooling bath.

The fracture toughness test was conducted on each compact specimen in the temperature range of -100ºC to -40ºC for each steel, in a cooling bath filled with liquid nitrogen and alcohol. Each specimen was held at the test temperature within ±1ºC for at least 20 minutes before testing, and loaded at a crosshead speed of 0.1 mm/s. The load and crack-mouth displacement V_g were measured with a load cell and a double-cantilever-type clip gauge. The crack-tip opening displacement (CTOD) was calculated from the mouth displacement V_g, according to the procedure specified in the British Standard of Fracture Mechanics Toughness Tests (BS7448-Part I).

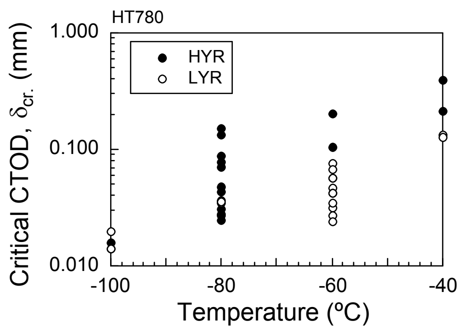


(a) Charpy specimen (b) Compact specimen

Fig. 1 Configuration of specimen used.



(a) Charpy impact test



(b) Fracture toughness test

Fig. 2 Charpy and fracture toughness test results.

The results of Charpy impact test and fracture toughness test are shown in Figure 2. The temperature at which the absorbed energy was equal to 20 J was -130ºC and -115ºC for HT780HYR and HT780LYR steels, respectively. On the other hand, the temperature at which the critical CTOD was equal to 0.1 mm was -80ºC and -50ºC for HT780HYR and HT780LYR steels, respectively. The temperature difference at brittle fracture initiation between the Charpy impact test and fracture toughness test was 50ºC and 65ºC for HT780HYR and HT780LYR steels, respectively. The figure shows that the work-hardening property of steel affects the relationship between the Charpy and fracture toughness test results.

Numerical analysis

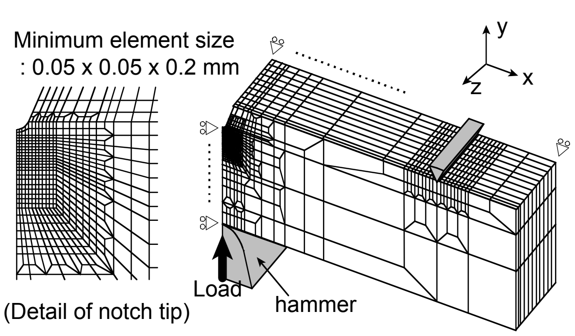
The stress fields in the Charpy and compact specimens were analyzed with FE-code, ABAQUS ver.5.8, which implements a procedure to solve the temperature and stress/displacement fields simultaneously.

Figure 3 shows the FE-models used. Because of symmetry, one quarter of the Charpy and compact specimens were modeled. Elements used were eight-node iso-parametric elements with eight Gaussian points. The Charpy model has a minimum element with dimensions of 0.05 x 0.05 x 0.2 mm near the notch tip while the compact model has one measuring 0.05 x 0.05 x 0.05 mm near the crack tip. The loading rate for the Charpy model was 5.4 m/s in accordance with the experimental measurement.

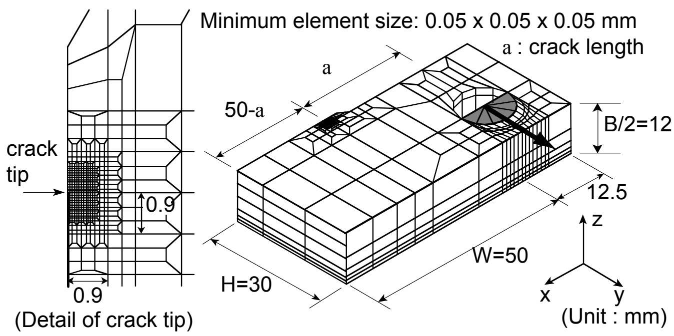
Flow properties of the material in the FEM follow the strain hardening in the form of

$$\bar{\sigma} = \sigma_Y \left(1 + \bar{\varepsilon}_p / \alpha\right)^n \ , \tag{1}$$

where $\bar{\sigma}$ and $\bar{\varepsilon}_p$ are the equivalent stress and equivalent plastic strain, respectively, σ_Y denotes the



(a) Charpy specimen



(b) Compact specimen

Fig. 3 FE-models used.

yield stress, n represents the strain hardening exponent, and α is a material constant. According to Eq. (1), the tensile strength σ_T and uniform elongation ε_T are given by Eqs. (2) and (3), respectively.

$$\sigma_T = \sigma_Y (n/\alpha)^n \exp(\alpha - n) \tag{2}$$

$$\varepsilon_T = \exp(n - \alpha) - 1 \tag{3}$$

The strain rate's effects on the flow stress were included in the FEM in the following manner: The dependence of the yield stress and tensile strength on the strain rate was evaluated by

$$\sigma = B \exp(C/R), \tag{4}$$

where B and C are material constants, and R is the rate-temperature parameter [1], which is expressed as

$$R = (T + \Delta T)\ln(A/\dot{\varepsilon}), \tag{5}$$

where $\dot{\varepsilon}$ is the strain rate, T and ΔT are the test temperature and temperature rise, respectively, and A is a material constant.

The uniform elongation ε_T was assumed to be independent of the strain rate and the temperature. Under the dynamic loading condition, high-speed straining will generate heat adiabatically. It was assumed in the FE-analysis that 90% of plastic work is transferred as heat.

The inertial effect produced by the acceleration of the specimen during dynamic loading was eliminated by a quasi-static analysis. Nakamura, et al. [2] introduced the concept of a transition time t_T, which defines the point in the response after which inertial effects diminish rapidly. t_T is defined when the kinetic energy is equal to the deformation energy of the specimen. They proposed and validated that a quasi-static analysis yields acceptable accuracy after the time greater than $2 \times t_T$ when inertial effects can be neglected. In the present Charpy test, the loading time-to-fracture initiation exceeded $2 \times t_T$. Hence, this quasi-static analysis can be used to evaluate Charpy impact testing.

Fracture toughness prediction

In this work, we discussed the applicability of correlation between Charpy absorbed energy and fracture toughness using the Weibull stress criterion. The Weibull stress [3] is given by integrating a near-tip stress σ_{eff} over the fracture process zone V_f in the form

$$\sigma_W = \left[\frac{1}{V_0} \int_{V_f} (\sigma_{eff})^m \, dV_f \right]^{1/m}, \tag{6}$$

where V_0 and m are the reference volume and a material constant, respectively. The Weibull stress σ_W is a fracture driving force. In this research work, it is assumed that the critical Weibull stress at brittle fracture initiation is independent of the loading rate and the specimen geometry.

The critical Weibull stress $\sigma_{W,cr}$ at brittle fracture initiation obeys the Weibull distribution with two parameters

$$F(\sigma_{W,cr}) = 1 - \exp\left[-\left(\frac{\sigma_{W,cr}}{\sigma_u} \right)^m \right], \tag{7}$$

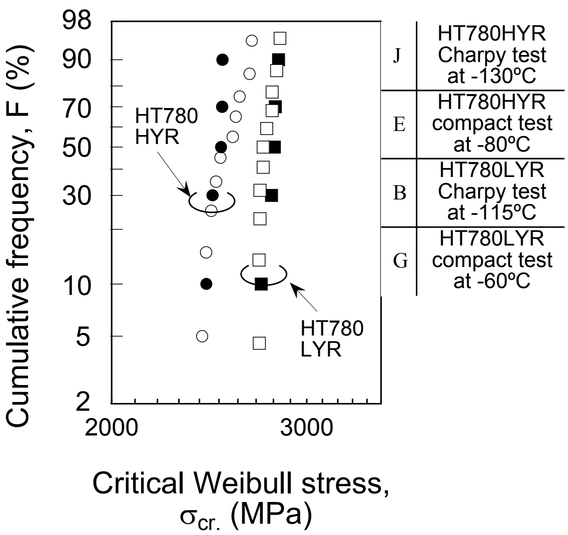


Fig. 4 Cumulative distribution of critical Weibull stress for Charpy and compact specimens.

where m and σ_u are assumed to be material properties independent of the specimen geometry and loading rate. The m-value was determined by using a maximum likelihood method [4] with compact test results for each steels, and the critical Weibull stress of the Charpy specimen was calculated with this m-value. The cumulative distribution of the critical Weibull stress at the onset of brittle fracture is shown in Figure 4. No remarkable difference can be seen between the distributions of $\sigma_{W,cr}$ for the compact and Charpy specimens.

Based on the Weibull stress criterion, the critical CTOD of the compact specimen was estimated from the Charpy impact test results. This estimation procedure is shown in Figure 5. Critical Weibull stress is determined by experimental results and calculated Weibull stress at brittle fracture

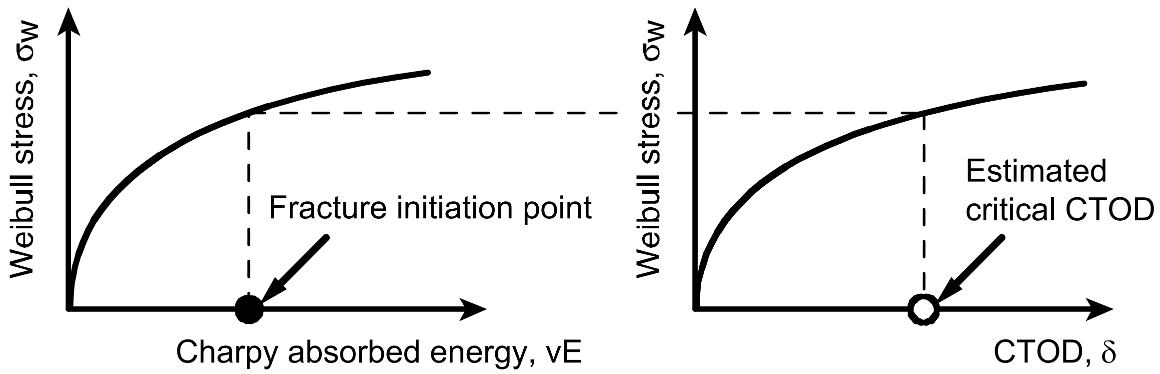
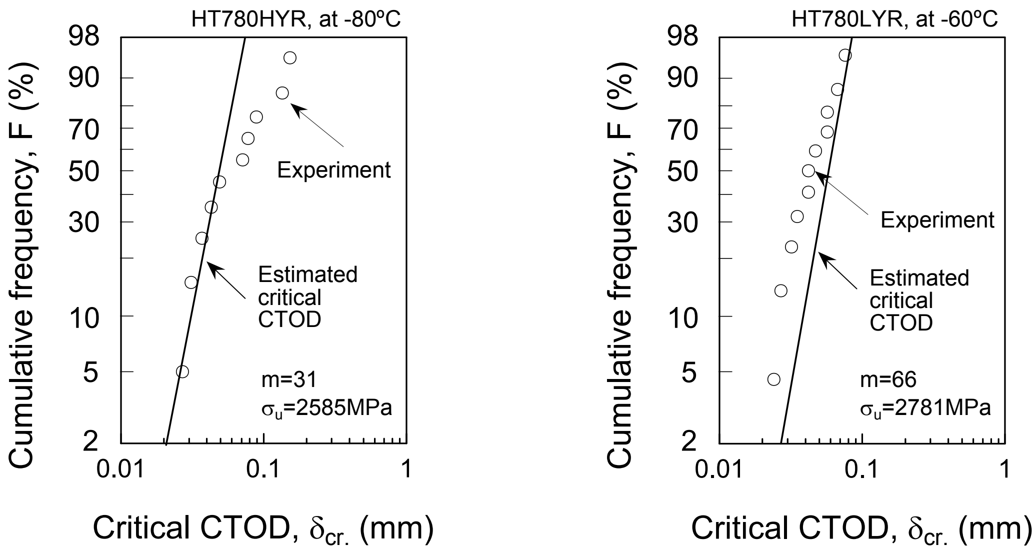


Fig. 5 Transfer of Charpy impact test results to material fracture toughness based on the Weibull stress criterion.



(a) HT780HYR (b) HT780LYR

Fig. 6 Cumulative predicted distributions of critical CTOD of compact specimen.

initiation. Next, we calculate the Weibull stress as a function of the CTOD at various temperatures, and finally estimate the critical CTOD.

Figure 6 shows the resulting prediction of the cumulative distributions of the critical CTOD. The numerical predictions of the critical CTOD agree well with experimental data, and it is clear that this method makes it possible to transfer the Charpy impact test results to the fracture mechanics-based material toughness for two steels with different work-hardening properties.

Conclusions

We discussed the applicability of an evaluation method for fracture mechanics-based material toughness from the Charpy impact test, which is based on the Weibull stress criterion by conducting instrumented Charpy impact tests and CTOD fracture toughness tests in the lower fracture transition-temperature range for two structural steels of the 780-MPa strength class with different work-hardening properties.

Evaluating a fracture's driving force with the Weibull stress makes it possible to transfer the Charpy impact test results to material fracture toughness. The compact specimen's critical CTOD estimated from the Charpy impact test results by the Weibull stress criterion agree well with experimental data.

Furthermore, we discussed the applicability of this method for steels with different work-hardening properties. Results indicate that the critical CTOD can be predicted for each steel by this method, and we have shown that this method enables researchers to evaluate the fracture mechanics-based material toughness from the Charpy impact test results of steels with different work-hardening behaviors.

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