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Brittle crack propagation/arrest behavior in steel plate – Part III: Discussions on arrest design

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ABSTRACT

The brittle crack arrest design of a steel plate is discussed based on systematic model simulations. The simulation results show that an essential crack arrest temperature (ECAT) exists in the temperature dependence curve of arrest toughness. Based on the investigations of the possible factors influencing the temperature dependence of the arrest toughness and the ECAT, an estimation formula is proposed for the required arrest toughness at the design temperature for arbitrary values of the plate strength and thickness. The prediction results obtained using the estimation formula are consistent with the experimental results obtained from past wide duplex crack arrest tests.

1. Introduction

In recent times, the strength and thickness of steel plates used for large ship structures have increased considerably. Such a situation could increase the possibility of brittle fracture, which has sometimes caused serious damage to large steel structures. The establishment of the concept of brittle crack arrest design in addition to brittle fracture initiation control provides "double integrity" to the structures. This concept is essential for the integrity of some large structures whose accidental failure could have major social consequences.

The current guidelines for the brittle crack arrest design of a steel plate for a ship structure have been prescribed in terms of the required arrest toughness as $K_{ca} \geqslant 190\ \mathrm{MPa}\sqrt{\mathrm{m}}$ ($K_{ca} \geqslant 6000\ \mathrm{N/mm^{3/2}}$) for a steel plate with a thickness of 80 mm or less at a design temperature of $-10\ ^\circ\mathrm{C}$ [1,2]. The effect of the arrest toughness K_{ca} on the design temperature is generally evaluated by the temperature gradient crack arrest test, whose standard is specified in WES 2815 [3]. However, the current arrest design regulated by the current guidelines has some problems from both academic and practical perspectives as listed below:

- The required K_{ca} represents the arrest toughness that can arrest a crack under any conditions of the applied stress and the crack length and is therefore the most important concept in current arrest design. However, the physical basis of the required K_{ca} has not yet been clarified.

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Nomenclature

a	crack length
a_0	initial crack length for model simulation
a_a	arrest crack length
a_t	arrest crack length in test plate
E	Young's modulus ($= 206$ GPa)
E_t	tangent modulus
f_K	correction factor for crack velocity with respect to dynamic stress intensity factor [18]
I_n	integration constant in Hutchinson–Rice–Rosengren solution [14]
k_0, K_0	material constants for empirical curve of temperature dependence of K_{ca} expressed by Arrhenius equation
K	stress intensity factor
K_{ca}	arrest toughness
K_d	dynamic stress intensity factor
K_{sl}	crack closure effect of uncracked side ligament as expression of stress intensity factor
K_σ	stress intensity factor by remote tensile stress
$\widetilde{K}_{ca(-10\,^\circ C)}$	required K_{ca} at design temperature of $-10\,^\circ$C
n	strain hardening exponent
(r, θ)	polar coordinate with origin at crack tip and $\theta = 0$ for crack propagation direction
r_c	length of process zone
s	stress singularity parameter
t	thickness of plate
T	temperature
T_0	room temperature ($= 293$ K)
T_{top}	temperature at top of specimen
V	crack velocity
V_R	elastic Rayleigh wave velocity
W	width of plate
(x, y, z)	coordinates
(α, β, γ)	coefficients of design formula in Eq. (11)
$\dot{\varepsilon}_e$	equivalent strain rate
$\dot{\varepsilon}_{e0}$	quasistatic equivalent strain rate ($= 5.0 \times 10^{-5}$ s^{-1})
ν	Poisson's ratio (= 0.3)
σ_{app}	remote applied stress
σ_f	fracture stress
$\sigma_{yy}[r, \theta]$	local tensile stress
$\sigma_Y[T, \dot{\varepsilon}_e]$	yield stress
σ_{Y0}	yield stress at room temperature
$\Sigma_e[\theta, V]$	nondimensional function (= 1 for $\theta = 0$)
$\Sigma_{ij}[\theta, V]$	component of nondimensional function tensor (= 4 for plane strain condition)
Ω_{sl}	area of uncracked side ligament

- The current guidelines are based on the experimental results of crack arrest tests using full-scale structural component specimens [4]. Therefore, the applicability of the required K_{ca} is limited to specific structural components having T-shape weld joints composing steel plates with thicknesses of 80 mm or less [1,2]. That is, the required K_{ca} based on the current guidelines cannot assure the arrestability of a simple plate. Past experimental results have shown that the required K_{ca} for a simple plate might be larger than that for a structure with welded joints using the same plate [4].
- The experiments underlying the current guidelines are limited to only a few conditions, and the generality of the evaluated value of the required K_{ca} has not been sufficiently validated. This is because the implementation of the wide duplex crack arrest tests or full-scale structural component model tests [4] is extremely expensive.
- The strength and thickness of steel plates used for large ship structures have dramatically increased in recent years. Although it has been known that a trade-off relationship exists between the strength and the brittle fracture initiation toughness, the influence of the strength on the brittle crack arrestability has not been sufficiently clarified. In addition, although it has been empirically known that a thicker plate may require a higher required K_{ca}, their quantitative relationship has not been clarified. Therefore, it is necessary to investigate the influences of these parameters on the required K_{ca} such that a reasonable brittle crack arrest design can be realized.

In the previous parts of this paper [5,6], we proposed a model to simulate brittle crack propagation/arrest behavior in a steel plate based on the local fracture criterion [7–9]. In the model, crack behavior is simulated by performing repeated cal-