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Brittle crack propagation/arrest behavior in steel plate – Part I: Model formulation

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ABSTRACT

A formulation to simulate brittle crack propagation/arrest behavior in steel plates is proposed based on the local fracture criterion. The crack behavior is simulated within a short time by repeated calculations solving the simultaneous governing equations at the crack front: (a) fracture condition, (b) strain hardening, (c) yield point and (d) dynamic stress intensity factor, without any arbitrary parameters and any complicated procedures. The crack is predicted to be arrested when the above simultaneous equations do not give any solutions or when the uncracked side-ligaments cover all the thickness of the plate at the crack front.

1. Introduction

Brittle fracture in large structures sometimes causes serious damages. Prevention of brittle crack propagation as well as crack initiation is essential as “double integrity” for structural integrity. Although it is the most important to prevent brittle crack initiation by controlling welding defects and fatigue cracks by the repeated load during service, it is actually difficult to remove welding defects completely. It is thus required to prevent brittle crack propagation together with proper crack arrest design.

Nippon Kaiji Kyokai recently published a guideline on brittle crack arrest design [1]. Subsequently, International Association of Classification Societies (IACS) published a unified requirement UR S33 [2]. Fundamental procedures to prevent brittle crack propagation in thick steel plates of hatch side coaming, which is the vertical wall surrounding an opening in a deck, of a containership are presented as the requirement of arrest toughness is $K_{ca} \geqslant 190\ \mathrm{MPa}\sqrt{\mathrm{m}}$ ($6000\ \mathrm{N/mm}^{3/2}$) to arrest any brittle crack propagation for steel plates with thickness of less than 80 mm.

The requirement is based on the results of systematic experiments using two types of brittle crack arrest tests, temperature-gradient tests and wide duplex tests [3–8]. The temperature-gradient tests are used to measure K_{ca} as a function of temperature T [9–11]. On the other hand, the wide duplex tests are used to clarify the required K_{ca} for design of actual structures. The outlines of the respective tests are described in the second part of the paper [12]. In addition, the detail of the

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Nomenclature

a	crack length
a_0	initial crack length for model simulation
$a_{\max}$	the maximum crack length for finite element analysis
d_{sl}	depth of uncracked side-ligament
d_{sl}^{i}	depth of uncracked side ligament for time step i
E	Young's modulus (=206 GPa)
E_t	tangent modulus
f_K	correction factor of crack velocity for dynamic stress intensity factor [46]
f_r	correction factor of crack velocity for depth of uncracked ligament
h	function of elastic wave velocities
i	calculation time step $(=1, 2, \ldots)$
k	parameter to express the intensity of stress in an asymptotic solution for elastic linear strain hardening solid [39]
k_{sl}	constant (=2)
K	stress intensity factor
K_{ca}	arrest toughness
K_d	dynamic stress intensity factor
K_p	stress intensity factor by a pair of point forces on crack surfaces
K_{sl}	crack closure effect of uncracked side-ligament as an expression of stress intensity factor
K_σ	stress intensity factor by remote tensile stress
l_{sl}	length of uncracked side-ligament
L	length of plate
n	strain hardening exponent
P	pair of point forces on crack surfaces
(r, θ)	polar coordinate with origin at crack-tip and $\theta = 0$ for crack advancing direction
r_c	length of process zone
r_p	plastic zone size for static crack
r_{pd}	plastic zone size for dynamic propagating crack
s	stress singularity parameter
s_0	stress singularity parameter s for $V = 0$ calculated by Amazigo and Hutchinson [41]
t	thickness of plate
T	temperature
T_0	room temperature (=293 K)
T_{ca}	crack arrest temperature
V	crack velocity
V_b	elastic bar wave velocity $(=\sqrt{E/\rho})$
V_R	the elastic Rayleigh wave velocity
W	width of plate
(x, y, z)	coordinates
α	normalized tangent modulus $(=E_t/E)$
β	normalized crack velocity $(=V/V_s)$
δ	crack opening displacement [49]
$\dot{\varepsilon}_e$	equivalent strain rate
ε_e	equivalent strain
ε_f	critical strain for shear fracture (=0.1)
$\dot{\varepsilon}_{e0}$	quasi-static equivalent strain rate $(=5.0 \times 10^{-5}\ \mathrm{s}^{-1})$
ε_{ij}	component of plastic strain tensor
$\varepsilon_{\mathrm{sl}}$	average shear strain at uncracked side-ligament
ν	Poisson's ratio (=0.3)
ρ	material density $(=7.87 \times 10^3\ \mathrm{kg/m^3})$
σ_{app}	remote tensile stress
σ_e	equivalent stress
σ_f	local fracture stress
σ_{ij}	component of stress tensor
σ_Y	yield stress
σ_{Y0}	yield stress at room temperature
$\dot{\sigma}_e$	equivalent stress rate
$\bar{\sigma}_{yy}$	average tensile stress within a process zone
Σ_e	non-dimensional function (=1 for $\theta = 0$)
Σ_{ij}	component of non-dimensional function tensor ($\Sigma_{yy} = 4$ for plane strain condition)
Ω_{sl}	area of uncracked side-ligament