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Surface cracks in finite thickness plates under thermal and displacement-controlled loads – Part 2: Crack propagation

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ABSTRACT

Surface cracks in finite-thickness plates subjected to thermal or displacement-controlled loads are considered with a focus on crack propagation. Detailed crack propagation analyses are performed and the effect of loading type on crack propagation patterns and lives are systematically investigated. The results show that although there are some slight differences between the crack propagation patterns and lives for the uniform stress and displacement loading, there exist increasingly higher differences for the bending stress and displacement loads during crack growth. It is shown that propagation lives are higher in the case of displacement/thermal loading compared to those of mechanical/stress loads.
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1. Introduction

Engineering structures are subjected to mechanical (load-controlled), thermal and/or displacement-controlled loading conditions. Some examples for thermal/displacement controlled-loads are parts in automotive engines, gas turbine engines and electronic equipment such as computer and cell phone chips. When there is no damage or crack in the structure and the operating temperatures are not too high to affect the material properties, the life prediction process is nearly the same for mechanical and thermal loading conditions. However, depending on the crack size, shape and its relative location with respect to the load transmission path on the part, the presence of a crack in the structure can make a significant difference between the fracture responses of two loading types, i.e., stress intensity factors on the crack front and the resulting crack propagation lives.

Numerical modeling of crack growth has been an active area of research in the last two decades. Early studies for simulation of crack growth focused on two dimensional problems. See, for example; [1–3]. More recent studies focused on three-dimensional problems and the development of simulation methods and tools for such problems. While initial efforts were given to boundary element technique [4,5], much more focus later is given to finite element-based techniques and simulation tools. Dhont [6] presented an algorithm for simulation of planar crack growth in mode-I conditions. FRANC3D [7,8] is a research program which is capable of performing crack growth simulation in conjunction with the finite elements. ZENCRACK is another software [9,10] used to introduce one or more crack fronts into the uncracked finite element mesh and crack growth is predicted by the computed fracture parameters. Schollmann et al. [11] developed a crack growth analysis system, ADAPCRACK3D, capable of predicting fatigue crack growth in arbitrary 3D geometries under complex loading by making use of finite elements and the modified crack closure method. The extended finite element method [12] has been used recently for crack growth simulation.

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Nomenclature

σ	uniform tensile or maximum bending stress
δ	displacement load
ΔT	uniform or maximum value of linear temperature change through the thickness
a	crack depth in thickness direction of the plate
c	half crack width on the plate surface
a_f	final crack depth
a_0	initial crack depth
c_0	half initial crack width
a/c	crack ellipticity ratio
da/dN	crack growth rate
N	number of cycles
N_F	number of cycles to failure
N_0	number of initial cycles
C,n	crack growth-related material properties
H	half plate height
W	half plate length
t	plate thickness
ΔK	stress intensity factor range
ΔK_{eqv}	equivalent stress intensity factor range
ΔK_{max}	maximum stress intensity factor range
Δa_{max}	maximum magnitude of crack extension distance along the crack front
K_{IC}	plane-strain fracture toughness
$x'_i - y'_i - z'_i$	local coordinate system
$x''_i - y''_i - z''_i$	extended local coordinate system
θ_i^p	locally relative crack propagation angle
$\Delta \vec{P}_i$	crack growth extensions (propagation vectors) of a node on the crack front

Most existing studies in the literature for three-dimensional fracture problems concentrate on mechanical loading or load-controlled conditions, i.e., pressure loads, concentrated loads, inertial/acceleration loads. There are studies also that address the fracture phenomenon when thermally induced/displacement-controlled loads are present in the structure. Tokiyoshi et al. [13] performed experiments and numerical analyses by also employing elastic–plastic J and creep C^* integrals for two-dimensional cracks in perforated plates under thermal fatigue loading. Rhymer et al. [14] combined linear elastic fracture mechanics (LEFM) methods, published material data, and a commercially available finite element analysis (FEA) code together to represent complex crack growth and arrest phenomena (two-dimensional) in a thin plate with residual viscoplastic stresses. Malesys et al. [15] presented a probabilistic model to predict the formation and propagation of crack networks in thermal fatigue. Gardin et al. [16] studied crack growth in a plate under thermal cycling based on both experimental observations and numerical simulations using the finite element method with re-meshing. Later, for the same problem, they also developed analytical models of stress intensity factors and crack propagation under thermal shock [17].

In this paper, the aforementioned differences in fracture responses under different load and displacement-controlled loading conditions are investigated in detail using detailed finite element fracture models. In Part 1 of this study, these differences are presented in terms of stress intensity factors. This part of the article focuses on fatigue crack propagation behavior of surface cracks under mechanical or thermal/displacement loads and is arranged as follows. First, the problems studied are described. Next, crack propagation patterns, variations of aspect ratios and propagation lives during fatigue crack growth are presented and compared with each other for both loading types. It is shown that although not much difference exists between crack profile shapes under uniform loads, i.e., aspect ratios during growth, there exists some difference for the bending loads. It is also shown that crack propagation lives under mechanical loads are lower than those of thermal/displacement-controlled loads.

2. Problem description

In this section, the mode-I fracture problems studied are described with geometric and loading details. The results from these problems were presented in terms of stress intensity factors along crack fronts in Part 1. Crack propagation patterns and lives are discussed in the following sections. The surface cracks in finite thickness plates studied are under ‘‘Uniform Far-Field Stress (UFFS)’’, ‘‘Uniform Far-Field Displacement (UFFD)’’, ‘‘Bending Far-Field Stress (BFFS)’’ and ‘‘Bending Far-Field Displacement (BFFD)’’ loads, which are described in the following subsections.

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