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Surface cracks in finite thickness plates under thermal and displacement-controlled loads – Part 1: Stress intensity factors

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ABSTRACT

In this study, surface cracks in finite-thickness plates subjected to thermal or displacement-controlled loads are considered. These loads produce a uniform or bending stress state, i.e., a linear distribution over the thickness, in the corresponding uncracked structure. Stress intensity factors are calculated using enriched crack tip finite elements and compared with those of the respective mechanical loads. It is shown that the stress intensity factors along the crack front for plates under thermal or displacement-controlled loads are lower than those of cracks under mechanical loads and that this difference increases with increasing crack size due to the increasing compliance of the structure.

1. Introduction

Although the majority of structures undergo mechanical loads, e.g., pressure, point or rotational loads, there are many applications that are subjected to displacement-controlled or thermal loads. Parts that are exposed to severe thermal gradients in such applications as automotive engines, gas turbine engines and electronic equipment are just some examples for these kinds of structures operating under thermal loads. In the absence of any defects or cracks, once the stress state is calculated for a location of interest in the structure under thermal load, the method of predicting fatigue crack initiation life, i.e., low-cycle fatigue, is no different than that of a structure under mechanical load, except that for the case of thermal loading pseudo-elastic S–N curves (ε–N curves) which are alternating stress/strain amplitude (S) versus number of cycles (N) to failure are generally used taking also into account temperature effects on material properties. On the other hand, once a crack initiates in the structure its compliance also increases with increasing crack length and its fracture response, i.e., stress intensity factor along the crack front, is different under mechanical load and the corresponding thermal/displacement-controlled load, which would produce the same stress state at the point of interest for the case of no crack in the structure. This difference in fracture response increases with increasing crack length and, therefore, the compliance. Hence, great care must be taken when employing fracture solutions of load-controlled applications for cracks in similar structures that are under displacement-controlled or thermal loads.

Analysis of three-dimensional surface cracks in structures has been an area of active research for the last five decades. Having been observed as an important computational problem by Irwin [1], who introduced correction factors for stress intensity factors, increasingly higher focus has been given to the surface crack problems to determine stress intensity factors

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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
H	half plate height
W	half plate length
t	plate thickness
θ	parametric crack front position angle
a/c	crack ellipticity ratio
K	stress intensity factor
K_N	normalizing stress intensity factor
ε	strain
α	coefficient of thermal expansion
ξ, η, ρ	local coordinates in the enriched element
Nj	regular finite element shape functions
u_j^k	nodal displacements
Z_0	zeroing function
f_j^k, g_j^k, h_j^k	mode I, mode II and mode III displacement components
K_I^i, K_{II}^i, K_{III}^i	nodal stress intensity factors
Γ	local isoparametric coordinate
Q	shape factor for elliptical crack

along the crack front. Some of the early studies used techniques such as alternating methods [2–4], boundary elements [5], virtual crack extension method [6,7], the line-spring model [8,9] and finite element methods [10–17]. Most studies existing 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 three-dimensional fracture phenomenon when thermally induced/displacement-controlled loads are present in the structure. Tokiyoshi et al. [18] 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. [19] 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. [20] presented a probabilistic model to predict the formation and propagation of crack networks in thermal fatigue. Fillery and Hu presented a compliance adjusted weight function (CAWF) method to compute the stress intensity factors (SIF) associated with restrained finite length edge cracked and semi-elliptical surface cracked plates [21,22] and hollow cylinders [23,24]. They also compared their results to those from finite element analyses for the deepest penetration point of the surface crack problem. Nabavi and Ghajar [25] derived a general weight function to evaluate the thermal stress intensity factors of a circumferential crack in cylinders (axisymmetric problem). Le and Gardin [26] developed an analytical approach based on the weight function method and on the Duhamel's principle to calculate the time-dependent stress intensity factor of a plate with an edge crack (two-dimensional) submitted to thermal cyclic loading. Gardin et al. [27] studied crack growth in a plate under thermal cycling based on both experimental observations and numerical simulations using 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 [28].

In an effort to systematically investigate and demonstrate the aforementioned differences in fracture responses, e.g., stress intensity factors and crack propagation rates and shapes, of surface cracks in plate-like structures under different stress and displacement-controlled loading conditions, detailed results from finite element analyses are presented in this paper. The stress intensity factor solutions are obtained using FRAC3D, a three-dimensional fracture analysis program [17]. To compute the stress intensity factors, FRAC3D makes use of 3-D enriched crack tip elements. These elements contain the analytically known displacement and strain crack tip fields in their finite element formulation. The enriched finite elements are very advantageous from the perspectives of pre- and post-processing of the finite element fracture model, i.e., no special mesh is needed near crack front and stress intensity factors are directly solved for at the same time as nodal displacements without any post-processing effort. In addition, since the approach is quite general, it is possible to apply this methodology to other types of fracture problems with different asymptotic singular fields. This is accomplished by suitably modifying the appropriate asymptotic expressions for displacement and strain in the enriched elements. In this part of