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Linear Damage Accumulation for Predicting Fatigue in Fiber Metal Laminates

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This paper presents the experimental and analytical research on the applicability of the linear damage accumulation approach for fatigue crack growth in fiber metal laminates under variable amplitude loading. A recently developed constant amplitude analytical prediction model for fiber metal laminates has been extended to predict fatigue crack growth under variable amplitude loading using a linear damage accumulation rule. The modified model has been compared with crack growth tests on fiber metal laminates center-cracked tension specimen. In the end, it is discussed to what extent or under which conditions the linear damage accumulation predictions are sufficiently accurate for fiber metal laminates structures.

Nomenclature

a = total crack length
a_D = delay distance
a_i = current crack growth increment
a_0 = initial/total crack length of previous loading cycle
C_{cg}, n_{cg} = crack growth relation constants
K_{bridging} = bridging stress intensity factor
$K_{\mathrm{far\text{-}field}}$ = far-field stress intensity factor
K_{tip} = crack-tip stress intensity factor
N = number of loading cycles
N_D = number of delay cycles
N_{OL} = number of overload cycles
$S_{\max}$ = maximum stress magnitude
S_{OL} = overload stress magnitude
R = stress ratio
$R_{K\mathrm{tip}}$ = crack-tip stress ratio
R_{OL} = overload stress ratio
ΔK_{eff} = effective stress intensity factor range

I. Introduction

FATIGUE is no doubt the main cause of failure in most load bearing components. The type of loading in nature is mainly based on variable amplitude which largely affects the severity and mechanisms of failure. In the case of metallic structures, the effect of variable amplitude (VA) loading is more pronounced due to large plastic zone sizes and crack growth retardation. On the other hand, to know about the fatigue life and crack growth in metals under VA loading, a number of prediction models have been developed [1]. These models range from simple models like linear damage accumulation (LDA) to the more complex yield zone, crack closure, and strip yield models. This variety of prediction models is the result of the required prediction accuracy. The trends of model development progress with the integration of physical phenomena like plastic zone and crack closure [2] in the formulation of the models. It has been observed that the fatigue crack growth predictions using the LDA rule are not accurate in metallic structures [3] due to the absence of consideration of plasticity and crack closure concepts. This has led to the fact that the LDA rule is unable to predict the crack growth retardation in the case of VA loading in metals.

Fiber metal laminates (FMLs), being a hybrid material of metal and composite, have metallic, composite as well as their unique properties [4]. It is assumed that LDA predictions for VA loading in FMLs are more accurate than in metals, due to the existence of fiber bridging which restrains the crack opening. As a consequence, crack closure in the wake of crack and the size of the retardation zones are supposed to be smaller than the one in monolithic metals.

II. Linear Damage Accumulation

The linear damage accumulation model is based on a cycle-by-cycle analysis independent of proceeding load cycles. It is an integration of calculated crack growth increments Δa_i using crack growth relations [5] to obtain a prediction for the full load spectrum. As a result, it is the simplest model to predict the crack growth under VA loading. The advantage of the LDA rule is computational efficiency, whereas the disadvantage is nonconsideration of nonlinear fracture mechanics concepts such as plastic zone formation in front of the crack tip, crack closure in the wake of crack, crack growth retardation, and crack growth acceleration. In general, the LDA rule can be presented mathematically as

$$a = a_0 + \sum_{i=1}^{n} f(\Delta K, r, \ldots) = a_0 + \sum_{i=1}^{N} \Delta a_i \tag{1}$$

III. Fiber Metal Laminates

After ARALL (aramid aluminum laminate) [6], GLARE (glass-reinforced) is the second member of the FML concept. Unlike ARALL, GLARE has good fatigue properties in combination with compressive loading [7]. Besides the excellent fatigue characteristics, GLARE also has good impact and damage tolerance characteristics [4]. GLARE is proved to be quite durable in case of corrosion, impact, and high temperature. The fiber/epoxy layers act as barriers against corrosion of the inner metallic sheets, whereas the metal layers protect the fiber/epoxy layers from picking up moisture. The laminate has an inherent high burn-through resistance as well as good thermal insulation properties.

FMLs are built up by alternating metal and fiber layers, as shown in Fig. 1. For standard GLARE, aluminum 2024-T3 sheets and S2-glass fibers are bonded together with FM94 epoxy adhesive to form a laminate. This stack is cured in an autoclave at 120°C and 6 bar for

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