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Remaining life prediction of cracked stiffened panels under constant and variable amplitude loading

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Abstract

This paper presents the methodologies for remaining life prediction of stiffened panels under constant and variable amplitude loading (CAL & VAL). Concentric and eccentric stiffeners have been considered. Stress intensity factor (SIF) has been computed using the parametric equations developed by conducting fracture analysis of stiffened panels utilizing numerically integrated modified virtual crack closure integral (NI-MVCCI) technique. Wheeler residual stress model has been employed to represent the retardation effects due to tensile overloads. Effect of various stiffener sizes and stiffener type (concentric and eccentric stiffeners) on remaining life has been studied under CAL & VAL. From the studies, it has been observed that the predicted life is significantly higher with concentric and eccentric stiffener cases compared to the respective unstiffened cases. Further, it has also been observed that the percentage increase in life is relatively more in the case of concentric stiffener case compared to eccentric stiffener case for the same stiffener size and moment of inertia. Expressions for remaining life have been proposed considering various loading conditions, type of stiffener and number of overloads. These expressions will be useful for designers to design the structural components/structures against fatigue and fracture.

Keywords: Remaining life; Stiffened panels; Stress intensity factors; Fatigue; Fracture

1. Introduction

The strength of structural components used in most of the industrial structures and other major infrastructures such as nuclear containments, reactor vessels, flyovers, high-rise buildings, aerospace structures, ship hulls and offshore structures are generally improved by providing stiffening members such as stiffeners or stringers. Stiffeners are mainly provided to improve the strength and stability of the structure and to provide a means of slowing down or arresting the growth of cracks in the panel. Remaining life prediction of the cracked structural components in these structures is a major problem facing the engineering community in this era of aging infrastructure facilities. This is due to the fact that strength assessment of the aging structures is necessary for their in-service inspection, planning, repair, retrofitting, rehabilitation, requalification and health monitoring. In view of these, it is essential to use the damage tolerant design concepts for designing these structural components. Fracture mechanics is a tool employed for investigation of the crack growth and fracture behaviour of structural components that are subjected to fatigue loading or static overloading.

Stiffened panels are often subjected to fatigue loading and in most of the cases, the loading may be either constant amplitude loading (CAL) or variable amplitude loading (VAL). In the case of VAL, a major influencing parameter to be considered is the influence of load history. Crack growth analysis and remaining life prediction of stiffened panels under VAL involves consideration of load interaction effects, which influence the remaining life significantly. A superimposed single overload during CAL is the simplest case of VAL. The application of single overload will cause significant decrease in the crack growth rate for a large

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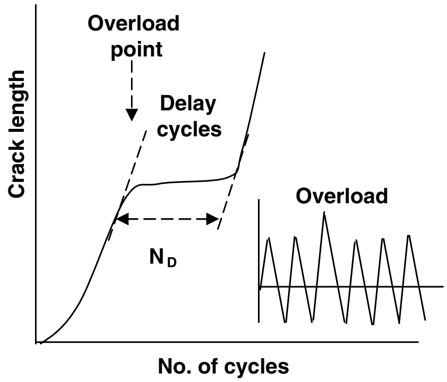

Fig. 1. Decrease in the rate of crack growth due to the overload followed by CAL.

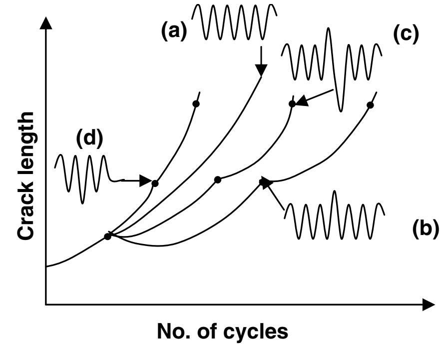

Fig. 2. Crack growth produced by: (a) CAL, (b) single overload, (c) single overload-underload and (d) single underload.

number of cycles subsequent to the overload as shown in Fig. 1. This phenomenon is referred to as crack retardation. As it is well known that the randomness in the data can also decrease the rate of crack growth. Application of fatigue underloads [negative overloads] has the detrimental effect on fatigue crack growth. The crack growth rate is augmented and fatigue life will be reduced [1]. The combination of overloads and underloads, singly or in blocks, leads to much more complex situation.

The widely used models to represent VAL are yield zone models, crack closure models and statistical models. Models based on yield zone concept such as Wheeler [2] and Generalised Willenborg residual stress model [3] are generally employed in the analytical investigation. These models are based on the assumption that crack growth retardation is caused by compressive residual stresses acting at the crack tip. Wheeler residual stress model is the simplest and preferred model among the various models available for VAL under yield zone concept [1].

The application of an underload immediately following overloading diminishes the effect of the latter to a greater or lesser extent depending on their relative values [1]. It was observed that the retardation effect is lesser due to a tensile overload followed by a subsequent higher compressive overload, which can even lead to an acceleration of the crack growth. Also, application of an underload prior to overloading may have no influence or even decrease the retardation effect of the overload, depending on the particular loading conditions. Some of the transient effects on crack growth and remaining life are illustrated in Fig. 2.

Poe [4] conducted fatigue tests on stiffened panels constructed with bolted and integral stringers. From the experiments, it was observed that the bolted stringers reduced the crack growth rate significantly below that for an equally stressed unstiffened panel, where as the integral stiffener had no significant effect. Vlieger [5] presented a method to predict the residual strength of a cracked sheet structure contains stiffening elements that can act as crack stoppers. This crack arresting action and its consequences for the residual strength were considered in the analysis. Chu et al. [6] conducted an experimental study to characterize the fatigue crack growth behaviour of stiffened panels under uniform lateral pressure loading. From the studies, they observed that the fatigue failure of the panels consisted of cracking of the stiffeners, followed by cracking of the skin. Ghassem and Rich [7] presented a detailed explanation for the use of fracture diagram in the design of stiffened panels. These diagrams can be utilized for post-mortem failure analysis and in preventive quality control, whereby design measures may be taken to avoid failure. The fracture diagrams are dimensionless and can be used for any material having significant yield strength and fracture toughness properties. Theoretical fatigue life of a stiffened panel was evaluated using fracture diagram and compared with that of the life computed by using linear elastic fracture mechanics (LEFM) principles. Michelle [8] explained a local tearing mechanism that can be used to examine the peeling of a stiffener from a plate. The detachment of a stiffener from a plate was described by the fully-plastic crack propagation in the web of a non-symmetric I-beam. The bifurcation point that marks the transition from a deformation without crack growth to deformation with crack growth was observed to be independent of the initial crack length, but depends on the relative magnitude of plastic modulus to the material flow stress, the specific nature of fracture, and the relative size of the tear zone and width of the flange. Sakano and Wahab [9] conducted fatigue test on 2 m long plate girder specimens with transverse stiffeners under CAL and two types of typical VAL. It was observed from their experiments that the fatigue cracks were initiated from the fillet weld toe at the top and bottom ends of the stiffeners. Load interaction effects were not considered in the case of VAL. Saves et al. [10] presented a simplified semi-analytical methodology to predict the behaviour of longitudinal cracks in cracked stiffened curved panels with frames. Their results showed a highly satisfactory correlation between prediction by calculation and experimental data. Dexter and Pilarski [11] conducted series of experiments to characterize the propagation of large fatigue cracks in welded stiffened panels under four point bending and observed that welded stiffeners substantially reduce the crack propagation rate relative to a plate with no stiffeners. The reduction in crack propagation rate