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NUMERICAL INVESTIGATION OF FATIGUED COMPOSITES UNDER CYCLIC COMPRESSION SPECTRA

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ABSTRACT

The effects of overloads on internal delaminations of IM7/G8552 graphite/epoxy composite laminates subjected to cyclic compressive load are investigated. An extensive numerical study has been performed on composites' fracture due to reduction in the intralayer and interlayer resistance resulting from randomly subjected overloads. The composite structure is already undergoing repeated buckling as a result of compressive loading. The energy release rate, G, is modeled considering the state of stress to be mixed mode, I and II. Fracture mechanics model and delamination buckling analysis deliver the required equations to build a model that incorporating the non-linearity caused by the overloads. The model predicts a relatively rapid accumulation of micro-damage due to overloads at the delamination front. Results are obtained with no restrictive assumptions on the plate thickness T and over varying mode mixity and delamination positions.

KEYWORDS

material, delamination, energy, fatigue, mode, numerical, overload, spectrum

INTRODUCTION

The damage tolerance of laminated composite components used in aerospace applications is dramatically altered once these structures are subjected to overloads. The overloads might be in the form of bird strikes, landings, wind gusts, shear winds and other mechanical and thermal types of loading. The present study investigates the prediction of variable amplitude fatigue loading with randomly applied overloads.

Broutman and Sahu [1] were among the first to do significant work on prediction of multi-stress level fatigue in composite materials. Overloads were integrated until Yang and Liu [3] introduced a single overload of different intensities at regular intervals throughout a fatigue test. Previous work done on similar grounds is limited and typically involves FALSTAFF (Fighter Aircraft Loading Standard For Fatigue), which is one of the popular spectra used by researchers especially in compressive loading [4, 5].

In the presented study simulations of IM7/G8552 graphite/epoxy composite specimens subjected to cyclic compressive loading were performed. By varying the ratio between the magnitude of the strain overload and the magnitude of the normal fatigue strain the severity of the overloads was measured. Continuous tracking of the energy release rate, G, and prediction of the energy release rate reduction during in service loading was achieved using the proposed model.

NUMERICAL MODEL

The energy release rate of fatigued composites under compressive loading, with infliction of overloads at regular intervals, exhibits a behavior similar to the one supported by previously performed experiments on cyclic loading. A perturbation procedure, which is based on an asymptotic expansion of the load and deformation quantities in terms of a distortion parameter, i.e., the deformation of the delaminated layer, is used [9]. The model accounts for post-buckling and growth behavior of delaminations and it is based on Kardomateas' [9] model. For the interested reader, the complete model for isotropic and orthotropic materials is illustrated in the Refs [6,7,9]. In the current analysis only the parts of the model pertinent to the overload effect on the energy release energy are presented. In particular, the energy release rate, G, of a plane strain interface crack for a homogeneous system and homogeneous material [8], is

$$G = \frac{1-n}{4m}\left(\frac{P^{*2}}{Ah} + \frac{M^{*2}}{Ih^3} + \frac{P^* M^*}{\sqrt{AIh^2}} \sin g\right) \tag{1}$$

where $$P^* = P \quad - C_1 P + C_2 \frac{\mathrm{M_d}}{\mathrm{h}}, \qquad \text{and} \qquad M^* = M_d - C_3 M \tag{2}$$

P^* and M^* are linear combinations of the loads from the post-buckling solution [9], and is the shear modulus. A and I are a positive dimensionless number and the angle which is restricted such that 2. More specifically:

$$A = \frac{1}{1+4h+6h^2+3h^3}\ ; I = \frac{1}{12(1+h^3)}\ ; \sin \quad = 6 \quad ^2 \left(1 + \quad\right) \tag{3}$$

Asymptotic expressions for the forces and moments with respect to the perturbation parameter, , from the post-buckling solution, gives:

$$P^* = P^{*(1)} + 2\, P^{*(2)} + \ldots \tag{4}$$

$$M^* = M^{*(1)} + 2\, M^{*(2)} + \ldots \tag{5}$$

Therefore, the energy release rate and mode I and II intensity factors can be written in the form:

$$G^* = 2\, G^{*(2)} + 3\, G^{*(3)} + \ldots \tag{6}$$

$$K_{I\,II} = K^{(1)}_{I\,II} + 2\, K^{(2)}_{I\,II} + \ldots \tag{7}$$

where $\Psi = \tan^{-1}\left(\mathrm{K}_{II} / \mathrm{K}_{I} \right)$ is the mode mixity.

The energy release rate of a delamination in an infinitely thick base plate, unlike the thin film model of Chai et al. [11], is predicted to be larger for higher levels of applied strain [12]. In this model the fatigue damage due to delamination is expressed as a function of the energy release rate, G, the load ratio, , and the mode mixity, Y, thus forming the following cyclic growth law:

$$\frac{da}{dN} = f(\overline{G}_{\max,}\, a, \Psi); \qquad \frac{da}{dN} = C(\Psi)\frac{\Delta \overline{G}^{\,m(\Psi)}}{1-\overline{G}_{\max}} \tag{8}$$

where $\overline{G}$ is the ratio of energy release rate over toughness. $C(Y)$ and $m(Y)$ values are determined independently using the following semi-empirical formulations:

$$m(\Psi) = m_1\left[1+(m-1)\sin^2\Psi\right] \qquad \text{where } m = \frac{m_{II}}{m_I} \tag{9}$$

$$C(\Psi) = C_1\left[1+(k-1)\sin^2\Psi\right] \qquad \text{where } \boldsymbol{k} = \frac{C_{II}}{C_I} \tag{10}$$

The overloads are introduced in the system by increasing the applied strain at regular intervals as a close simulation of the performed experiments. More specifically, every 30-step change in delamination length an overload of 5% change of the applied strain, for a period of five steps, is imposed to each specimen. That is

$$\boldsymbol{e}_{appl} = \begin{cases} \boldsymbol{e}_0 & for \quad \mathrm{mod}(n*I,30) \neq 1 \\ \boldsymbol{e}_0 + \boldsymbol{e}_{overload} & for \quad \mathrm{mod}(n*I,30) = 1 \;\; to \;\; n*I+5 \end{cases} \tag{11}$$

where n is the number of step increment in delamination, and
I is the unit step increment in delamination.

Considering five steps of overloading state of which the strain is increased by less than 5% of its initial strain, each overload cycle is described by:

$$e_0 = \frac{P}{E}; \qquad e_{overload\leq} 1.05 * e_0 \tag{12}$$

Therefore, the energy release rate expression will be modified as follows:

$$G(e_{appl}, \ell) = \frac{1}{2} \; Eh(1 - n^2)(e_{appl} - e_{cr})(e_{appl} + 3e_{cr}) \tag{13}$$

where $e_{cr} = \dfrac{p^2 h^2}{12(1-n^2)}$ and the applied strain, $_{appl}$, as described in Eq. 11.

Numerical simulations of delamination buckling and growth in graphite/epoxy composites under cyclic compressive loading were developed based on the aforementioned model. The three specimen configurations that yielded interesting data during the experimental approach were used to simulate the system. The compressive loading in this case is simulated by an increase in the delamination length. Simulation results are presented in Figures [1, 2]. In each graph, the energy release rate of composites against the delamination ratio is plotted. Figures 1 and 2 demonstrate the reduced growth resistance of laminates through the reduction of *G* during delamination growth for three different delamination positions though the thickness of the specimens, i.e. h/T ratio. In particular, the graphs describe the behavior of composites with increased h/T ratio, i.e., 4/15, 5/29 and 4/24. As illustrated in these plots, the energy release rate reduces as the delamination length increases indicating that delamination growth requires smaller amounts of energy in order to progress. As seen in Figure 1, higher values of h/T ratio result in higher values of the energy release rate.

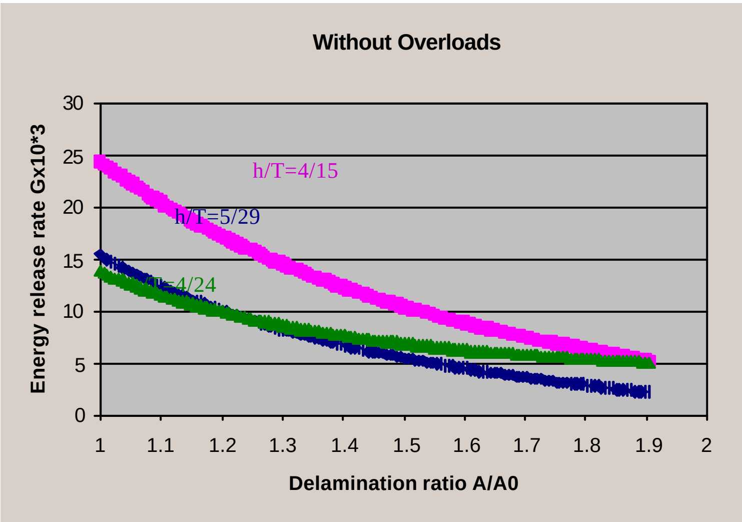

Figure 1: Growth behavior of IM7/G8552graphite/ specimens subjected to cyclic compressive loading

The graph in Figure 2, illustrates the energy release rate of the structure when subjected to an overload causing 5% change in applied strain at regular intervals as indicated above against the delamination ratio.

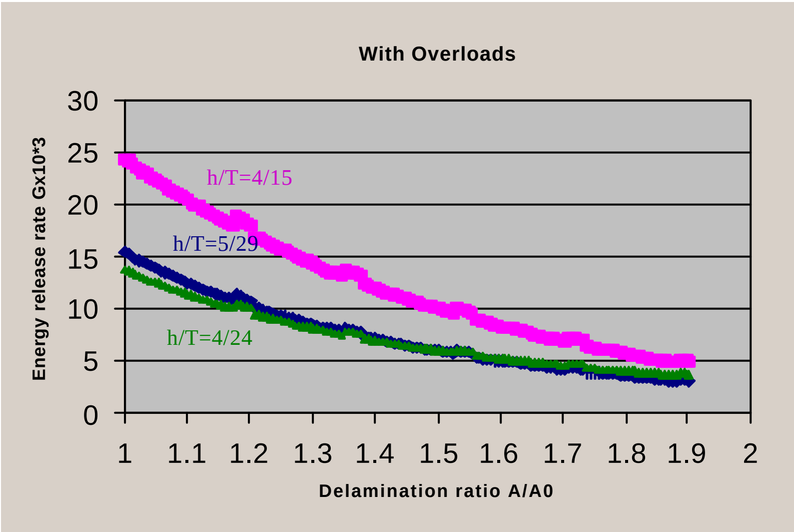

Figure 2: Growth behavior of IM7/G8552 graphite/epoxy specimens subjected to cyclic compressive overloads for varying h/T ratio.

The behavior observed in Figure 2 is similar, with the exception of the overloads, to the structural integrity degradation behavior observed in Figure 1. As the delamination length increases and the energy release levels decrease the effect of the overloads diminishes (compare the *G* peak values of the first and fourth overloads in Figure 2). Furthermore, the effect of the overloads is more severe when the delamination length is small and its energy release levels are high. This observation complements the findings of Refs [4, 6] in which small delamination length indicated large mode I (opening) component of the mode mixity. Here, as the delamination grows, the shear component increases and the effect of the overload diminishes. The increase in energy release rate due to overloads supports the inference from the experimental results, i.e., faster crack growth at the beginning of the experiments when the delamination length is relative small. Moreover, the formation of intralayer cracks during, or after, the overloads may be associated to the high levels of energy release rate during the overload application. Simulations indicate that as the delamination progresses the effect of the overloads on the system diminishes, see overload peaks in Figure 2.

CONCLUSIONS

In this paper, a numerical approach to variable amplitude cyclic compressive testing was performed on graphite/epoxy composite laminates. These simulations revealed that the energy release rate reduces as the delamination length increases indicating that delamination growth requires smaller amounts of energy in order to advance. Furthermore, higher values of applied strain result in higher levels of energy release rate independently of the overload application. Finally, as the delamination grows the number of intralayer cracks decreases implying that the energy release rate available for intralayer "jumps" reduces. This model can estimate the energy release rate of a certain composites under service loading and thus in turn predicting the life of the composite. Future work will involve matching the numerical prediction using experimental results by imposing random overloads [13] onto the cyclic compressive loading spectra. .

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