Fatigue life prediction of holed laminated composites based on Finite Fracture Mechanics

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Finite Fracture Mechanics (FFM) is a failure criterion that assumes a discrete crack extension of amount L by coupling stress and energy conditions. The distance L is not just a material property, but depends on the geometry as well. In the static framework, the FFM approach writes as follows:

$$\begin{cases} \frac{1}{L}\int_0^L \sigma dx = \sigma_u \\ \frac{1}{L}\int_0^L K_I^2 da = K_{Ic}^2 \end{cases} \tag{1}$$

The first equation consists of a stress criterion, which states that failure occurs when the (average) stress ahead of the notch tip over L achieves the critical value of the strength, namely the ultimate tensile stress σ_u. The second condition represents the discrete energy balance: failure happens when the available energy for a finite crack extension L reaches the a critical threshold. In Eq. 1, the latter condition is rewritten in terms of the stress intensity factor (SIF) and fracture toughness K_{Ic} by means of Irwin's relationship.

The FFM was generalized to the fatigue limit regime as follows:

$$\begin{cases} \frac{1}{L}\int_0^L \Delta\sigma dx = \Delta\sigma_0 \\ \frac{1}{L}\int_0^L \Delta K_I^2 da = \Delta K_{th}^2 \end{cases} \tag{2}$$

where $\Delta\sigma_0$ represents the fatigue limit or the high-cycle fatigue strength of the material, and ΔK_{th} is the threshold value of the SIF range.

Since finite fatigue life lies in between static and fatigue limits, the basic idea behind the FFM extension to fatigue life estimation consists in varying the critical stress and SIF amplitude on the number of cycles to failure [1]. For this purpose, Basquin equation can be used to describe their dependency on the number of cycles, using both plain and cracked (or notched) geometries, respectively:

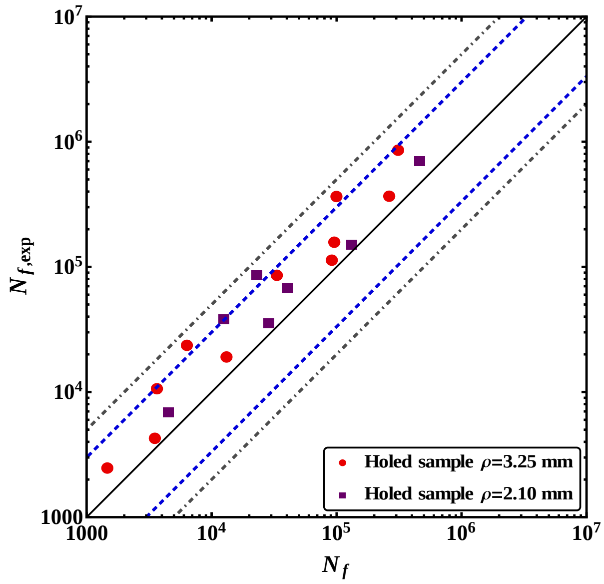
$$\sigma_c = \sigma_c(N) = a_s\ N^{-b_s} \tag{2}$$
$$K_{If} = K_{If}(N) = a_k\ N^{-b_k} \tag{3}$$

All in all, to estimate the lifetime of notched structures, FFM can be recast as follows:

$$\begin{cases} \frac{1}{l}\int_0^l \sigma_y(x)\,dx = \sigma_c(N) \\ \frac{1}{l}\int_0^l K_I^2(a)\,da = K_{If}^2(N) \end{cases} \tag{4}$$

The set of experiments we use to validate the model is related to notched laminated composites with two different lay-ups, $[0/90]_{2s}$ and $[90/0]_{2s}$, as presented in [2]. The specimens were made of carbon fiber (T300-12K, 200 g/m^2) and a low viscosity epoxy resin (Araldite LY 5052) cured with Aradur 5052 Hardener in a weight fraction of 100:38, employing the vacuum-assisted resin injection method. Except the plain sample, the specimens were weakened by a crack with total length of a = 15.4 mm, and two holes with two different radii of ρ = 2.1, 3.25 mm. The tests were performed under tension-tension loading (R=0.1). We used the plain and cracked sample data to get the functions in Eqs. (3) and (4), using the holed sample data as blind predictions. Fig. 1(a) presents a depiction of a holed sample, and Fig. 1(b) illustrates the predictions by FFM for $[90/0]_{2s}$.

(a)



(b)

Figure 1. (a) Holed specimen (b) Estimated fatigue lives for $[90/0]_{2s}$ vs experimental results [2].

Considering Fig. 1(b), it can be stated that the FFM model provides accurate (and conservative) predictions regarding the fatigue life across different notch geometries, given the complexity of the problem, with all results falling within the scatter band of 1/5 to 5.

REFERENCES

1. Mirzaei, A.M.; Cornetti, P.; Sapora, A. A novel Finite Fracture Mechanics approach to assess the lifetime of notched components. Int J Fatigue, 107659 (2023).
2. Mirzaei, A.M.; Mirzaei, A.H.; Shokrieh, M.M.; Sapora, A.; Cornetti, P. Fatigue life assessment of notched laminated composites: Experiments and modelling by Finite Fracture Mechanics. Compos Sci Technol, 246:110376 (2024).