A Study of Composite Laminates Containing a Central Hole

Hyungwon Kim*

ABSTRACT

Predicting microcracking properties of the composite laminates in nonuniform stress conditions was the subject in this paper. The uniform stress field meant the stresses were independent of the width direction. The material was the 954-2A/IM7 laminates containing a central hole. Microcracks initiated at the edge of the hole and propagated into the laminate. Because the tensile stress concentration decreased with distance, the microcracks were arrested before the edge ofthe laminate. Because carbon fiber composites were opaque, a x-ray method was used to detect the length of the propagating microcracks. The microcracking at the near edge of the hole could be reasonably predicted by considering the local laminate stressesand the microcracking toughness measured in unnotched laminates. However, the date away from the hole did not agree with the predictions. The local microcrack density was always much higher than that predicted by the local laminate stress.

Key Words: nonuniform stress field, microcracking, microcrack density, variational approach, unnotched

1. Introduction

Bolt holes and rivet holes are necessary at joints. Despite careful design, practically any structure contains stress concentrations due to holes. It is not surprising that perhaps the majority of service cracks nucleate in the area of stress concentration at the edge of a hole. For a homogeneous material, a number of papers solved the hole problems, but for composite materials only a few papers treated them.

Predicting microcracking properties of the composite materials near a hole by microcracking theory was the subject in this paper. Microcracking theory without a hole is capable of taking a G_{mc}measured in one laminate and predicting the microcracking properties of any other laminate with 90° plies. All of the laminates have 90° plies in which the stresses are uniform. By uniform, I mean the stresses are independent of the width direction in the laminate. However, in the case of the laminate with a hole which stresses are nonuniform, the prediction of microcracking properties is more complex. The first step is to find the microcracking fracture toughness(G_{mc}) of the laminate without a hole. In the uniform stress conditions microcracks propagate rapidlyacross the entire laminate in the width direction.

In contrast to uniform stress conditions, nonuniform stess conditions should lead to slow microcrack propagation. The holes will cause a tensile stress concentration in the 90°plies which will decrease with distance away from the hole. It is expected that

* Agency for Defense Development R&D 4 dept.
E-mail : hwk4539@hanmail.net

microcracks will initiate at the edge of the hole and propagate into the laminate. Because the tensile stress concentration decreases with distance, the microcracks will arrest before they reach the edge of the laminate. After the testing of the laminates with a hole, the local microcrack density which will be defined in the next chapter is obtained.

The goal of this paper is to predict the local crack density as a function of local axial stress using the microcracking theory.

2. Experiment

2.1 Microcracking Tests of 954-2A/IM7 Laminates without a hole

The first experiment was to get the microcracking fracture toughness for the 954-2A/IM7 laminates without a hole. The $[0/90_2]_s$ laminates were done tensile tests first. All laminates exhibited sufficient amounts of microcracking to yield good plots for the microcrack density as a function of applied load. The experimental data were fitted to the line obtained by the variational analysis. The variational mechanics analysis determines all components of the stress tensor in the x-z plane.In this paper, we only requiredthe tensile stress in the 90° plies. The result was[1]

$$\sigma_0 = \frac{1}{k_m^{(1)}}\left(\sqrt{\frac{G_{mc}}{C_3 t_1 Y(D)}} - k_{th}^{(1)}T\right) \tag{1}$$

Where, the terms $k_m^{(1)}$ and $k_{th}^{(1)}$ were the effective mechanical and thermal stiffnesses of the 90° plies.

$$k_m^{(1)} = \frac{E_x^{(1)}}{E_c^0} \quad \text{and} \quad k_{th}^{(1)} = -\frac{\Delta\alpha}{C_1} \tag{2}$$

Here E_c^0 wasthe x-direction modulus of the laminate, $E_x^{(1)}$ was the x-direction modulus of the 90° plies, $\Delta\alpha = \alpha_x^{(1)} - \alpha_x^{(2)}$ was the difference between the x-direction thermal expansion coefficients of the 90° plies and the (S) sublaminate, and C_1, C_3 were the constants defined in the Ref(3). $D = \frac{N}{L}$ was the average crack density, N was the number of cracks and L was the sample length and Y was a function defined in Ref. (1). In eq. (1), there are two unknowns G_{mc} (microcracking fracture toughness), T(the temperature difference that determines the level of residual stresses). T could be measured by various means. Therefore if we had an unknown G_{mc} , we could predict the experimental results (stress(σ_0) vs microcrack density(D)). The unknown G_{mc} could be obtained from the comparison the experimental data with the theoretical line drawn from eq. (1) using a single value of G_{mc} . After measuring G_{mc} the $[+45/0/-45/90]_s$ laminates were also tested to confirm the microcracking toughness of $[0/90_2]_s$ laminates of 954-2A/IM7.

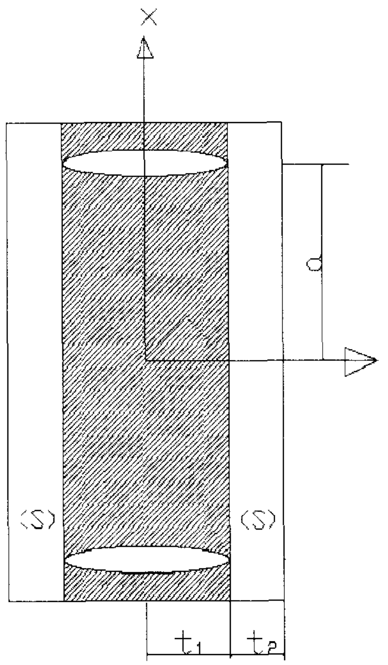

Fig. 1 Edge view of microcracks in the 90° plies of $[(S)/90_n]_s$ laminates. ((s) is sublaminates)

2.2 Microcracking Tests of 954-2A/IM7 Laminates with a hole

In this section, the microcracks emanating from a central hole in $[0/90_2]_s$ laminates of 954-2A/IM7 would be tested. The specimen was 10" long by 1.5" wide and 0.03" thick with a nominal diameter of 1/4". In fig 2, L_0 was a hole size measured from the hole center line to the hole edge. L was total crack length measured from the hole center line to the end of a crack. $(L-L_0)$ was a net crack length. The hole was expected to cause a stress concentration and promote the formation of microcracks in the 90° plies. As the microcracks propagated, they would experience decreasing stresses and therefore stop propagating before reaching the edge of the laminate. In experiments on the samples without a hole, the microcracks were observedon the edges of the laminate using a optical microscope. Because carbon fiber composites were opaque, x-ray methods were used to detect the length of the propagating microcracks. The laminates were loaded to a series of loads and then a dye penetrant solution was applied to the surface of the hole. The penetrant solution was 60g of zinc iodide and a few drops of surfactant in 10ml of ethanol and 10 ml of distilled water. The zinc iodide was to provide contrast in the x-ray images. The surfactant was to aid penetration of the solution into the microcracks. The samples were then exposed in a medical x-ray machine at 30 kV and 5mA for 210seconds. The microcracks showed up as white lines that could be measured directly on the x-ray image.

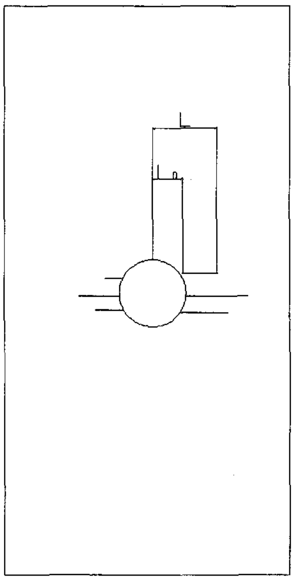

Fig. 2 The microcracks for various positions in a $[0/90_2]_s$ laminates of 954-2A/IM7 with a central hole. $L_0$is the hole size measured from the center line and L is a crack size measured from the center line

3. Results and Discussion

3.1 Microcracking Tests of 954-2A/IM7 Laminates without a hole

Figure 3 gave the experimental results for 954-2A/IM7 laminates. The triangles were the results from $[0/90_2]_s$ laminates and the diamonds were the results from $[+45/0/-45/90]_s$ laminates. The solid lines were predictions using Eq. (1) with G_{mc} =0.3 J/m^2 and $\triangle T$=-125°C. When comparing the $[0/90_2]_s$ and the $[+45/0/-45/90]_s$ results, it was noted that they could both be fit with the same G_{mc}. Both the experimental results and the theoretical predictions were hardly influenced by the lay-up. This lack of influence was

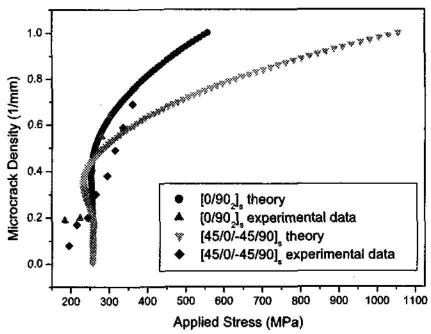

Fig. 3 The microcrack density as a function of applied load in $[0/90_2]_s$ laminates and $[+45/0/-45/90]_s$ laminates of 954-2A/IM7 without a central hole

actually a coincidence. The effect of changing the supporting laminates from [0] to [+45/0/-45] nearly canceled the effect of changing the number of 90° plies from 2 to 1.

In retrospect, it might have been preferable to select laminates with more divergent microcracking properties. However, at least the lack of effect predicted by the theoryagreed with the lack of effect in the experimental results.

3.2 Microcracking Tests of 954-2A/IM7 Laminates with a hole

Two $[0/90_2]_s$laminates of 954-2A/IM7 were tested. Each laminate was loaded to five different loads. At each load, thecrack length was measured on either side of the hole. Four sets of microcracking data were thus recorded around holes. In this section, one of those results would be discussed. The other three results were similar. Figure 4 ploted the length of each observed microcrack as a function of applied stress. There were a total of four microcracks initiating on the surface of the hole. The first microcracks initiated at a stress of about 49 MPa (see Fig. 4). Each microcrack slowly increased with length as the applied load increased until it reached the edge of the specimen or until the testing was stopped. This stable propagation of microcracks was a sequence of the nonuniform stress state around holes. In microcracking of unnotched $[0/90_2]_s$ laminates, stable microcrack propagation was never observed.

The crack length data were converted to local microcrack density data. Consider some position from the edge of the hole. At each stress level, the crack length data could be used to count the number of cracks that have grown past that position in the laminate (see Fig. 5). For a crude estimate of density, that number was divided by the length between the bottom and the top microcrack. The microcrack density at any position in the laminate was determined as a function of the applied stress.

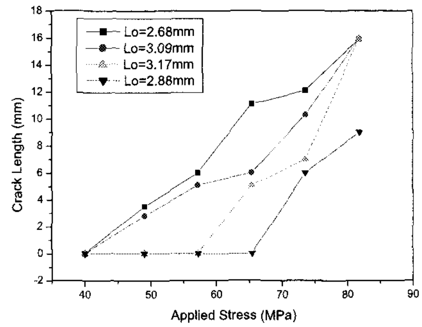

Fig. 4 The lengths of various microcracks emanating from a contral hole as a function of applied stress in a $[0/90_2]_s$ laminates of 954-2A/IM7. The crack lengths were measured from the edge of the hole.

One model to predict such data was to assume that the crack density was given by Eq. 1 where $G_{mc}$was given by the results from the laminates without a hole but the stress in the 90° plies , $\sigma_{x0}^{(1)}$, was derived from the local stress in the laminate rather than the far field applied stress. This local laminate stress was calculated by finite element analysis (FEA).

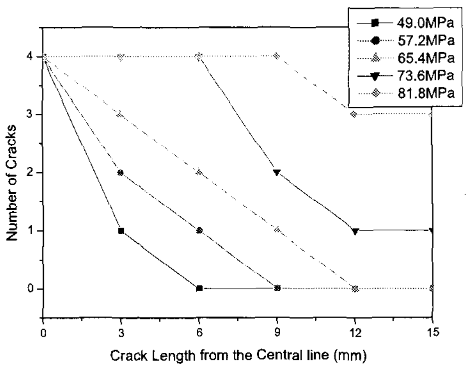

Fig. 5 The number of cracks as a function of crack length for various positions from the central line in a $[0/90_2]_s$ laminates of 954-2A/IM7

The plate was divided into elements. A high density of elements was used in the region around a hole. For each specific stress state, the crack length and location data were used to select elements near the microcracks. These elements were assigned the properties of a $[0/90_2]_s$ laminate of 954-2A/IM7 in which the 90° plies were discounted by assuming they had zero modulus. All other elements were assigned the mechanical properties of an undamaged $[0/90_2]_s$ laminate. From the resulting FEA analysis, the stress was plotted as a function of position from the edge of the hole to the edge of the laminate. This local laminate stressstress as a function of position was associated with the microcrack density at the corresponding position.Next the local microcrack density was plotted as a function of local laminate stress (see Fig. 6).

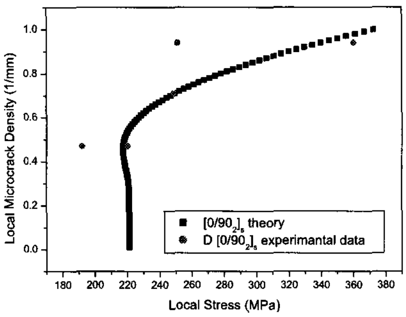

Fig. 6 The local microcrack density as a function of local stress in $[0/90_2]_s$ laminates of 954-2A/IM7 with a central hole. The data are the microcrack density 3.13 mm from the central line of the laminates

The results at several positions with respect to the edge of the hole were given in Fig. 6. The smooth line was a prediction of microcrack density based on the toughness measured in unnotched laminates of 0.25 J/m^2 microcracking toughness. The crack density at the edge of the hole (or at 3.13mm from the center of the laminate with a 6.26mm diameter hole) was close to the fracture mechanics predictions. The data away from the hole (at 6, 9, 12, and 15mm from the center of the laminate), however, did not agree with the prediction. The local microcrack density was always much higher than predicted by the local laminate stress.

4. Conclusion

In this paper, predicting the local crack density as a function of local axial stress using the microcracking theory was studied.

The microcracking fracture toughness in $[0/90_2]_s$laminates and $[+45/0/-45/90]_s$ laminates of 954-2A/IM7 without a central hole was G_{mc} =0.3 J/m^2 . When comparing the $[0/90_2]_s$ and the $[+45/0/-45/90]_s$ results, it was noted that they could both be fit with the same G_{mc}. Both the experimental results and the theoretical predictions were hardly influenced by the lay-up.

The local crack density as a function of local axial stress near the edge of the hole could be predicted using the microcracking theory. The data away from the hole (at 6, 9, 12, and 15mm from the center of the laminate), however, did not agree with the prediction.

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