AN INTEGRATED DAMAGE ANALYSIS OF LAMINATED COMPOSITE PLATES

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INTRODUCTION

The use of instrumental Nondestructive Evaluation (NDE) techniques to assess the nature of impact damage in composite structures is vital to the repair and maintenance of these structures. Unfortunately, instrumental NDE (as it currently exists) is not capable of revealing the entire characteristic damage state (CDS) of damaged composite structure. The CDS is necessary if a complete restoration of the damaged composite structure is to be achieved [1]. Using instrumental NDE techniques such as ultrasonics and radiography, it is possible to image the CDS to a certain extent. The utilization of ultrasonics to reveal a portion of the CDS of impact damaged composite plates has been described in the literature[2]. Reference [2] is a preliminary attempt to integrate pulse-echo time-of-flight ultrasonics with a meaningful analysis to assess the complete CDS and the post-impact damage tolerance of impacted composite plates. The work from reference [2] has been expanded and the current results exist in references [1], [3], [4], and the work described in this paper. Reference [3] describes in detail the K-rule mechanisms (as they are currently understood) introduced in reference [2]. In reference [3] the complete CDS is described without quantifying the lateral extent of the laminate delaminations, only the locations of the delamination planes are determined by the K-rule. A preliminary "propagation" failure criteria to quantity the lateral extent of the delaminations, throughout the laminate, is presented in reference [4]. Use of the complete CDS in a preliminary damage tolerance model is described in reference [1].

It is becoming increasingly clear that verification of the existence of the coupling transverse (CT) cracks is necessary if a general model of damage tolerance is to be achieved. As discussed in reference [3] the CT cracks couple the delamination of one interface plane with the delamination of another interface plane. The location of these cracks, their angular orientation with respect to the plane of the laminate, and the analytical verification of their existence are the main topics of this paper. By locating the CT cracks analytically, the CDS (as partially determined by the K-rule [2], [3]) can be reconstructed to reveal features of the CDS not imaged by instrumental NDE. To size the delaminations, a preliminary propagation failure criteria was introduced in reference [4]. In the present paper, a preliminary "initiation" failure criteria is introduced which locates and orients the CT cracks partially revealed by using the K-rule [2], [3].

OBJECTIVE AND APPROACH

The objective of this work was to develop an initiation failure criteria concerned with the development of the coupling transverse cracks of impacted composite plates.

The approach used to develop this criteria was as follows:

1) Impact a quasi-isotropic laminated plate (T-300/934) with a specified impact energy [2].
2) Ultrasonically C-scan (pulse-echo) the damaged area (both faces of the plate) [2].
3) Cut and polish the impacted laminate in the 0^{o} direction through the point of impact [2], [3].
4) Conduct a stress analysis of the impact event [5].
5) Transform the global strains and transverse shear forces into a two-dimensional set of strains in a plane normal to the fibers of the ply under investigation.
6) Conduct a principal strain analysis with the 2-D strain state to obtain the principal strains and the planes on which they act (these strains are identified as initiating strains).
7) Compare the transverse coupling crack initiation strains with the ultimate transverse tensile strain for the ply material used. If the initiation strain is greater than the ultimate strain, failure exists (i.e. a coupling transverse crack exists at the analytically and K-rule determined location).
8) Compare analytical results with the actual failed part (cut and polished section mentioned in task 3) and any appropriate nondestructive evaluation technique (i.e. time-of-flight pulse-echo ultrasonics).
9) Assess results.

RESULTS

The laminate system described in reference [2] together with the C-scans and photomicrographs presented in references [2] and [3] were used to develop the initiation failure criteria described below. Tasks 1 through 3 of the approach section were accomplished by using the results from references [2] and [3]. The laminate [2] was impacted with a twelve pound weight (hemi-spherical nose) dropped from a height of eighteen inches. Methods described by Dobyns [5] were used to develop the impact stress analysis. The load patch dimensions used in the analysis were 0.3 inches square. The global laminate strains and transverse shear loads from the impact analysis [5] were transformed into a continuum of five strains for the laminate. The impact analysis [5] does not determine the normal strains in the laminate thickness direction. However, by utilizing a principal strain analysis [3] it can be shown with elementary finite element or finite difference methods that the normal strains in the thickness direction are principally confined to a zone directly beneath the load patch area. These strains decrease rapidly away from the load patch boundary. Furthermore, the principal strain analysis (using the results of numerical methods) will yield compressive principal strains in the vicinity of the load patch. Following the arguments of reference [3], if the principal strains are not tensile the CT crack will not exist and delaminations will not initiate. By ignoring the normal strain distribution (through the thickness) under the load patch, the impact analysis by Dobyns [5] is justified for the work described in this paper. The "Closure Zone" described above can physically be observed in Figure 2 [3]. Figure 1 is a traced copy of Figure 2 [3] presented here for clarity.

A linear distribution of the normal and in-plane shear strains through the laminate thickness was assumed in accordance with classical plate theory. The transverse shear forces were transformed into transverse shear strains using methods described by Whitney [6]. The transverse shear strains were assumed to be parabolically distributed through the laminate thickness.

For the present case, the global strain state was determined at the laminate's maximum transverse response. By using the methods described above, the total strain at any point in the laminate can be determined. Since the initiation failure criteria is concerned with the initiation of CT cracks, the strain state at the midplane of each ply is of prime interest. From Figure 1 it is clear that CT cracks in the top ply (impact side) initiate near the load patch boundary (as would be expected). The K-rule mechanisms emphasize an angular dependence between CT cracks in succesive plys through the thickness as shown in Figure 1c [3]. Obviously if the layup is such that this dependence exists throughout the laminate (as it does for the present case) then the classical "stairstep" delamination pattern will result [2]. The stairstep mechanism will tend to force CT cracks to exist further away from the load patch boundaries as they proceed through the laminate thickness (see Figure 1). Therefore, it becomes necessary to determine the angular orientation of each CT crack so that superposition of successive CT cracks through the thickness may be achieved.

The initiation failure criteria compares a ply material's ultimate transverse tensile failure strain with the results of a principal strain analysis conducted in a plane normal to the fiber direction of the ply under investigation. The strains in the top ply (impact face) are transformed into a two-dimensional set of strains set in a plane normal to the ply's fiber direction. Transformed strains not in this plane are mathematically independent of the strains in the plane normal to the fiber direction of the ply. The principal strain analysis is conducted at that point in the ply (at the ply midplane) determined by the K-rule in the plane normal to the ply fiber direction. The principal strains (if positive) are compared to the ultimate transverse tensile strain of the ply material to determine if failure exists. If both principal strains are positive the K-rule mechanisms determine which is to be used in the failure criteria. For T-300/934 the ultimate transverse tensile strain was determined to be 0.0056 in/in by methods presented in the literature [7].

By studying Figure 2 [3] and Figure 1 it is apparent that the locations of the CT cracks are a function of the K-rule mechanisms and the analysis discussed above. These figures also emphasize the need to analyze the laminate as a function of time. If the CT crack located at point B (Figure 1) is dependent on the location of the CT crack at point A (and all other CT cracks in between) then the strain distribution must change after each CT crack (and it's associated delaminations) has been initiated and developed. For the present case, the transverse shear strain was dominate with respect to all other strains. If new surfaces are created as a function of time within the laminate then the transverse shear strain distribution within the laminate must be changed since transverse shear strains cannot be supported at free surfaces.

Incorporating this transverse shear strain redistribution concept into the analytical methods discussed earlier, the initiation failure criteria can now be applied to the laminate of references [2] and [3]. Since in the present case the transverse shear strains are dominate the planes on which the principal strains act are approximately 45^{o} with respect to the plane of the laminate. The orientation of the CT cracks are 90^{o} out of phase with these planes [3]. The analysis can be conducted for each ply (from the impact side first) to locate all CT cracks in the laminate. In Figure 1, the maximum principal strains of the CT cracks at locations C and D are presented. Each strain exceeds 0.0056 in/in. CT crack D is particularly significant since it is located far from the load patch boundary where the total strain has been significantly reduced.

CONCLUSIONS

A preliminary method for locating and orienting coupling transverse cracks in impacted composite plates has been presented. The method involves a midplane (ply) principal strain analysis at the location where CT crack should exist (K-rule). A redistribution concept has been introduced to determine the true state of strain anywhere in the laminate as a function of damage propagation. A preliminary "initiation" failure criteria has been presented to verify the existence of the CT crack. Integrating the initiation failure criteria with the K-rule and the preliminary propagation failure criteria [4] the entire CDS can be reconstructed for an impact damaged composite structure using pulse-echo ultrasonics as the only historical input of the impact event.

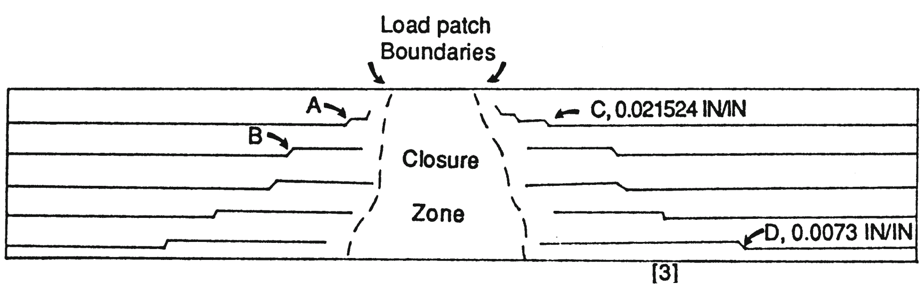

Figure 1. Graphical Representation of Figure 2.

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