A QUANTITATIVE NONDESTRUCTIVE EVALUATION TECHNIQUE FOR ASSESSING THE
COMPRESSION-AFTER-IMPACT STRENGTH OF COMPOSITES PLATES

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INTRODUCTION

The use of composite materials in primary structural applications is becoming an accepted practice. Unlike structural components comprised of metal, damage due to impact is usually not evident in composite structures. Severe internal damage can result from impacts such as dropped objects, low velocity vehicular collisions, or other sources of impact. It is apparent that a reliable nondestructive technique for assessing impact damage in composite structures is needed if composites are to be used in primary structural components.

In this paper we describe a procedure for nondestructively assessing impact damage in composite plates. The procedure consists of an instrumental nondestructive evaluation (NDE) of an impact damage parameter, an analytical reconstruction of the entire state of the impact damaged region, and finally an illustration of how this reconstructed damage state could be used to determine the residual post-impact compressive strength of the plate. The entire procedure represents an application of nondestructive materials analysis.

OBJECTIVE AND APPROACH

The long term objective of this work is to integrate the output of an appropriate field applicable instrumental nondestructive evaluation (NDE) technique with an analytical model which will reconstruct the impact damage state (through-the-thickness) and determine residual strength as a function of the reconstructed damage state, component geometry, layup, prepreg tape properties, service loading conditions, and support boundary conditions. The present approach consists of scanning impacted composite plates with an appropriate instrumental NDE technique and using the output of this technique to yield information regarding some parameter of the impact damaged state. The NDE output is integrated with an analytical model to develop the reconstructed damage state. The impact damage of simply supported composite plates (center impacted) consists primarily of delaminations and transverse (through-
the-thickness) cracks. These transverse cracks can couple delaminations allowing some delaminations to join with other delaminations at specific spatial locations and depths.

BACKGROUND

Investigators have observed the crack morphology described above with little explanation for its formation. It is generally held by most designers of composite structures that an accurate description of the impacted damage state is desired before a reliable post-impact strength assessment of the damaged composite structure can be realized. Therefore, not only must surface delaminations be observed, but the position and spatial geometry of all delaminations through-the-thickness must be identified as well. In addition, transverse cracks (through-the-thickness) must be located and the delaminations they couple determined. To our knowledge such a practice has not been documented in the literature.

Attempts to utilize instrumental NDE output to predict residual compression strength of impacted composite plates have been reported in the literature. The majority of these attempts are primarily empirical in nature and consists mainly of measuring a structural parameter of the damaged composite utilizing a through-transmission C-scan. For example, the lateral extent of impact damage can be determined in this manner and it is some aspect of this area which is usually correlated to the destructively determined residual compressive strength. It is a generally accepted opinion that this approach possesses many drawbacks including a lack of consistent correlations when changing the stacking sequence of the layup. It is apparent that a more general description of the impact damage is needed before a reliable residual strength assessment can be conducted.

In this paper we describe a preliminary method for nondestructively assessing the residual compression strength of impacted composite plates. The method consists of ultrasonic pulse-echo scanning of impacted composite plates utilizing time-of-flight information to determine first-echo delamination spatial and depth geometry from one side (both sides are scanned). The delamination depth maps are recorded digitally and later photographed. A knowledge of support boundary conditions and composite plate properties are integrated with the delamination depth map and incorporated into an analytical model (based on a strength of materials approach) to reconstruct the impact damage state. The usefulness of the reconstructed damage state is illustrated by identifying critical Euler instabilities within the damage region as a function of the post-damage loading condition. Classical laminate analysis is then used to determine the residual compressive strength of the impacted composite plate.

EXPERIMENTAL

Composite Laminate Description

Two composite systems were utilized in this study. The 934/T-300 prepreg was used to fabricate 6" x 4" composite plates with a (45, 90, -45, 0)\(_3\) layup. The 8551/IM7 system employed a (45, 0, -45, 90)\(_3\) layup. Figure 1 illustrates the plate geometry and layup orientation. Boeing specifications were used for panel fabrication, impact loading, and compression testing. Panels were center impacted with a twelve pound weight dropped from various heights (6" - 28").
Ultrasonic Pulse-Echo Scanning of the Impacted Composite Plates

Depth-amplitude scans of composite impact damage are derived ultrasonically by an Ultrasonic Data Recording and Processing System (UDRPS) connected to an automation industries scan bridge and an automation industries S-80 ultrasonic instrument. The S-80 has been modified for compatibility with the UDRPS by the addition of an external trigger capability and a signal conditioning output amplifier.

The UDRPS, manufactured by Dynacon, Compton, CA., consists primarily of a Hewlett Packard Computer, an analogic array processor, and a Ramtek 9465 color display system. A 70 megabyte hard disc holds the system software and scan data storage.

The video ultrasonic pulse-echo signal generated by the S-80, which contains the amplitude and time-of-flight information of the test part front and back surfaces and all internal reflections, is digitized at a 32 MHz rate by the array processor for storage, along with the x-y coordinate information. Image reconstruction performed by the Ramtek display presents the C-scan amplitude and depth plots in a rainbow color scheme, where lowest amplitudes and near front surface reflections are deep red, progressing through orange, yellow, green, blue, and finally violet for maximum amplitudes and depths. Maximum resolution for both features is one part in 255. Once the C-scan images are reconstructed, cursor controlled x-y position and amplitude-depth data may be obtained for any position in the scan.

In addition to conventional C-scan format images, where only x-y coordinates, amplitude and time-of-flight to the highest level reflector are recorded. The UDRPS system can store the full digitized A-scan for each point in the scan. This permits the display of B-scan sections, topographical A-scan plots and oscilloscope viewing of selected A-scans.
Figure 2 is a photograph of a pulse-echo C-scan of an impacted composite plate scanned from the front side. Figure 3, is an illustration of a pulse-echo C-scan of an impacted composite plate. An illustration is presented in Figure 3 rather than a photograph, to emphasize pertinent features of the C-scan which may not be evident in a photograph reproduced for publication. Figure 3a is an illustration of an impacted composite plate scanned from the impact side. Figures 3b is an illustration of another impacted composite plate scanned on the back side. When scanning the back side of impacted composite plates the plate is usually scanned front side first and then turned over in such a manner that the top of the plate is now the bottom. The back side of the plate is scanned with this orientation.

Post-Impact Compression Testing of the Impacted Composite Plates

Once the impacted panels were scanned and the pulse-echo C-scans recorded photographically they were compression tested according to Boeing specifications. All panels were loaded in compression at a rate of 0.05 inches per minute. The panels were laterally supported along all four edges to prevent global buckling of the laminate.

IMPACT DAMAGE STATE RECONSTRUCTION

A mathematical analysis of the reconstructed damage state is beyond the scope of the paper. The mathematical approach to the mechanics of damage generation due to impact is work currently under investigation by the authors and will be presented in a later paper.
For purposes of illustration an approximate graphical approach will be used in this paper for damage reconstruction. All damage discussed will be a function of low velocity impact only (4-16 ft/sec). The approximate graphical analysis is primarily a function of the K-rule. The K-rule is a method of determining delamination position through-the-thickness provided that both a pulse-echo depth map and information regarding the laminate layup are available. Application of the K-rule is illustrated in Figure 4. Figure 4a shows the generation of transverse cracks in the surface ply (45°) as a function of the impact load (center circle). Similar transverse cracks are generated in the second ply (90°) and are shown in Figure 4b interacting with the surface (45°) transverse cracks creating a delamination between them. The process is continued down through-the-thickness in Figures 4c and 4d. Continuation of the process will yield an image similar to that shown in Figure 3a.
By approximating transverse crack orientation through-the-thickness as 45°, the damage through-the-thickness (delaminations and their coupling transverse cracks) can be reconstructed. The approximate reconstruction is quite similar to the actual damage as determined by metallography. Using metallography and the pulse-echo C-scan as a guide, sections can be produced which reveal actual crack distributions through-the-thickness. Figure 6 shows the metallographic sections of a typical impacted composite plate using the pulse-echo C-scan of the impact damage as a reference. Figure 7 illustrates the crack distributions in the sections using the approximate analysis. Again, illustrations are used to amplify pertinent points. Figure 7 is an exaggeration of damage size and only shows the coupling transverse cracks for the 0° plies, their nearest neighbors, and the associated delaminations as discussed with respect to Figures 4 and 5.

Graphical approximate techniques were used in this paper to illustrate how the internal damage of impacted plates can be reconstructed. Figures 8 and 9 are actual photographs of polished sections corresponding to Sections A and B of Figure 5.

ILLUSTRATION OF A POST-IMPACT COMPRESSIVE STRESS ANALYSIS UTILIZING THE RECONSTRUCTED DAMAGE PLATE

Through observation of the compression testing of impacted composite plates it is apparent that some type of Euler-type instability is primarily responsible for the resulting catastrophic failure of the compressively loaded impacted composite plates. By reconstructing the damage state it can be seen that the impact damage consists primarily of a parallel series of sub-laminates, see Figure 7. If it can be hypothesized that an Euler instability is primarily responsible for the catastrophic failure then the identification of the instability(s) for any given post-impact load state together with an appropriate instability analysis should yield a failure stress close to the destructively determined compressive failure stress. For the laminates in this paper the critical instability was determined to be the middle triangular sub-laminates on the tension side (934/T-300) are the middle triangular sub-laminates one sub-laminate in from the tension side.
Figure 6. Metallographic Sections of an Impacted Composite Plate with Ultrasonic Guidance

Figure 7. Metallographic Cut Sections of the Plate in Figure 6
Figure 8. Section B

Figure 9. Section A
Figures 10 and 11 illustrate how the critical region was modeled as a simply supported composite plate (layup determined by damage reconstruction). A buckling analysis using classical laminate analysis was performed to determine the critical buckling stress using the parameters shown in Figure 10. Once this sub-laminate buckled all others are assumed to follow. The results of this analysis are shown in Figure 12.

Figure 10. Location of the Back Side Middle Triangular Sublaminates

Figure 11. Modeling of the Euler Instability
CONCLUSION

An appropriate NDE technique has been identified to locate first-echo delamination positions from the surface of an impacted composite plate. By using an approximate graphical analysis (the K-rule) and the pulse-echo C-scan, a description of the impacted damage state can be determined anywhere in the laminate damage zone. By utilizing the reconstructed damage state it has been illustrated how the residual compression strength of an impacted composite plate could be determined through the identification of a critical Euler instability.

FUTURE WORK

Work must be continued to mathematically verify the validity of the K-rule. And finally, a fracture mechanics approach must incorporated in the residual stress analysis for a more complete stress analysis.

REFERENCES

2. S. M Lee, 17th National SAMPE Technical Conference
3. Boeing Specifications BS 7260