

Buckling and Fracture Analysis of Composite Skin/Stringer Panel Using VCCT

Summary

The use of composite materials in the aerospace industry is increasing. Composite materials offer a relatively high strength-to-weight ratio as well as the ability to create large, integrated structures. One composite component can replace 10 or more traditional metal parts, which can dramatically reduce manufacturing time and cost.

The Boeing 787 will be the first airliner to use composite materials in the majority of the aircraft construction. Analysis tools that can accurately simulate the behavior of composite materials are critical to the successful design and use of composite structures. Through the Composites Affordability Initiative (CAI), Boeing developed a finite element implementation of the Virtual Crack Closure Technique (VCCT). Dassault Systèmes SIMULIA Corp. teamed with Boeing to provide this technology as a feature of Abaqus/Standard. This capability allows for the simulation of brittle interfacial crack propagation due to delamination/debonding.

This technology brief examines the behavior of a stringer-stiffened composite panel subjected to in-plane shear loading. The Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) experimentally tested single stiffener panels with a defect introduced in a portion of the bond between the skin and the stringer. Using the VCCT fracture analysis capability, the panel test is simulated and the results are compared to experimental data.

Background

One of the main failure modes for the skin of an aircraft is buckling. Stringers are often bonded to composite panels to help increase the panel's buckling strength. The analysis of such panels often investigates the total strength assuming an initial flaw, such as a crack in the bond between the skin and the stringer, and the strength of the panel during crack growth.

The information that the analyst and designer seek from the simulation of stringer-stiffened panels includes:

1. the total load carrying capability of the panel
2. the load at which a crack in the stringer bond line initiates
3. the stringer debond/crack growth characteristics

The VCCT fracture analysis capability in Abaqus simulates crack growth in bonded composite structures.



Key Features and Benefits

- VCCT in Abaqus is applied during run time, so remeshing, reanalysis, and stand-alone post-processing are not necessary.
- Supports active propagation of delamination/debonding during loading.
- Calculates crack growth based on linear elastic fracture mechanics (LEFM).
- Allows mixed-mode crack growth, and includes three popular mode mixity criteria.
- Can be included in a nonlinear analysis, and includes frictional contact to prevent penetration of cracked surfaces upon load reversal.
- Does not require a specialized postprocessor—Abaqus/Viewer postprocesses all VCCT results.

Description of Problem

The goal of the CRC-ACS test and analysis program is to determine the load carrying capability of a composite aircraft panel. The particular failure mode under investigation is buckling of the panel under in-plane shear loading. The buckling is induced by applying a displacement to opposite corners of the panel. The panel being investigated, which is schematically shown with the test fixture in Figure 1, is flat and utilizes a single stiffening stringer.

The stringer is co-cured to the panel. The panel and the stringer are made out of similar composite materials and similar ply lay-ups. The analysis and testing presented here investigate the load carrying capability of the panel assuming a flaw in the skin-stringer bond line. Flaws of this type are typically assumed to represent the largest undetectable flaw or crack. To simulate this flaw, a release film is used to create an unbonded region in the bond between the panel and the stringer.

There are two main effects of the introduction of a flaw in the bonded structure. First, there is a reduced maximum load capability. Second, and more important, under load the crack will grow and further reduce the strength of the panel. Both of these effects are investigated through the test program and analytical simulation of the panel.

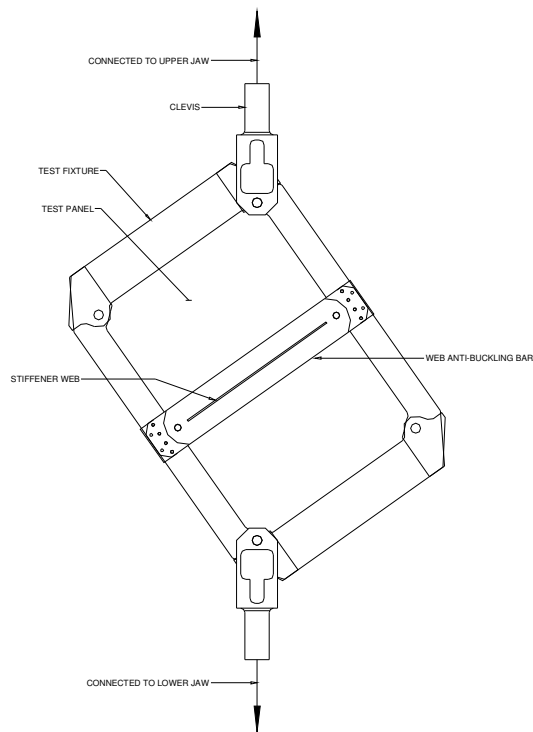


Figure 1: Schematic diagram of panel buckling test
(Copyright CRC-ACS LTD., 2005)

Finite Element Analysis Approach

For this problem CRC-ACS previously developed a finite element model of the panel that was used for design analysis studies. This model, which was in NASTRAN bulk data format, is converted into an Abaqus model using the **fromnastran** utility and then imported into Abaqus/CAE for further definition of model and analysis parameters.

The finite element model, which is shown in Figure 2, is mainly comprised of layered shell elements.

The region around the area of the initial flaw is more finely meshed than the remainder of the panel. Mesh tie constraints are used to join the fine mesh region to the coarse mesh region and to connect the panel to the stringer away from the crack region. The mesh tie constraint facilitates modeling by automatically connecting meshes of different densities with a surface-based formulation.

The fine mesh areas of the panel and the stringer are connected using contact surfaces. Within the contact surfaces the areas that are initially bonded and debonded must be defined. In Figure 3 the initially debonded area is orange and the initially bonded area is dark blue.

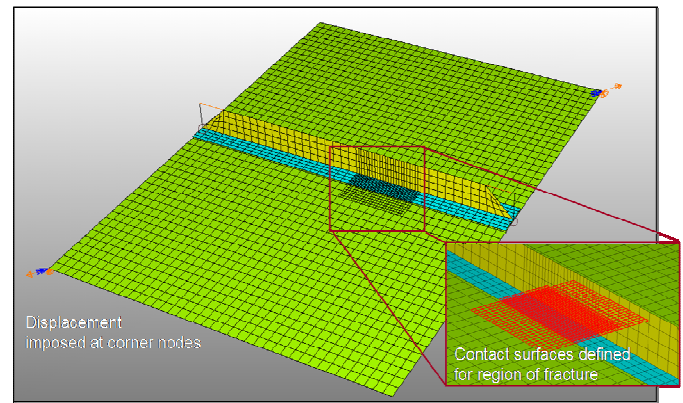


Figure 2: Abaqus model of the skin-stringer panel with contact surfaces defined between the skin and the stringer in the region of the initial crack and possible crack growth

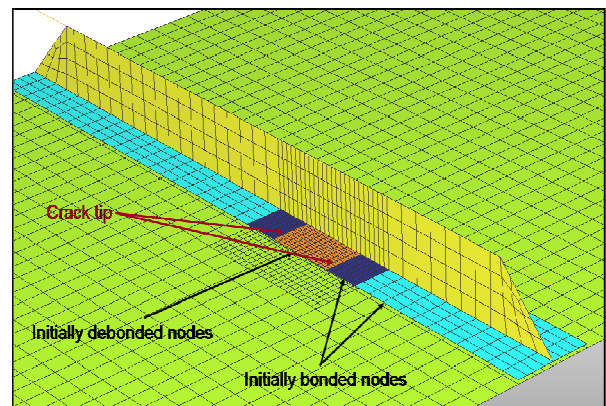


Figure 3: Initially debonded area

Definition of VCCT Fracture Properties

The preparation of a VCCT analysis begins with the definition of the surfaces for the region of possible debonding; these surfaces are then used in a contact pair. The interaction properties for this contact pair are then defined to include the fracture parameters, such as the fracture toughness and the mode mixity criteria.

Three common mode-mix criteria are provided: the B-K law (see Ref. 1), the power law (see Ref. 2), and the

Reeder law (see Ref. 3). For the present analysis the power law model is used:

$$\frac{G}{G_C} = \left(\frac{G_I}{G_{IC}} \right)^m + \left(\frac{G_{II}}{G_{IIC}} \right)^n + \left(\frac{G_{III}}{G_{IIIC}} \right)^o$$

Loading

The skin-stringer panel is loaded by applying an enforced displacement at the corner nodes of the panel (Figure 2).

Output

The results recovered from the simulation mirrored the measurements that were made during the actual panel testing. The load versus deflection is recovered along with out-of-plane displacements of the panel and strain measurements at various locations along the panel. In addition, the load at crack initiation and the crack growth characteristics are also recovered.

Results and Discussion

The panel did indeed buckle under the imposed displacement. The scaled deflected shape computed by Abaqus is shown in Figure 4. The buckling began before the crack in the panel grew, and growth of the crack did reduce the overall stiffness of the panel.

Representative crack initiation and growth results are shown in Figures 5–7, where the debonded region is shown in red. The crack growth initiated (first node released) at a load of 116 kN, but further growth of the crack did not occur until 146 kN, at which point many nodes released and the crack continued to grow with increasing load. These results are very close to observations during the test program. Three nominally identical panels were tested. Based on audible acoustic emissions, crack initiation/growth for the panels occurred at 146 kN, 154 kN, and 175 kN. These load values agree well with the crack growth predicted in the simulation.

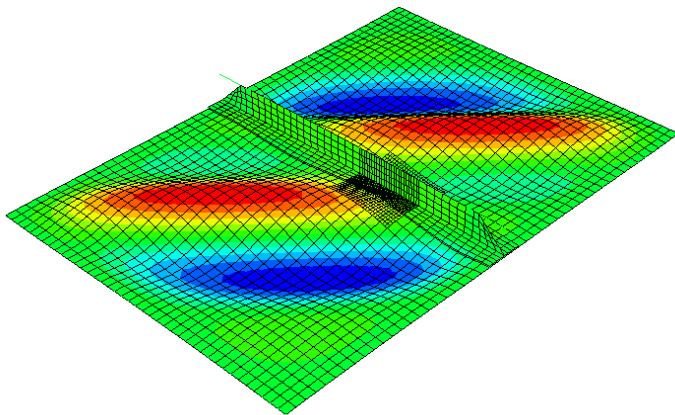


Figure 4: Deflected shape of the buckled panel

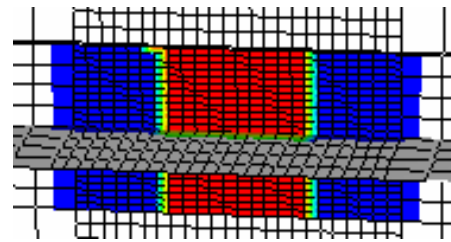


Figure 5: Debonding at load of 116 kN

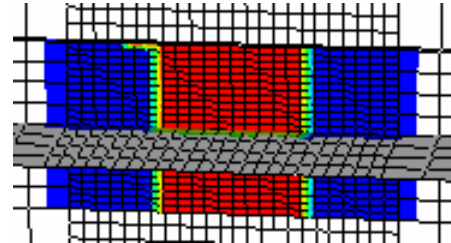


Figure 6: Debonding at load of 148 kN

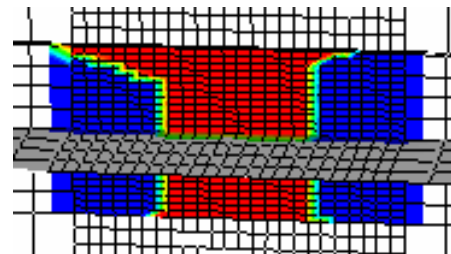


Figure 7: Debonding at load of 216 kN

The shape of the predicted crack growth correlated well with that observed experimentally. Figure 8 shows a photograph of the debonded region in Panel 2 at the end of the test.

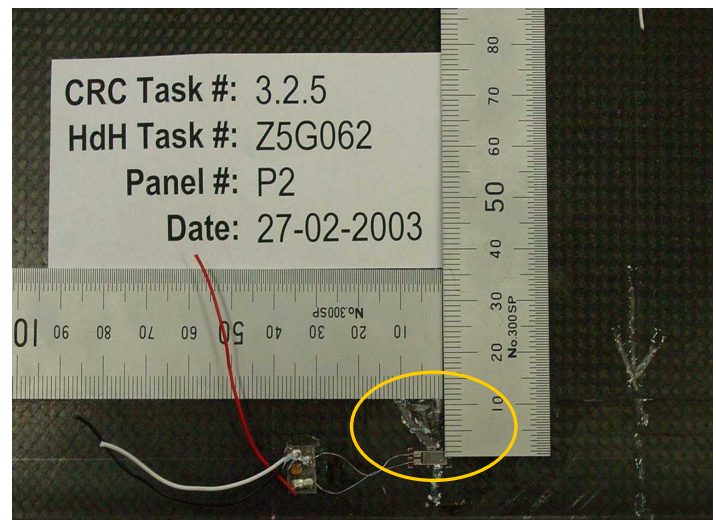


Figure 8: Panel 2 crack growth occurred in the upper left position, which matches analytical predictions (Copyright CRC-ACS LTD., 2005)

Along with the observations of the debonded region, the panel out-of-plane displacements (buckling magnitude) and strain measurements were compared between test and analysis. In Figure 9 the locations of the linear variable displacement transducers (LVDT) are shown in red, while the strain gage locations are shown in blue. Both LVDTs are on the stiffener side of the panel. Strain gages were mounted on the stiffener side of the panel at location 1 and on both sides of the panel at location 2.

The LVDT measurements are plotted against the Abaqus simulation results in Figures 10 and 11. Strain measurements are compared against analytical predictions in Figures 12, 13, and 14.

In Figure 11 the buckling magnitude is calculated as the difference between the readings of LVDT 1 and LVDT 2; the corresponding Abaqus output is also shown.

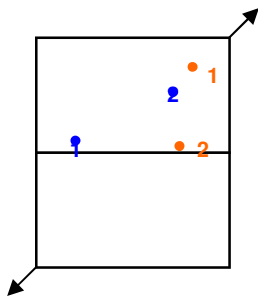


Figure 9: LVDT and strain gage locations

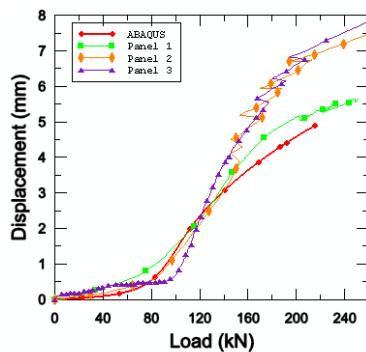


Figure 10: Out-of-plane displacement (LVDT 1) comparison between test and analysis

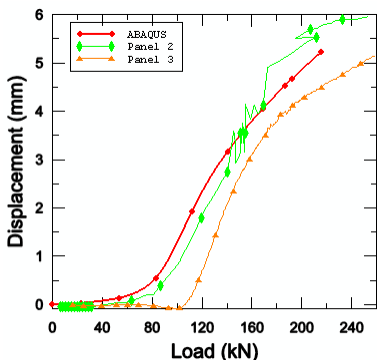


Figure 11 Out-of-plane displacement comparison between test and analysis

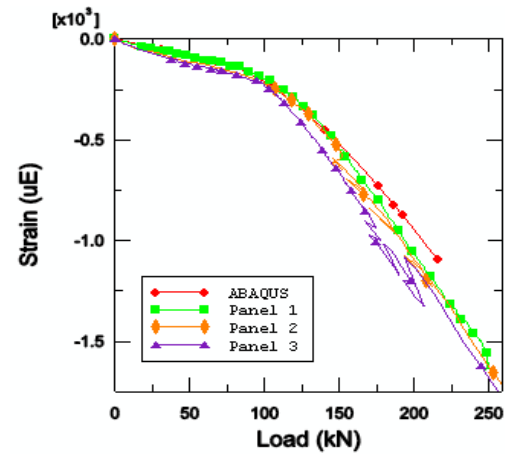


Figure 12: Comparison of measured strain and analytically predicted strain on the stringer (gage location 1)

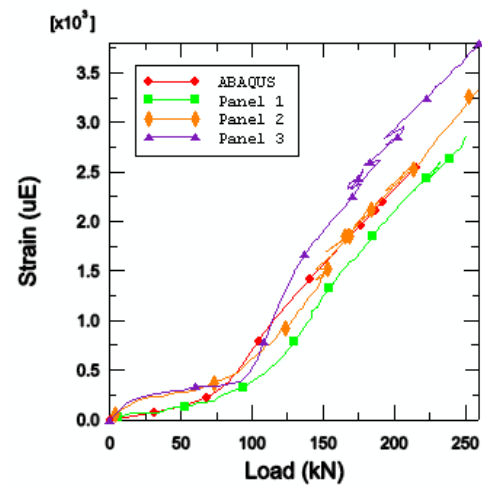


Figure 13: Comparison of measured strain and analytically predicted strain on the panel (gage location 2, stiffener side)

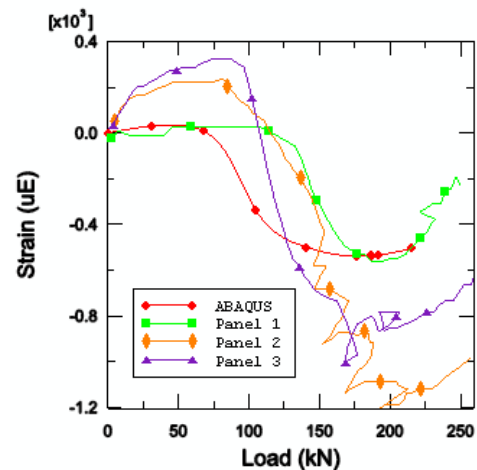


Figure 14: Comparison of measured strain and analytically predicted strain on the panel (gage location 2, back side)

Conclusion

The load carrying capabilities of a composite bonded skin/stringer panel were analyzed, and the analytical predictions were compared to test measurements. Good correlation between the analysis and test were observed. Abaqus VCCT capabilities were utilized to model the crack growth in the bond between the stringer and the panel, and the predicted cracking characteristics of the structure matched between test and analysis.

References

1. Benzeggagh, M., and M. Kenane, "Measurement of Mixed-Mode Delamination Fracture Toughness of Unidirectional Glass/Epoxy Composites with Mixed-Mode Bending Apparatus," *Composites Science and Technology*, vol. 56, p. 439–449, 1996.
2. Wu, E. M., and R. C. Reuter, Jr., "Crack Extension in Fiberglass Reinforced Plastics," T and M Report, University of Illinois, vol. 275, 1965.
3. Reeder, J., K. Song, P. B. Chunchu, and D. R. Ambur, "Postbuckling and Growth of Delaminations in Composite Plates Subjected to Axial Compression," 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, vol. 1746, p. 10, 2002.

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, see the following Abaqus 6.13 documentation references:

- Crack propagation analysis, Section 11.4.3 of the Analysis User's Guide

About SIMULIA

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