

# Compression Response Of Notched Composite Stiffened Panels: Analyses And Experiments

**Damodar R. Ambur and David M. McGowan**

NASA Langley Research Center  
Hampton, VA 23681-2199

**Donald J. Baker**

Vehicle Technology Center - ARL  
NASA Langley Research Center  
Hampton, VA 23681-2199

## ABSTRACT

An experimental and analytical evaluation of the compressive response of two notched composite stiffened panels representative of primary composite wing structure is presented. A three-dimensional full-field image correlation technique is used to measure the three displacement components over global and local areas of the test panels. Full-field displacement results obtained using the image correlation technique are presented and compared to experimental results and analytical results obtained using nonlinear finite element analysis. Both global and global-local image correlation results are presented and discussed.

## 1 INTRODUCTION

One of the requirements for airframe structures development is the demonstration of structural damage tolerance for a panel with a two-stringer-bay-wide notch. The response of notched panels made of composite materials and loaded in compression or tension is not well understood. Experimentally validated analysis methods that predict the damage initiation and growth at the notch location are needed. Such methods can eventually be used to predict the residual strength of composite primary structures. Evaluating the response of structures with discontinuities such as cutouts and damage in the form of notches requires full-field information that represents the experimental in-plane and out-of-plane displacement components of the structure.

A promising method for full-field displacement measurement is the three-dimensional image correlation technique described in Ref. [1]. The measurement system using this technique is described herein as VIC3D (Video Image Correlation in 3 Dimensions). This field-displacement measurement technique described in the above reference utilizes a camera-based stereo vision system to monitor the three-dimensional locations of points on the surface of the loaded test specimen. This system is a non-intrusive system since

the only part of the measurement system that comes into contact with the test specimen is the speckle pattern that is applied to the surface of the specimen to establish the displacement tracking points. The resolution of the measurement data is a function of the speckle pattern density and the distance between the cameras and the specimen. The accuracy of the displacements measured in the present study range from  $\pm 8.89 \times 10^{-5}$  cm. to  $\pm 4.3 \times 10^{-3}$  cm. Another application of this displacement measurement technique is to monitor displacements in a global-local manner. In such an application, coarser full-field measurements are made over a larger area of the specimen, and higher-accuracy measurements are made over a smaller, local area within the larger area. The local area monitored may be centered about some structural feature with large displacement gradients or damage. These types of measurements can be very important to obtaining a better understanding of the effects of local details like cutouts or damaged areas on the load distribution in built-up structures and load path redistribution corresponding to failure initiation and propagation.

The present paper describes an experimental and analytical evaluation of the compression response of two composite stiffened panels with a central notch. Full-field displacement results obtained using the three-dimensional image correlation technique mentioned previously are presented and compared to experimental results obtained using conventional displacement measurement devices and analytical results obtained using nonlinear finite element analysis.

## 2 TEST PANELS, APPARATUS, AND TEST CONDITIONS

The two stiffened composite panels studied in the present paper were machined from either the upper or lower cover panels of a 3.66-m.-long, stitched graphite-epoxy wing box manufactured by the Boeing Company (formerly McDonnell Douglas). The cover panels were fabricated from Hercules, Inc. AS4/3501-6 and IM7/3501-6 graphite-epoxy materials

that were stitched together using E.I. DuPont de Nemours, Inc. Kevlar® thread. IM7 graphite fibers were only used as the 0-degree fibers in the lower cover panel. The skin and stringers of the panels were fabricated from pre-kitted stacks of nine layers of dry graphite material forms. Each pre-kitted stack of material was approximately 0.14-cm. thick and had a  $[45/-45/0_2/90/0_2/-45/45]_T$  laminate stacking sequence. The skin and stringers of the wing box were fabricated by stitching several of these pre-kitted stacks of material together to provide the desired thickness at different locations in the wing box. The wing box was fabricated using the Resin Film Infusion (RFI) process described in Ref. [2].

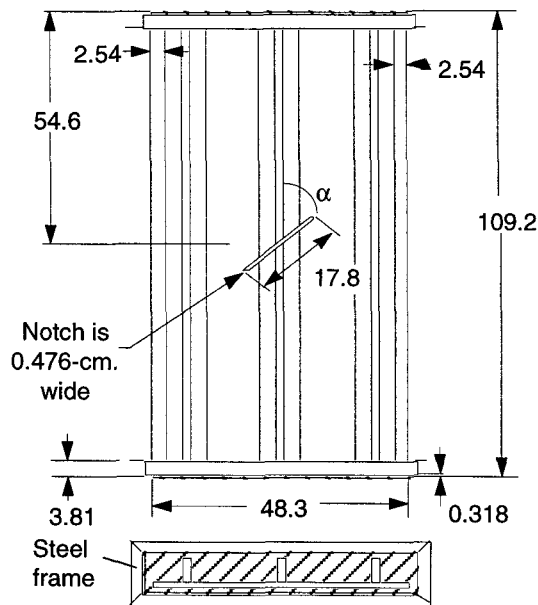


Fig. 1. Schematic of a stitched, graphite-epoxy panel with a centered, machined notch through the center stringer (dimensions are in centimeters).

A schematic of the panels studied in the present paper is given in Fig.1. Each three-stringer panel had a 17.8-cm.-long by 0.476-cm.-wide notch machined through the center stringer and oriented at an angle  $\alpha$  to the center stringer. The value for  $\alpha$  was  $90^\circ$  for the upper cover panel and  $60^\circ$  for the lower cover panel. The height of the stringer blades was 6.04 cm. for the upper cover panel and 5.08 cm. for the lower cover panel. The loaded ends of both panels were encased in 3.81 cm. of epoxy potting compound to prevent an end-brooming failure, and those edges were machined flat and parallel to each other. The unloaded edges of the panels were supported with knife-edge supports to provide a simple support boundary condition along those edges.

A photograph of the test set-up for the upper cover panel is given in Fig. 2. Full-field displacements were monitored in a region that was approximately 17.5-cm. wide by 11.5-cm.

long that was centered horizontally at one of the notch tips. The speckle patterns for the tests of the composite panels were produced by printing a computer-generated pattern on an adhesive-backed Controllac™ Plus vinyl sheet manufactured by the 3M company. Details of the use of this material are given in [3]. The speckle patterns were applied to the unstiffened surface of the panels.

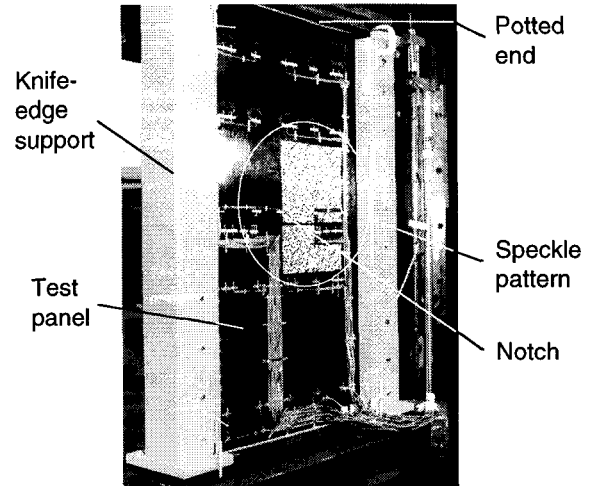


Fig. 2. Photograph of the upper cover panel.

A photograph of the lower cover panel and the speckle pattern used for this test is shown in Fig. 3. The global-local three-dimensional image correlation technique was used for this test. The global region monitored was approximately 38.1-cm. wide by 69.9-cm. long. The local region monitored was approximately 19.6-cm. wide by 11.7-cm. long, and was centered on one of the notch tips. The details of the VIC3D setups used for these tests are given in [3].

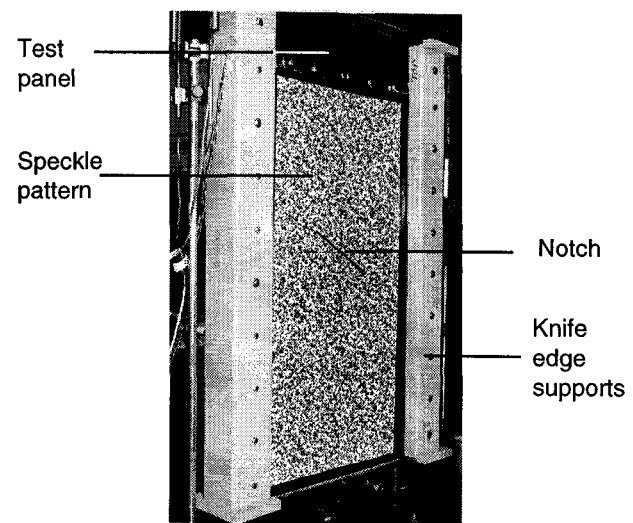


Fig. 3. Photograph of the lower cover panel.

### 3 ANALYTICAL MODELS

The analytical results described in the present paper were obtained from nonlinear analyses performed using the Structural Analysis of General Shell Structures (STAGS) finite element code [4]. The finite element model used to analyze the lower cover panel (with  $\alpha = 60^\circ$ ) is shown in Fig. 4. The finite element mesh is much more refined in the local notch region to allow for an accurate representation of the strain field in the vicinity of the notch tip. A similar model was used to analyze the upper cover panel. The nominal elastic material properties used in the analyses are given in Table 1 for the stitched/RFI (S/RFI) AS4/3501-6 and AS4/IM7/3501-6 material systems used to fabricate the present panels.

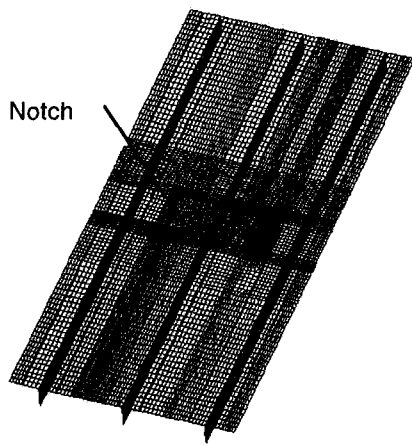


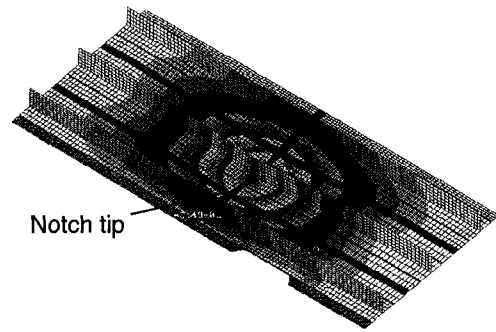
Fig. 4. Finite element model of the lower cover panel.

Table 1. Nominal elastic properties for the stitched/RFI material systems.

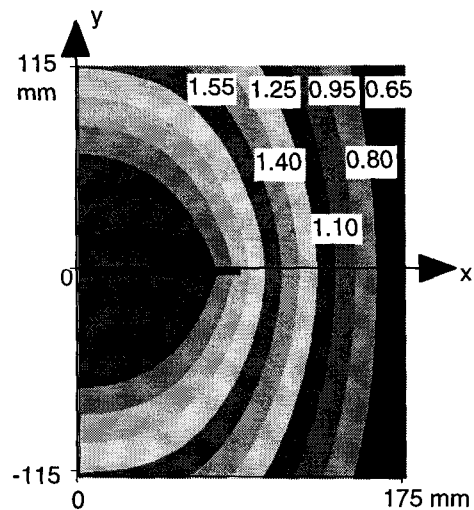
	AS4/3501-6	AS4/IM7/3501-6
$E_x$ , GPa	56.3	68.8
$E_y$ , GPa	30.8	30.7
$G_{xy}$ , GPa	16.2	17.7
$\nu_{xy}$	.458	.409

### 4 UPPER COVER PANEL RESULTS

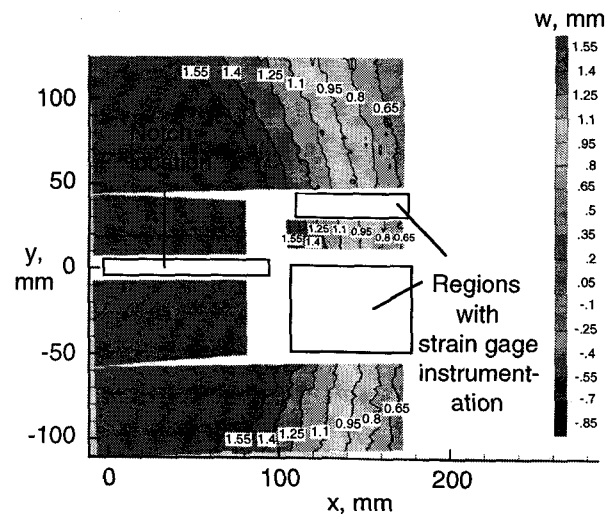
Out-of-plane displacement results obtained from a geometrically nonlinear finite element analysis of the upper cover panel are shown in Fig. 5. A plot of the deformed shape of the panel predicted by the nonlinear analysis at an applied load of 1.07 MN is shown in Fig. 5(a). Out-of-plane displacement contours obtained from the analysis at an applied load of 1.07 MN are shown in Fig. 5(b), and the corresponding contours obtained from the full-field measurements at this load are shown in Fig. 5(c). A comparison of the location and magnitude of the displacements suggests an excellent correlation between the two results.



a. Results obtained from nonlinear finite element analysis



b. Results obtained from nonlinear finite element analysis

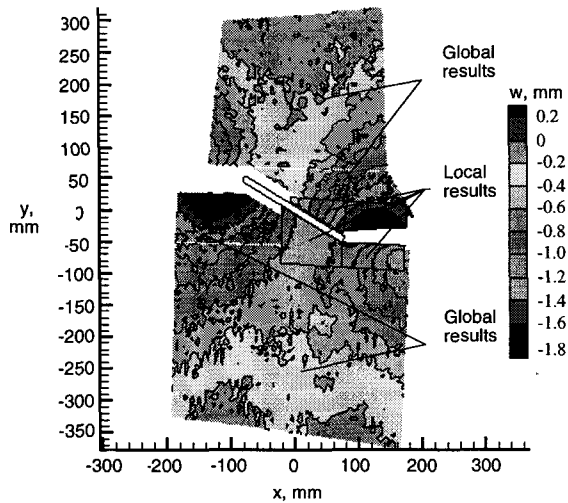


c. Results obtained using the full-field displacement measurement system

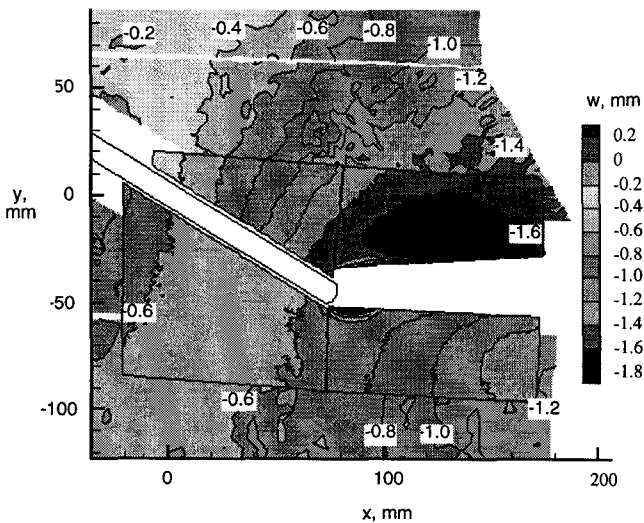
Fig. 5. Out-of-plane displacement contours for the composite upper cover panel for an applied load of 1.07 MN.

## 5 LOWER COVER PANEL RESULTS

Out-of-plane displacement contours obtained using the VIC3D system are presented in Fig. 6 for an applied load of 1.29 MN (just prior to failure). The contour plots shown in this figure contain global and local full-field results that have been merged into one data set. There are no data shown in a selected area near the notch tip. This area was in the path of the growing notch, and the resulting outward brooming of the surface fibers caused very localized increases in the measured displacements that were not included in these results. The results shown in Fig. 6(a) are for the entire global and local areas monitored during this test. A detailed view of the local results is shown in Fig. 6(b).



(a) Results for the complete field monitored



(b) Detailed view of the local results

Fig. 6. Full-field, global-local out-of-plane displacement contours measured with the VIC3D system for an applied load of 1.29 MN.

One important result shown in Fig. 6 is the degree to which the global and local results can be matched at the boundaries between the two areas. Although the global results have less fidelity than the local results (evidenced by the contours shown in Fig. 6(b)), the two data sets match very well at the interface. The small region of very large displacement gradients near the notch tip are due to the presence of surface fiber failures that were present in the areas in which data were selected to be presented. These results indicate that a global-local approach to monitoring full-field displacements can be useful for tracking the propagation of damage as a function of load as well as adding insight into the redistribution of load in the structure as the damage propagates.

## 6 CONCLUDING REMARKS

Compression tests of two notched graphite-epoxy stiffened panels were conducted using a three-dimensional full-field image correlation technique for displacement measurement. Each three-stringer panel had a notch machined through the center stringer that was oriented at an angle to that stringer. Full-field displacement results obtained using the image correlation technique were compared to experimental results and analytical results obtained using nonlinear finite element analysis. Results obtained using both global and global-local image correlation techniques were compared. The comparison of the image correlation results with the experimental and analytical results indicated excellent agreement of global and global-local results. The results obtained using the global-local displacement measurement technique also indicated that these types of measurements can be very important for obtaining a better understanding of the effect of local details like cutouts or damaged areas and propagating damage on the load redistribution in built-up structures.

## REFERENCES

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