Out-of-Plane Restraint under Tension In-Plane Loading

Dawn C. Jegley[1], W. Allen Waters Jr.[2], and Alana Zahn Cardona[1]

[1]NASA Langley Research Center, Mail Stop 190, Hampton, VA 23681

[2]Analytical Mechanics Associates, Inc., 21 Enterprise Parkway, Suite 300, Hampton, VA 23666

ABSTRACT
The development and description of a test fixture designed to restrict out-of-plane motion in the center region of tension-loaded carbon-epoxy panels are presented herein. The test fixture was used to impose displacement conditions consistent with those in an analytical tool being developed to predict panel behavior in the vicinity of a central notch, which included the assumption that there would be no out-of-plane displacement and no buckling. However, pretest analysis using finite element models for a panel loaded without any out-of-plane restraint in the region of the notch indicated that with an imperfection magnitude equal to 20 percent of the thickness of the thin-skin panel, an unacceptable amount of out-of-plane deformation would occur as Poisson effects induced compression loads in the region of the notch. Therefore, to validate this tool in a test program, a restraint fixture which would suppress out-of-plane motion was required. The panel could not be encased in restraining plates because instrumentation and visibility were required in the vicinity of the notch. Therefore, a fixture that would restrict out-of-plane motion while still allowing access to the surface of the panel at the notch edges for instrumentation and line-of-sight access for cameras was required. To satisfy these requirements, a fixture was designed to restrict only out-of-plane motion near the center of the notch. Two 1.78-m-long test panels were loaded in tension to failure using this fixture. Out-of-plane deformations were not directly measured during testing, so back-to-back strain gages were used to obtain an indication of buckling. Strain results indicated that the restraint fixture performed as designed and buckling did not occur.

Key words: Transverse buckling, Fixtures, Carbon-epoxy, Notches, Out-of-plane restraints

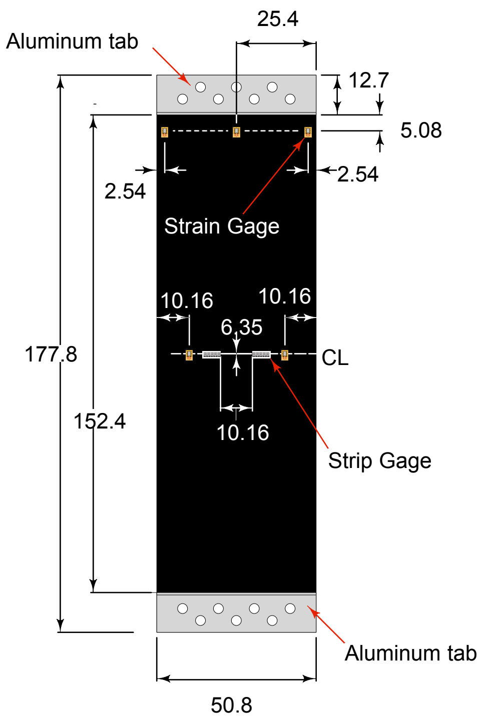
INTRODUCTION
The goal of performing a mechanical test must be defined prior to designing the test arrangement. For example, an experiment may be intended to simulate a real-world condition in a laboratory environment, or be designed to enforce a simple and easily modeled condition to support the development of an analytical tool. Using the appropriate test fixturing can be a critical part of conducting a successful experiment on any structure. Even relatively simple experiments can require complex restraints or load-introduction systems to ensure the desired conditions are imposed on the test article.

The purpose of the test program supporting the tests described herein was to support the validation of a non-finite-element prediction methodology that could be used as a preliminary assessment and design tool to predict behavior of carbon-epoxy stiffened panels with large notches. This validation effort required analysis and testing with tensile and compressive loads applied to two sizes of unstiffened panels as well as two stiffened panels of the same size that were larger than the unstiffened panels. The testing of some of the unstiffened test articles are described in Ref [1] and [2].

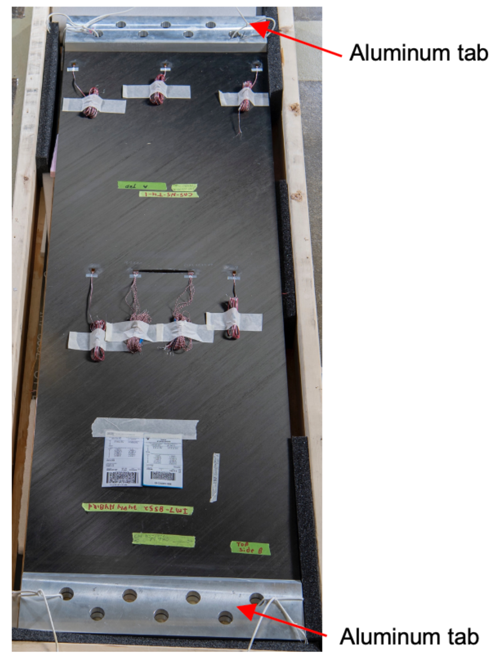
The tool being developed contained the assumptions of uniform tension or compression load introduction, no buckling, and no other out-of-plane displacement. An earlier version of this analytical tool is discussed in Ref [3]. The need for validation of the preliminary-design rapid tool dictated the test-article geometry, stacking sequence, load, and boundary conditions. The validation effort involving the larger of the unstiffened panels loaded in uniaxial tension is discussed in this document. The testing of two carbon-epoxy panels with a central lateral notch were used to obtain the desired information for validation of the methodology for tensile loading.

PANEL DESCRIPTION

For validation of the rapid tool, a carbon-epoxy laminate with stacking sequence $[+45/90/-45/0_2/+45/90/-45/0]_s$, containing 18 plies with total thickness of approximately 0.33 cm, was chosen. Tension-loaded panels were 1.78 m long, 0.51 m wide and contained a test section length of 1.52 m. Each panel contained a mid-length lateral notch which was 10.16 cm long with 0.635-cm-diameter circular ends. The notches widened in the center to 0.953 cm. This notch shape was chosen to be the same as the notch in similar compression-loaded panels (not discussed herein) to avoid contact of the notch edges during loading. The 0º fiber orientation was the loading direction. A sketch of the panel is shown in Figure 1a, and a photograph of one of the test panels is shown in Figure 1b.



a) Panel geometry



b) Panel prior to installation in the test machine

Fig. 1 Geometry of the tension panels with dimensions in cm

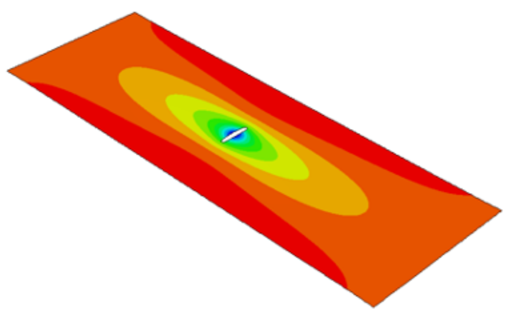
EXPERIMENT DESIGN

Prior to panel fabrication, an analysis was conducted using the finite element code Abaqus [4] to support selection of the test machine, to enable design of the load introduction interfaces, to develop the instrumentation plan, and to determine the need for a restraint system to prevent out-of-plane motion. Since the focus of the analytical tool was the behavior of the panel in the region of the notch, the behavior of the panel away from the notch was considered less important to the success of the test. An important assumption in the analytical tool was that no out-of-plane deformation would take place. Therefore, the pretest finite element analysis included an evaluation of the out-of-plane deformation that would occur in the region of the notch.

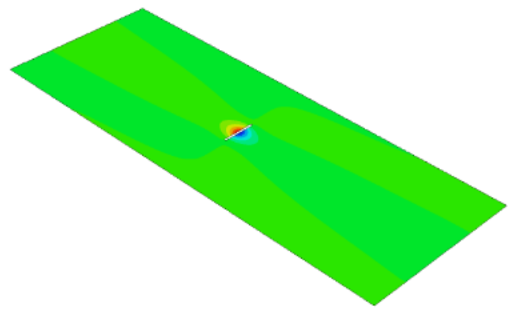
Geometric imperfections in thin-walled structures can have a significant influence on panel behavior [5]. These imperfections are critically important with respect to the buckling behavior of compression-loaded panels. In the case of the tension-loaded panel described herein, the central notch opened the possibility that the notch region might deform out-of-plane due to Poisson effects and therefore, geometric imperfections were assessed for their influence. In order to account for potential geometric imperfections, symmetric and antisymmetric deformation shapes were considered. The symmetric and antisymmetric imperfection patterns shown in Figure 2 were investigated. This pretest analysis indicated that the antisymmetric mode was the more critical mode so only that mode is discussed herein.

An imperfection magnitude equal to 20% of the panel thickness for the antisymmetric imperfection case with out-of-plane restrictions only at the loaded edges of the panel resulted in an induced deformation at the notch tip of up to 18% of the panel thickness. This out-of-plane deformation at the notch tip of 0.0597 cm was deemed inappropriate for the validation effort, so a restraint fixture that would suppress out-of-plane motion was required. The test program required instrumentation and visibility in the region of the notch, so the panel could not be encased in supporting plates. A restraint system that would prevent out-of-plane motion, but would allow access to the surface of the panel near the notch edges for instrumentation and line-of-sight access for cameras was required.

Further analysis indicated that, if restraints to out-of-plane motion were added to the nodes mid-width as shown in Figure 3, the deformation was reduced to 9.07% of the panel thickness, or 0.0299 cm. This value was deemed adequate to support validation of the analytical tool. Since only the center region of the panel was of interest, and after feedback from the industry partners responsible for the development of the analytical tool, the length of the restraint was shortened to only include only the central 10.16 cm portion of the panel (5.08 cm above and below the notch).



a) Symmetric



b) Antisymmetric

Fig. 2 Assumed imperfection shapes of geometrically-imperfect panel

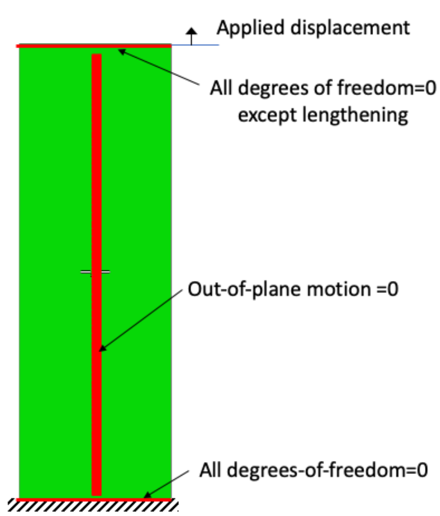


Fig. 3 Out-of-plane restraints

PANEL PREPARATION

Test panels with the same geometry and stacking sequence as analyzed were fabricated from unidirectional prepreg tape using the IM7/8552 carbon-epoxy material system [1]. The loaded edges of the panels were bonded to aluminum tabs with EA934 adhesive and several bolts were passed through both the plates and the test article near each end where the panels were mounted in the L-grip fittings. The bolt holes in the tabs can be seen in Figure 1. The outer surfaces of the aluminum tabs were machined to ensure a symmetric cross section.

Both panels were instrumented with electrical resistance strain gages that were oriented axially and placed in back-to-back pairs. The strain gage pattern is shown in Figure 1. Specifically, strain gages were placed in a row along the top of each panel and at the notch tips. The notch tip gages were strip gages where each strip gage consisted of five gages adjacent to each other in one line. These gages were located as close to the notch tip as possible, placing the center of the strain gage nearest the notch tip 1.02 mm from the notch edge. Additional gages were placed outboard mid-length away from the notch. The strain gage locations in the strip gages at the notch tips are shown in Figure 4.

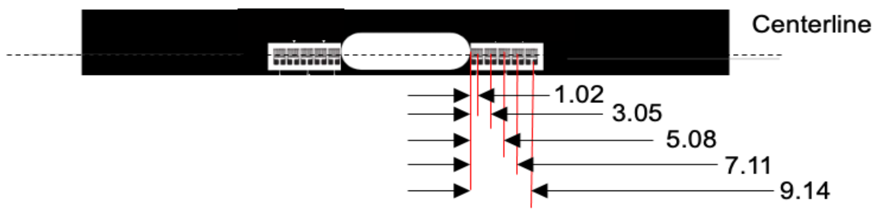
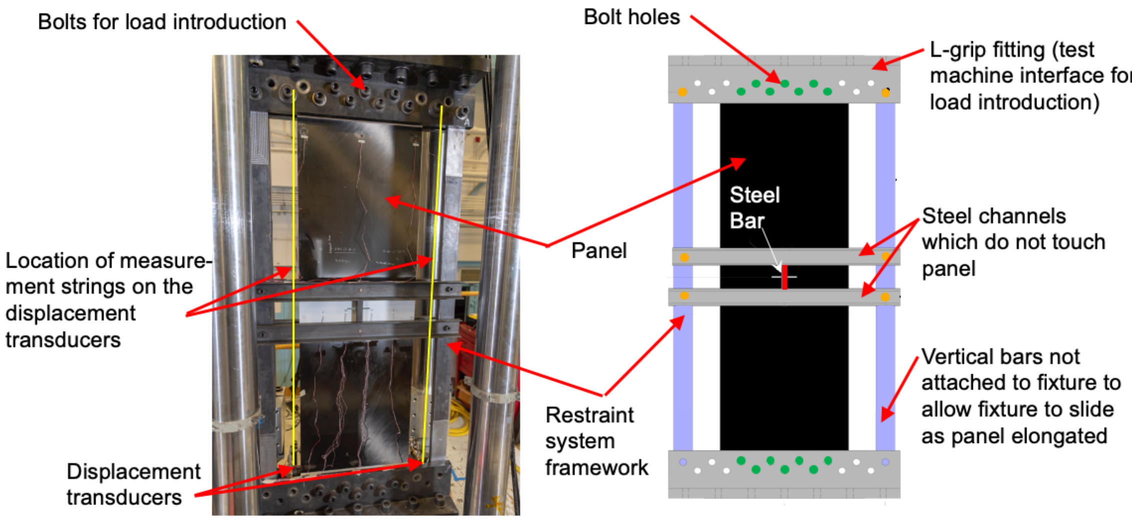


Fig. 4 Strain gage locations in strip gages relative to the notch tip with dimensions in mm (not to scale)

TESTING ARRANGEMENT AND PROCEDURE

Panels were subjected to uniaxial tensile loading via displacement control. A photograph of one panel in the test machine and sketch of a panel in the test configuration are shown in Figure 5. Note that the same fixture arrangement was used on the front and back surfaces of each panel. Load was introduced into the panel through both friction between the aluminum tabs and the L-grip fittings, and through bearing via the bolts at the top and bottom of the panel. The L-grip fittings are shown in gray and the bolts are shown in green in Figure 5b. The aluminum tabs are hidden in Figure 5b by the L-grip fittings, but are shown in Figure 1. Panels were centered in the test machine and loaded to failure through displacement control at a rate of 0.254 mm/min. Changes in panel length were monitored with displacement transducers to capture panel axial displacement independent of test machine mechanism influences. Displacement transducers were placed to the left and right of the panel, in line with the panel, as shown in Figure 5. Note that the “measurement strings” on the transducers are not visible in the photograph in Figure 5a, but they were attached to the bolts at the top of the test fixture on each side of the panel and their locations are highlighted in yellow. The displacement transducers measured from 0.70 m below to 0.81 m above the notch. Out-of-plane deformations were not monitored. The surfaces of central region of the panel were painted white to make cracks more visible for photography.



a) Photograph of the panel b) Schematic detailing fixtures

Fig. 5 Panel in the test machine

As discussed earlier, a restraint system to minimize mid-length out-of-plane motion was designed and implemented, and is shown for the front of the panel in the schematic in Figure 5b. In this system, a 10.16-cm-long vertical line at the centerline of the notch on the front and back of the panel was restrained by using two horizontal steel channels (shown in gray) and a short vertical steel bar (shown in red). Only the vertical steel bar at the center of the notch made contact and restrained the panel. The horizontal steel channels supported the vertical bar but were positioned away from the panel surface. Thin Teflon film inserts were placed between the short vertical steel bars at the center of the notch and the panel surfaces to reduce friction with the panel (Figure 6). The longer steel bars parallel to the panel unloaded edges, shown in purple in Figure 5b also did not contact the panel but were instead attached to the top L-grip fittings and were not attached to the bottom L-grip fittings. This arrangement allowed them to move with the top L-grip fitting as the panel lengthened. The thickness of each vertical steel bar was reduced at the bottom end to fit inside the L-grip fittings. Since the inside surfaces of the L-grip fittings are serrated, Teflon film inserts were placed between the long vertical steel bars and the bottom L-grips fittings to mitigate a potential problem of binding between them to ensure the vertical bars could slide. No binding of these bars was experienced during the tests.

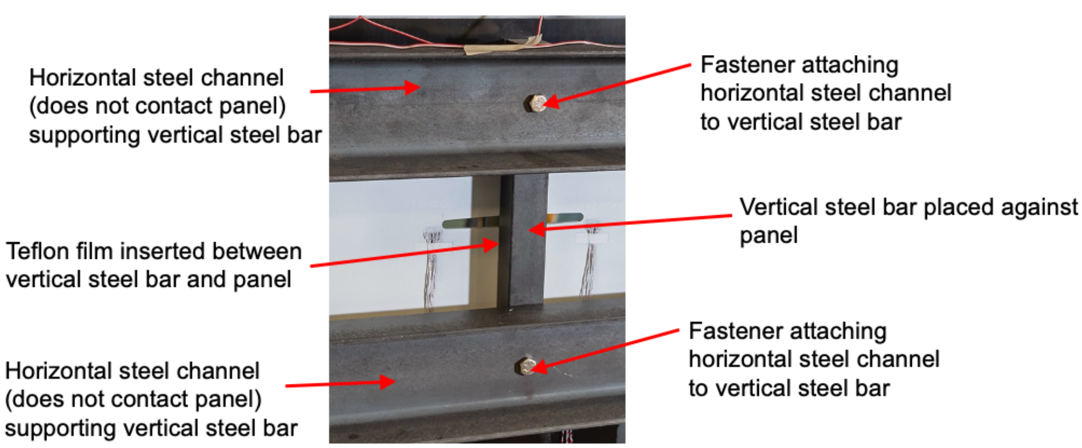


Fig. 6 Out-of-plane restraint in the notch area

RESULTS AND DISCUSSION

The lengthening of the panel and strains in the vicinity of the notch are presented for nominally identical panels T4-1 and T4-2. Additional strain results are presented in Ref [1] and [2]. This information is used to infer out-of-plane behavior since no direct measurements of out-of-plane deformations were obtained during the tests.

The change in length of each panel, as measured by the displacement transducers on either side of the panel, is presented in Figure 7 where data from panels T4-1 and T4-2 are shown in red and blue lines, respectively. Measurements on the left side of the test panels are shown as the solid lines, and measurements on the right side of the panels are shown as the dashed lines of the same color. All curves show the same slope, and the results are nearly indistinguishable from one another for loads up to 400 kN, indicating that the two panels had the same stiffnesses and the displacements were initially applied uniformly. Results from T4-1 diverge from those of T4-2 at approximately 400 kN, but the left and right sides of T4-1 continue to show the same slope until a load of approximately 415 kN. The load-versus-length results for the left and right of panel T4-2 remain together until a load of approximately 490 kN. These patterns imply that any failures occurring at loads less than 400 kN were local and did not impact the global response of the panel.

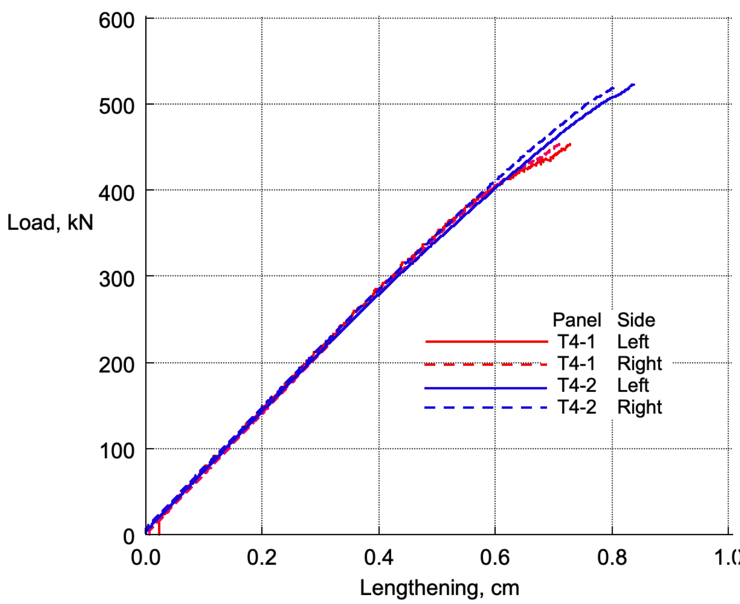


Fig. 7 Panel lengthening

Out-of-plane deformation can be inferred from differences between axial strains on the front and back surfaces of a panel. If there is no difference between the axial strains, there is no bending and no out-of-plane deformation (or only rigid body motion). The greater the difference between the surface strains for the same in-plane location, the more out-of-plane deformation. Only strains measured prior to any local failure can be used in this manner since once local failures have occurred, the laminate may not be intact and/or one or both gages on the surface may be damaged or have separated from the laminate surface. All strains measured 1.02 mm from the notch tip indicate failures of the strain gages or panel surface relatively early in the loading, and therefore, cannot be used to evaluate out-of-plane displacement so they are not included in the following discussion [1],[2].

Strains measured in the gages located 3.05 mm, 5.08 mm, and 7.11 mm from the notch tips within the four strip gages on each panel are shown in Figure 8. Strains at 3.05 mm, 5.08 mm, and 7.11 mm from the notch tips are shown in blue, green, and red, respectively. Strains on the front of the panel are represented by solid lines, while strains on the back of the panel are represented as dashed lines. Each line definition in the figure legend represents two locations, one on the left side and one on the right side of the panel. The consistency among the results for both notch tips of both panels is shown in Figure 8, but in order to evaluate out-of-plane behavior in more depth, it is necessary to break these results apart. Only panel T4-1 will be discussed further since it is representative of both panels.

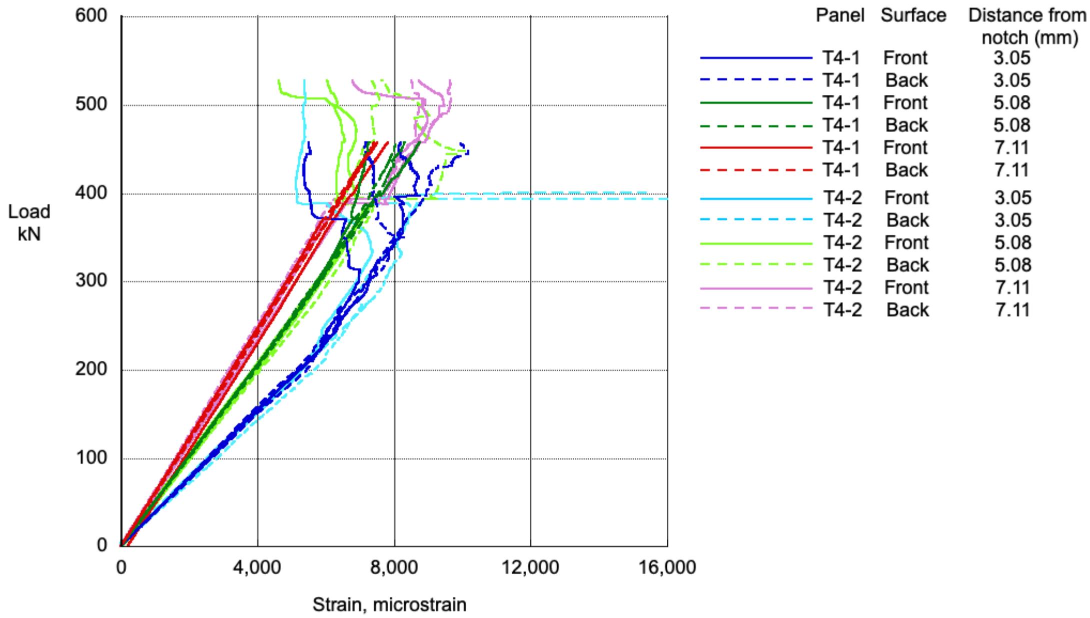


Fig. 8 Measured strain 3.05 mm, 5.08 mm, and 7.11 mm from the notch tips in panels T4-1 and T4-2

Strains from these same locations as shown in Figure 8 are shown in Figure 9 for panel T4-1 in a slightly expanded view. In panel T4-1, the load-strain relationship 3.05 mm, 5.08 mm, and 7.11 mm from the notch tips is linear for loads less than approximately 200 kN, 360 kN, and 454 kN (failure), respectively. The difference in measured surface strains at any point in this linear region is within the accuracy of the gage, so no out-of-plane displacement can be detected using these gages. In panel T4-1, at 3.05 mm from the notch tips, some nonlinearity is apparent between loads of 200 kN and 300 kN, but strain continues to increase in all gages and back-to-back strains do not diverge, so no out-of-plane displacement is detected. For greater loads, strains in the front and back surface show disjointed behavior indicative of local failures. In panel T4-1, at 5.08 mm from the notch tips, the gold lines representing the back-to-back pair of gages on the right side of the panel diverge from each other at a load of approximately 360 kN, while the green lines representing the back-to-back pair of gages on the left side of the panel separate at a load of approximately 400 kN. However, both show erratic behavior at these loads which is likely indication of a failure or shift in the structure, so any differences between surface strains cannot be interpreted as representative of out-of-plane displacement. In panel T4-1, at 7.11 mm from the notch tips, all four load-strain relationships show approximately linear results for the entire loading range.

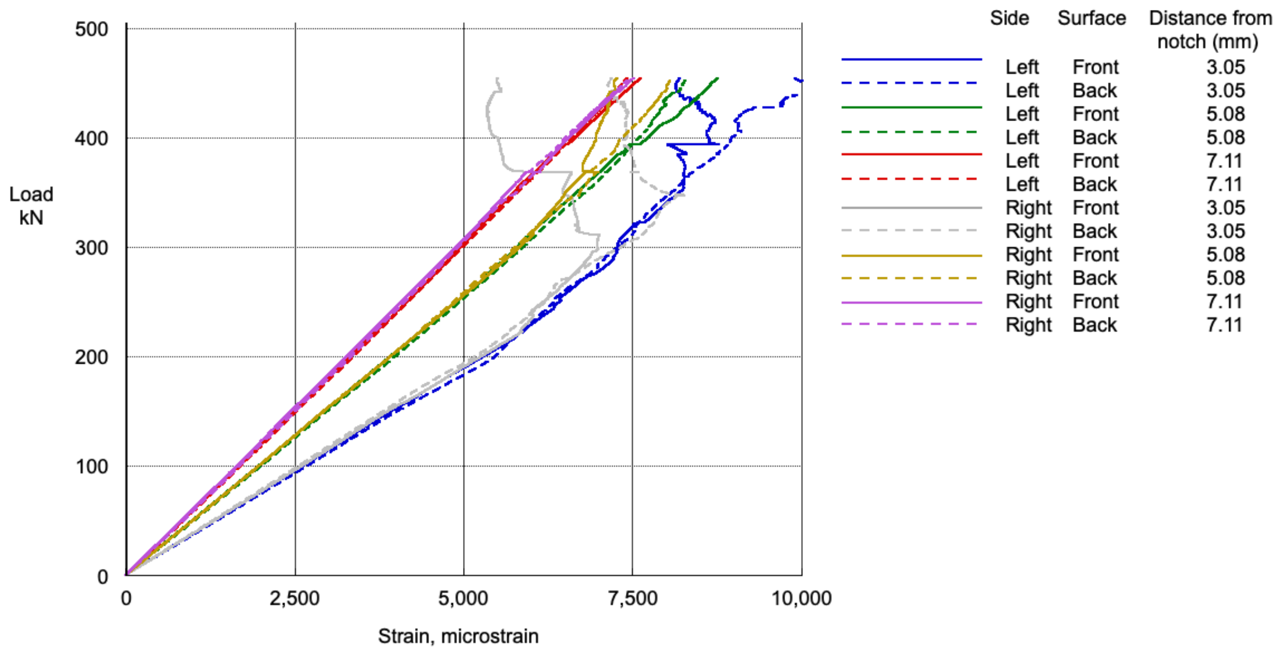
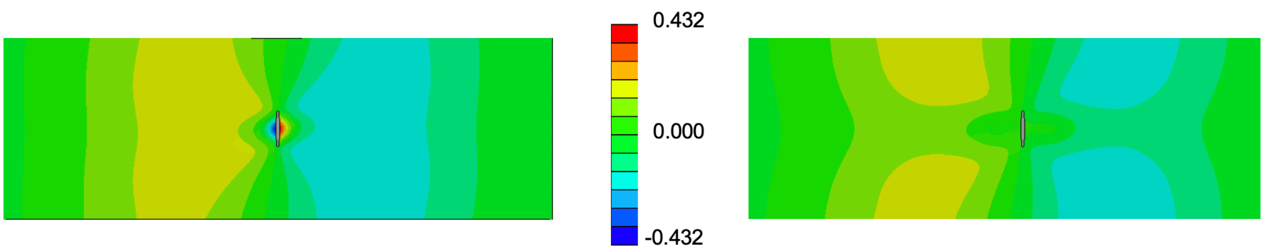


Fig. 9 Strain 3.05 mm, 5.08 mm, and 7.11 mm from the notch tips in panel T4-1

The conclusion to be drawn from these results is that out-of-plane displacement did not occur in either panel. Since neither panel was loaded without the presence of the out-of-plane restraint, the influence of the restraint on the deformation pattern cannot be determined experimentally. Therefore, finite element analysis was used to predict the deformation shape. Since the initial geometric imperfections were not measured prior to testing, an antisymmetric imperfection pattern was assumed and these analysis results are shown in Figure 10. The change in deformation pattern is shown in Figures 10a and 10b where the deformation pattern is without the out-of-plane and with the out-of-plane restraint, respectively. These two contour plots are on the same scale so it is clear that the restraint produces very localized changes to the deformation pattern at the notch but has little impact elsewhere in the panel.



a) Without restraint **b)** With out-of-plane notch restraint

Fig. 10 Out-of-plane displacement contours with scale in mm

CONCLUDING REMARKS

A simple methodology was developed and successfully implemented to suppress out-of-plane deformations, including buckling, for long unstiffened panels with central mid-length notches. This system allowed the panel to slide in-plane within the restraint system without reducing the opportunity to include strain gages within the restrained area and allowed visibility to document the initiation and progression of failure from the central notch.

REFERENCES

[1] Jegley, Dawn C., Waters, W. Allen, Jr. and Zahn, Alana, "Testing of Composite Laminate Specimens with Mid-Length Lateral Notches," NASA TM-2020-5001774, May 2020.

[2] Zahn, Alana, and Lovejoy, Andrew, “Test and Analysis Correlation of Standard and Hybrid Standard/Thin-Ply Composite Notched Test Specimens,” AIAA SciTech Forum 2020, Orlando, FL, January 6-10, 2020, Paper No. AIAA-2020-0478.
[3] Enjuto, Patrick, Walker, Thomas H., Lobo, Mark, Cregger, Eric, Wanthal, Steven, “Investigation of Stiffening and Curvature Effects on the Residual Strength of Composite Stiffened Panels with Large Transverse Notches,” AIAA SciTech Forum 2018, Kissimmee, FL, January 8-12, 2018, Paper No. AIAA-2018-2251.
[4] Abaqus Analysis User’s Manual 6.10. Dassault Systèmes, 2010. Accessed on March 8, 2019. [Online] Available: https://www.sharcnet.ca/Software/Abaqus610/Documentation/docs/v6.10/books/usb/default.htm?startat=pt05ch21s03abm43.html.
[5] Jones, Robert M., **Buckling of Bars, Pates and Shells**, Bull Ridge Publishing, Blacksburg, VA, 2006.