Applying a Stitched, Rod-Stiffened Concept to Heavily Loaded Structure

Dawn Jegley

ABSTRACT

NASA and The Boeing Company have worked to develop new low-cost, light-weight composite structures for aircraft. A stitched carbon-epoxy material system was developed to reduce the weight and cost of transport aircraft wing structure, first in the NASA Advanced Composites Technology (ACT) program in the 1990's and now in the Environmentally Responsible Aviation (ERA) Project. By stitching through the thickness of a dry carbon fiber material prior to cure, the labor associated with panel fabrication and assembly can be significantly reduced and the need for mechanical fasteners is almost eliminated. Stitching provides the benefit of reducing or eliminating delaminations, including those between stiffener flanges and skin. Stitching also reduces part count, and therefore, cost of the structure. The stitched panel concept used in the ACT program in the 1990's used simple blade-stiffeners as stringers, caps and clips. Today, the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) concept is being developed for application to advanced vehicle configurations. PRSEUS provides additional weight savings through the use of a stiffener with a thin web and a unidirectional carbon rod at the top of the web which provides structurally efficient stiffening. A comparison between the blade-stiffened structure and PRSEUS is presented focusing on highly loaded structure and demonstrating improved weight reduction.

INTRODUCTION

NASA and The Boeing Company have worked to develop new low-cost, light-weight composite structures for aircraft. As a consequence of this effort, a stitched carbon-epoxy material system was developed with the potential for reducing the weight and cost of transport aircraft wing structure in the NASA Advanced Composites Technology (ACT) program in the 1990's [1]. By stitching through the thickness of a dry carbon fiber material prior to cure, the labor associated with panel fabrication and assembly can be significantly reduced and the need for mechanical fasteners is almost eliminated. Stitching provides the benefit of reducing or eliminating delaminations, including those between stiffener flanges and skin. Stitching reduces part count, and therefore, cost of the structure.

Dawn C. Jegley, NASA Langley Research Center, Mail Stop 190 Hampton, Virginia 23681, U.S.A.

The technology developed in the NASA ACT program in the 1990's used simple blade-stiffeners as stringers and spar caps. Stitching allows for the elimination of fasteners in panel acreage, and its damage arresting capabilities make it suitable for wing structure. Today, in NASA's Environmentally Responsible Aviation Project (ERA), NASA and Boeing are advancing stitching technology by developing a Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) concept [2,3] for application to advanced vehicle configurations. An example of an advanced vehicle configuration is high-aspect ratio wings which will improve aerodynamic performance. Either the stitched blade-stiffened or PRSEUS concept can be applied to high-aspect ratio wings and simultaneously reduce vehicle weight.

The stitching concept consists of carbon-epoxy panels fabricated from dry components, stitched, and then infused with resin. In both blade-stiffened and PRSEUS concepts, skins, flanges, and stiffeners contain layers of graphite material forms using Hercules, Inc. AS4 fibers that are prekitted in multi-ply stacks. Several stacks of the prekitted material are used to build up the desired thickness and configuration. The prekitted stacks have a $[45/-45/0_2/90/0_2/-45/45]_T$ laminate stacking sequence resulting in a [44/44/12] percent distribution of 0-, $\pm$45-, and 90-degree plies. Nominal stack thickness was approximately 0.055 inches for blade-stiffened panels and approximately 0.052 inches for PRSEUS panels. Any number of stacks can be assembled to obtain the desired thickness. The 0-degree orientation of the stacks in the skin is parallel to the stringers. All elements in the blade-stiffened panels and all elements except the rods and foam in PRSEUS are constructed from stacks of this material. All stiffener flanges are stitched to the skin and no mechanical fasteners are used for joining.

Blade-stiffeners are stitched with Kevlar threads in a double-sided stitching process and infused in an autoclave with 3501-6 resin using metal tooling to support the inner and outer moldlines (IML and OML, respectively). A sketch of the blade-stiffened cross section is shown in figure 1. Intercostals are positioned perpendicular to the blade-stiffeners and are composed of stacks of material and assembled in the same manner as the stringers.

PRSEUS panels are stitched together with Vectran threads in a single-sided stitching process and are infused in an oven using vacuum pressure with HexFlow VRM 34 resin and using hard metal OML tooling and inexpensive lightweight bags for IML tooling to enforce panel geometry. A PRSEUS structure includes a stiffener consisting of a thin web and a unidirectional carbon rod at the top of the web to provide structurally efficient stiffening in one direction while foam-filled frames are positioned perpendicular to the rod-stiffeners to provide stiffening in the other direction. A sketch of the cross section of a PRSEUS rod-stiffened stringer is shown in figure 2 and the intersection of the stringer and frame in the PRSEUS concept is shown in figure 3. The frames have two stacks of material wrapping around Rohacell 110WF foam. The rods are Toray unidirectional T800 fiber with a 3900-2B resin. Notice that the frames have small cutouts for the rod-stiffeners to pass through to provide an unbroken load path in the axial direction. Note that the number of stacks around the rod (overwrap stacks) is always half the number of web stacks. Similarly, the number of stacks in the flange is always half the number of stacks in the stringer web.

The PRSEUS concept has all the advantages of blade-stiffened stitched structure, integrates more stiffening elements into the panel, and moves more of the load-

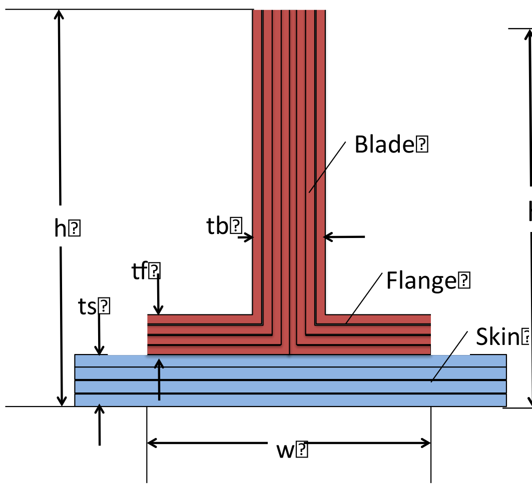

Figure 1. Illustrative blade-stringer cross section.

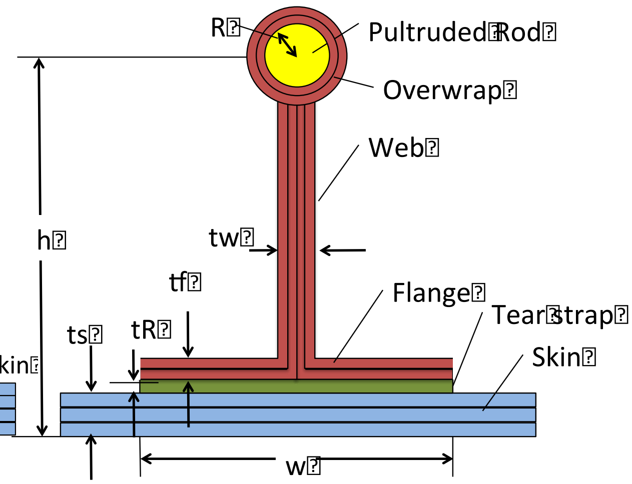

Figure 2. Illustrative rod-stringer cross section.

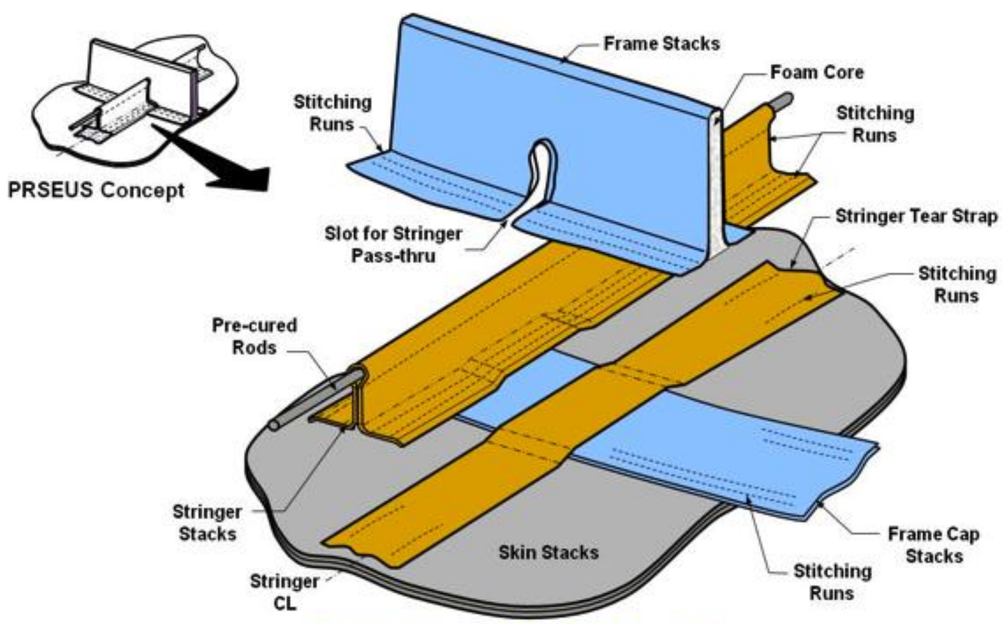

Figure 3. Exploded view of intersection of PRSEUS stiffeners.

carrying material away from the skin compared to traditional structural concepts. Most evaluations of PRESUS to date have focused on lightly-loaded fuselage-type structures. Applying PRSEUS to heavily loaded structure such as a wing is the subject of this paper. The weight benefit potential by using PRSEUS is determined by analytically comparing PRSEUS panels to wing panels evaluated in the ACT program. ACT showed that wing structural weight could be reduced by 25 percent compared to the state-of-the-art aluminum panels from the year 2000. The objective of this paper is to demonstrate additional weight savings that could be achieved by using PRSEUS for compression-critical structure such as wing upper cover panels. Experimental and analytical displacements and strains for the blade-stiffened specimens are presented first to establish the accuracy of the analytical methodology. PRSEUS panels with the same overall geometry are then examined to determine how much weight could be saved by switching from blade-stiffened to PRSEUS concepts.

EXPERIMENTAL BASELINE PANEL DESCRIPTION

Numerous Design Development Test Articles (DDTA's) were studied in a building block approach in the ACT program to evaluate the behavior of stitched structures. The knowledge gained from these articles was used in the design of a 40-foot long wingbox [1]. ACT DDTA's are used herein as baseline structures to evaluate compressive loading of wing cover panels. Three blade-stiffened DDTA's from ACT are compared with PRSEUS panels in this study to determine if there is a potential weight savings by using pultruded-rod stringers rather than blade stringers.

The blade-stiffened compression-loaded panel identified as DDTA 6 consisted of three blade-stiffeners (spaced 8 inches apart) and two intercostals (spaced 30 inches apart), resulting in a 90-inch-long panel that was 21.2 inches wide panel. Blades and intercostals ranged from 2.25 to 2.75 inches tall down the length of the panel. Stringer flanges were 3.2 inches wide for each stringer. Stringer blades were 8 stacks, stringer flanges were 4 stacks and the skin ranged from 5 to 7 stacks. A sketch of the test article geometry is shown in figure 4. Details about this specimen and its behavior are presented in reference 4.

The blade-stiffened compression-loaded panels identified as DDTA D2-1 and D2-4 consisted of four blade-stiffeners, contained no intercostals, and were 27 inches long and approximately 26.65 inches wide. Blades were 2.54 inches tall in D2-1 and 3.24 inches tall in D2-4. The skin was composed of 2 stacks in D2-1 and 4 stacks in D2-4. Blades contained 8 stacks in D2-1 and 10 stacks in D2-4. Flanges were half as thick as the blades and were 2.64 inches wide for each stringer. A sketch of the DDTA D2-1 is shown in figure 5 (D2-4 looks the same except for a slightly taller blade). Details about this specimen and its behavior are presented in reference 5. Geometry of each test article is given in Table 1. Measured values for the skin thickness for D2-1 and D2-4 are shown in Table 1 since the skins were found to be thicker than the nominal value.

Table 1. Test Article Geometry*

Element+	DDTA 6	DDTA D2-1	DDTA D2-4
Skin thickness (ts), in.	0.26 to 0.364	0.132#	0.246#
Stiffener height (h), in.	2.25 to 2.75	2.54	3.24
Flange width, (w), in.	3.2	2.64	2.64
Blade thickness (tb), in	0.416	0.416	0.550

*Element nomenclature defined in figure 1.
+Flange thickness (tf) is always half the thickness of the web
#Measured

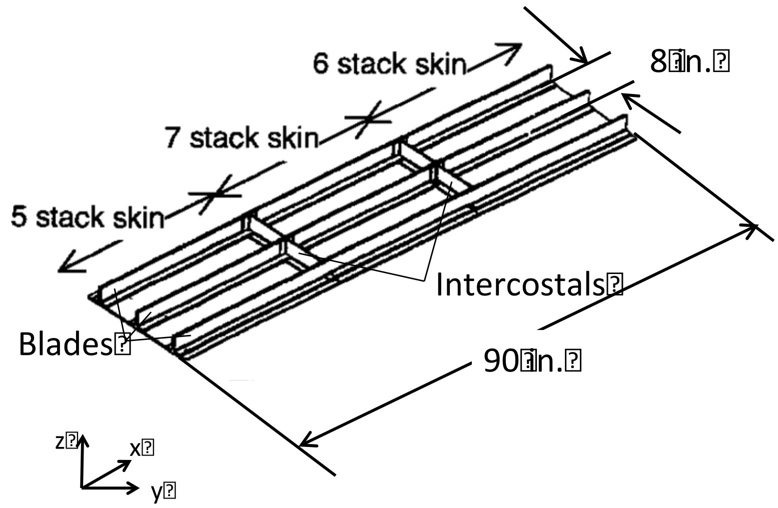

Figure 4. DDTA 6.

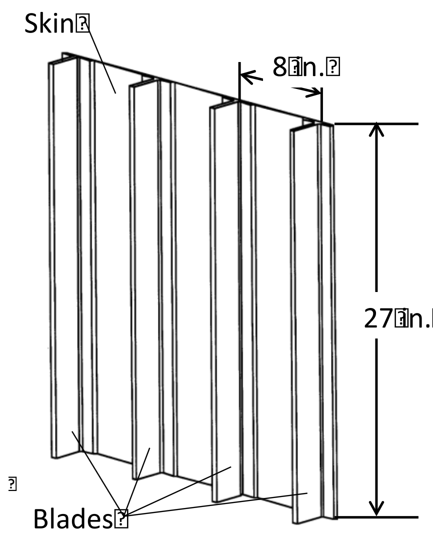

Figure 5. DDTA D2-1.

TEST PROCEDURE AND INSTRUMENTATION

Test panel DDTA 6 was loaded in unidirectional compression with simulated simply supported loaded edges at the Boeing Long Beach facility [4]. Twenty-two strain gages, four lateral displacement transducers and one longitudinal displacement transducer were used to monitor panel behavior. Buckling and failure behavior were noted. The unloaded edges were unrestrained in the experiment. One inch on each loaded end was restrained in an epoxy compound and this fixture was trimmed to allow the load to be introduced along a line parallel to the skin but offset to approximately the panel centroid. The loading was applied to the potted ends in a fixture which allowed the ends to rotate as shown in figure 6. A fixture prevented the intercostals from moving out-of-plane but rotations and other displacements were not restricted at the intercostals. The calculated weight of this panel is 67.3 lb.

Test panels DDTA D2-1 and D2-4 were loaded in unidirectional compression with clamped loaded edges at the NASA Langley Research Center [5]. 37 strain gages, four lateral displacement transducers and two longitudinal displacement transducers monitored panel behavior. Buckling and failure behavior were noted. The unloaded edges were unrestrained in the experiment. One inch on each loaded end was restrained in an epoxy compound and the ends ground flat and parallel so a uniform displacement was induced as load was increased. The calculated weight of panel DDTA D2-1 is 15.7 lb. The calculated weight of panel DDTA D2-4 is 25.2 lb.

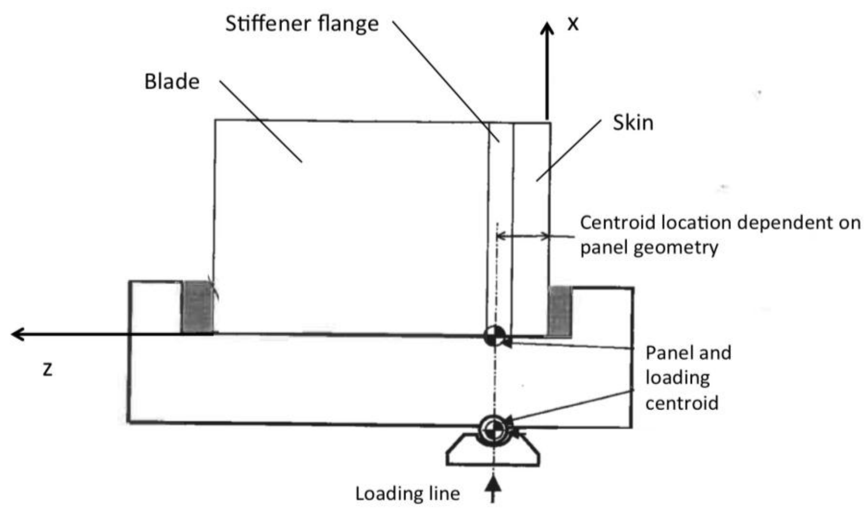

Figure 6. Load introduction for DDTA 6. (Not to scale)

ANALYSIS APPROACH

Finite element analyses of the blade-stiffened panels were conducted to compare analytical results to the test data. The analyses were conducted using the finite element code STAGS [6]. All parts of the panel were modeled using shell elements with the properties shown in Table 2 [2]. Element size was nominally 0.5 inches per side.

To simulate the simply supported boundary conditions for DDTA 6, a load was applied on one end of the specimen at one node on each blade at approximately the centroid of the cross section. These nodes were constrained to move the same amount lengthwise to enforce uniform end shortening. Simulated simply-supported boundary conditions were applied by restricting the skin motion at one end in the loading direction. Restraints due to the potting were simulated by restraining lateral motion for one inch within each end in the skin and blades. Out-of-plane motion was restrained at the intersection of the intercostals and the skin and at the centroid of the cross section at each end of the panel. This combination of restraints allowed the blades to rotate and the panel to buckle in a global mode. The model contained 40,247 elements and 244,578 degrees of freedom.

TABLE 2. Nominal In-plane Material Properties

Property	Stack*	Foam	Rod
Longitudinal stiffness, Msi	9.23	0.0261	18.0
Transverse stiffness, Msi	4.66	0.0261	1.0
Shear stiffness, Msi	2.26	0.0102	6.0
Poisson's ratio	0.397	0.29	0.2
Density (lb/ft^3)	0.057	0.0044	0.057

*Stack is [44/44/12] percent 0/±45/90; 0.055 inches thick for blade-stiffened, 0.052 inches thick for PRSEUS

To simulate the clamped boundary conditions for DDTA D2-1 and D2-4, all degrees of freedom on one end of the panel were restrained while lateral and out-of-plane displacements were restrained on the other end. Load was applied such that a uniform end shortening was enforced. For both panels, the unloaded edges were unrestrained in the experiment so they were not restrained in the analysis. The model contained 5,913 elements and 36,432 degrees of freedom.

PRSEUS panels were modeled using shell elements for skin, flanges, stringer webs and frames. Beam elements were used to model the combination of the pultruded rod and the surrounding overwrap stack(s) of material. The same stack properties were used for the PRSEUS panels as for the blade-stiffened panels. Additionally, foam and rod properties, as shown in Table 1, were used. Element sizes were similar to the blade-stiffened model. The same methodology for modeling PRSEUS structures is used in references 7-9.

Several PRSEUS models were created to determine what weight savings could be achieved while meeting the design requirements. Rod diameter, flange width, rod-stringer height, web thickness, skin thicknesses, and tear strap thickness were varied. Panels were evaluated to determine if PRSEUS panels could be designed to be lighter than the blade-stiffened panel that did not exceed the same stress allowables and whose nonlinear behavior did not demonstrate a lack of load-carrying ability at a load level less than that of the test articles. Local buckling between the stiffeners was permitted since test data has indicated that stitched panels (blade-stiffened and PRSEUS) can support load far in excess of their local (skin) buckling load [7,8]. Finite element models of PRSEUS panels with the same length and width as the test articles were subjected to the same loadings and boundary conditions. The PRSEUS model of DDTA 6 contained approximately 43,827 elements, and 272,826 degrees of freedom. The PRSEUS model of DDTA D2-1 and D2-4 contained approximately 6,188 elements, and 38,088 degrees of freedom.

Differences between blade-stiffened panels and PRSEUS include changing the thick blade to a thin web, the addition of the pultruded rods at the top of the web, and modifying the intercostals to be frames which are foam-filled blades and are taller than the rod-stringers (required for manufacturing purposes). In fabricated PRSEUS panels, the pultruded rods are typically shaped like a teardrop but for simplification, a circular cross-section pultruded rod was used in this study. Nonlinear analysis of each promising design was performed to determine if the panel would support the same load with the same boundary conditions as the blade-stiffened panel. Global buckling, local buckling, crippling, stress, and strain levels were considered.

RESULTS AND DISCUSSION

Experimental and analytical displacements and strains for the blade-stiffened specimens are presented. PRSEUS panels with the same overall geometry are then examined. In each plot, experimental data is shown with solid black curves and filled symbols. Analytical results are shown as dashed red curves and open symbols for blade-stiffened panels and dashed blue curves and open symbols for PRSEUS panels.

DDTA 6 Panel

Experimental results for test article DDTA 6 show that it was loaded in axial compression to failure and that it failed through the stringers near the midlength of the panel. The panel displayed nonlinear strain and displacement behavior as it approached failure load. The maximum experimental load was 316 kips. Strain and displacement data taken from the test report [4] are shown in figures 7 and 8, respectively. Axial strains are shown on the OML skin midwidth and on the side of the central blade near the top edge, as indicated in the figure. Both gages are located six inches away from the midlength position. Skin and blade strains are in good agreement until the panel begins to deform in a global bucking mode when the strains diverge. End shortening at the load introduction line (as shown in figure 6) are shown in figure 8. Linear end shortening behavior is seen until just prior to the maximum load.

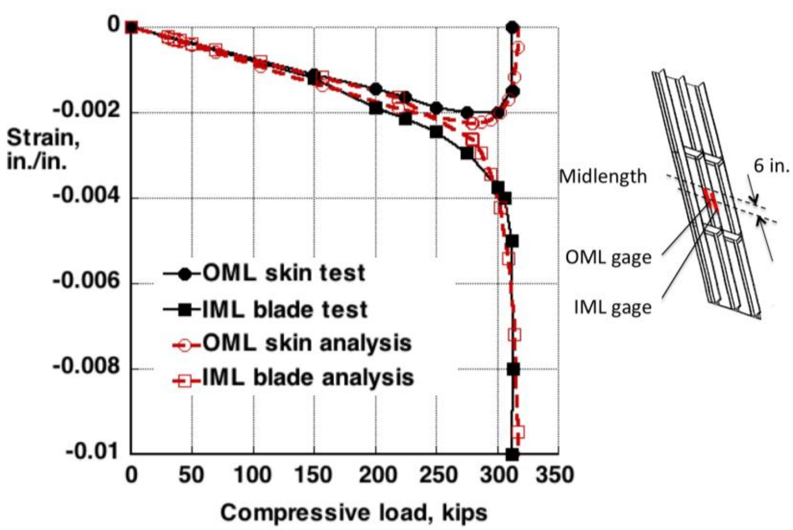

Figure 7. Axial strain versus load for test article DDTA 6.

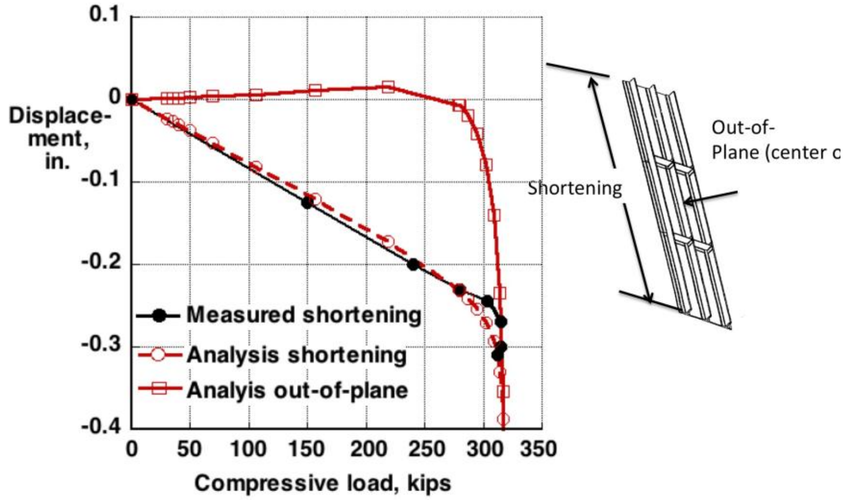

Figure 8. Displacement versus load for test article DDTA 6.

The results for the analysis of the panel are also shown in figures 7 and 8 to verify that the methodology used for the analysis is adequate. Excellent agreement is shown between test and analysis.

Predicted end shortening and out-of-plane displacement at the panel center are shown in figure 8. Only analytical results for out-of-plane motion are shown because the test report does not provide out-of-plane test data. Analysis indicates that the out-of-plane displacement grows rapidly as the panel deforms in a global mode. The test and analysis results shown in figures 7 and 8 indicate a failure due to buckling or reaching a limit point should occur at approximately 318 kips.

The predicted deformed shape of the panel at the maximum load of 318 kips and a close-up of the deformation in the center section of the panel after the load has dropped to 300 kips are shown in figure 9. The deformation at 318 kips shows a global deformation where the subsequent shape shows the same global deformation, but with a superposed local deformation of the blades in the center section of the panel. Representative end and intercostal support locations are shown in figure 9. The deformed shape is not symmetric because the skin thickness and blade height differs along the length of the panel, as described above. The primary difference between these initial deformations at 318 kips and the subsequent displacement at 300 kips is that the blades show deformation in the lateral direction in the center section of the panel after the load drop. A similar change in the pattern of predicted axial strain can be seen by comparing the strains in figures 10 and 11 for 318 and 300 kips, respectively. The maximum magnitude of measured strain was a compressive strain in the blade shown in figure 10. This maximum measured strain was the location of the IML gage for which data is shown in figure 7. The location of this peak strain corresponds to the failure location of the panel. This strain level corresponds to a failure load of 317 kips.

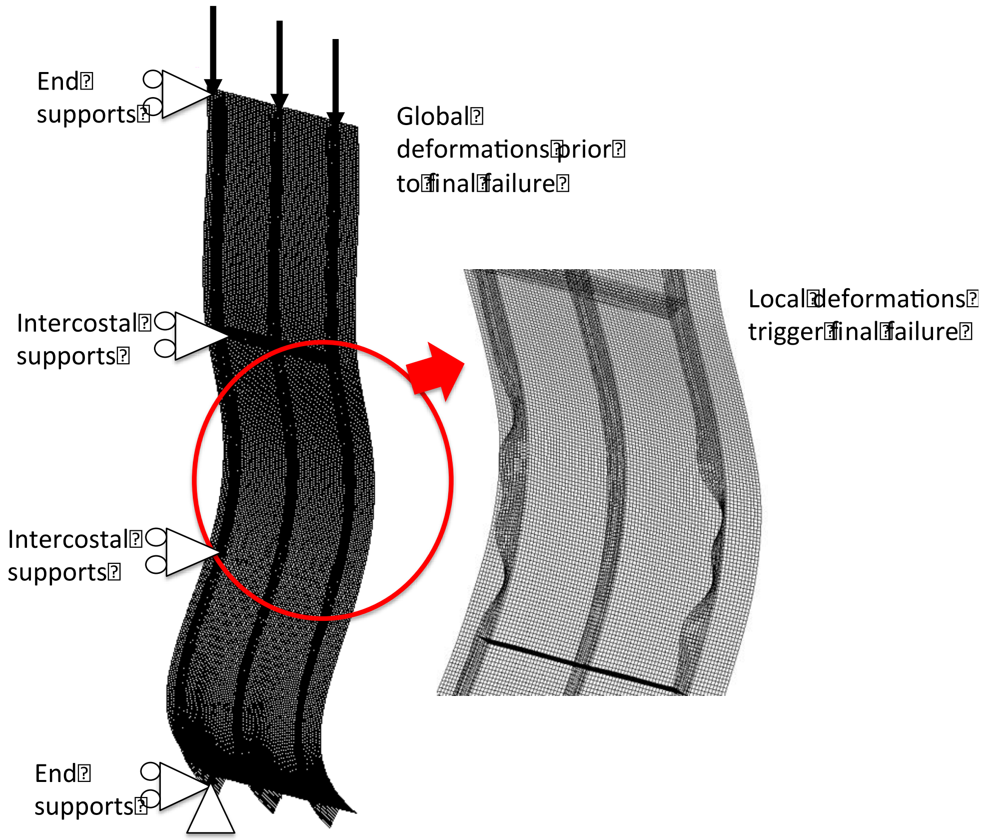

Figure 9. Predicted deformation of DDTA 6 test article.

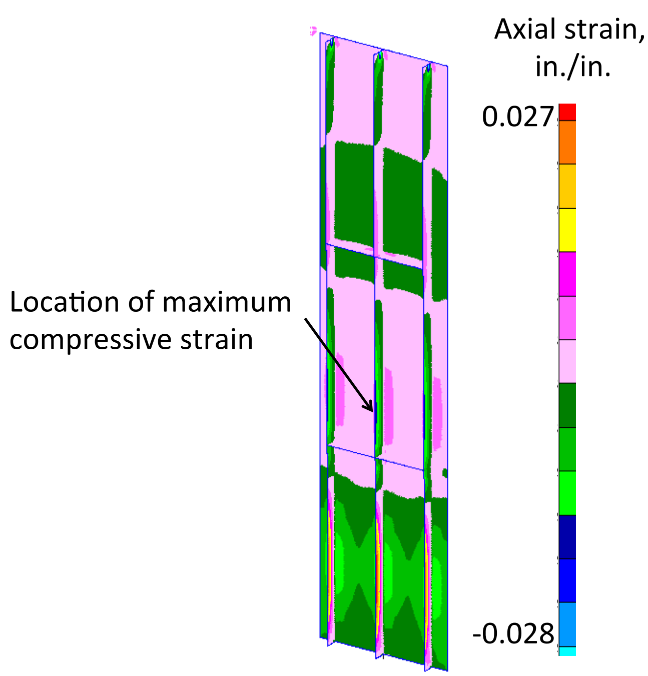

Figure 10. Predicted axial strain in DDTA 6 test article at a load of 316 kips.

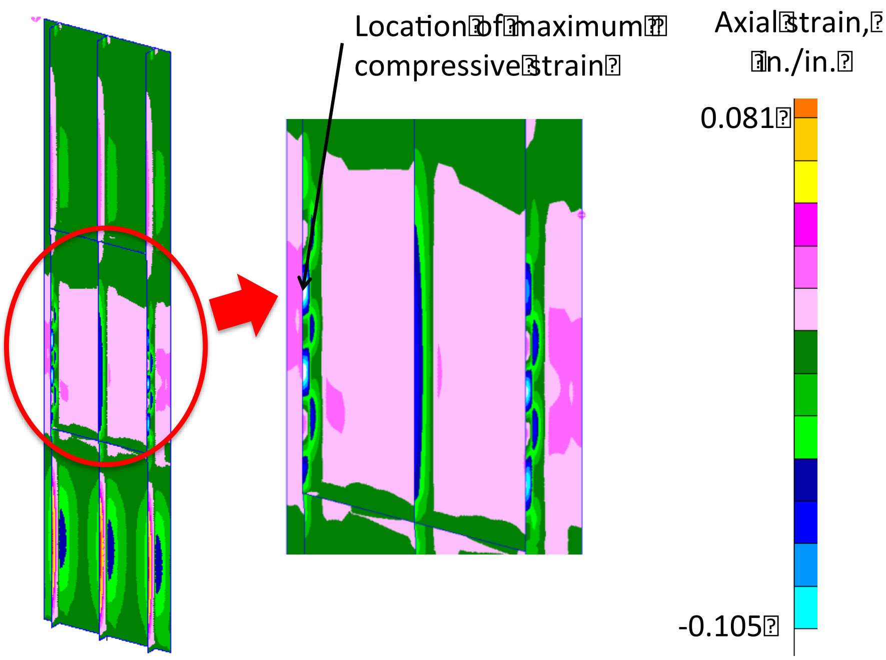

Figure 11. Predicted axial strain in DDTA 6 test article at after load reduction to 300 kips.

Several PRSEUS panels with similar geometry to the baseline DDTA 6 panel were modeled using the same approach as for the test panel. Global buckling, local buckling, crippling and stress levels were considered. The weight of each panel was also calculated and compared to the blade-stiffened panel weight.

In previous studies involving lightly loaded structure [2] (approximately 40,000 lb/stringer), panels have been designed to have a minimum gage skin thickness of one stack, a minimum thickness stringer web of two stacks and the corresponding overwrap thickness of one stack. To create a panel which can support the load supported by DDTA 6 (105,000 lb/stringer), the skin thickness of the PRSEUS panel was initially assumed to be the same as that of DDTA 6 while rod radius, stringer height and the number of stringer web stacks (and corresponding overwrap stacks) were varied.

The stringer flange width was reduced to 2.0 inches, which is more in agreement with the lightly-loaded PRSEUS panel construction. Then a series of rod radii were considered while the web thickness remained two stacks, causing the overwrap to be one stack thick. However, even though larger rod radii allow the stringer to carry more load, the thinnest 2-stack web develops local buckles at relatively low loads, limiting the structural efficiency of the panel and causing it to buckle well before the required panel load is reached. Therefore a four-stack stringer web was examined. The stringer height in DDTA 6 varied from 2.25 to 2.75 inches. For the PRSEUS panels in this study, a constant stiffener height was considered for each panel and varied from 1.25 to 2.75 inches. Rod radius was varied between 0.125 and 0.625 inches. In the standard PRSEUS construction, frames have been 6 inches tall. For manufacturing purposes the frame must be taller than the stringer but a one inch difference is adequate so a one inch difference is assumed for the PRSEUS panels herein. Note that for this loading condition, with no lateral loading, the frames are mostly parasitic weight.

The thickness and height variations indicate that a PRSEUS panel with a 2.75-inch-tall stringer with four stacks in the stringer web, and a 0.125-inch radius rod supports a buckling load of 303 kips based on a linear bifurcation buckling analysis. Nonlinear analysis shows that the panel will support loads greater than 325 kips. The maximum compressive stress away from the boundaries (which would be reinforced in a real structure) is 48,300 psi in the thinnest skin at the edge of the frame flange at a load of 325 kips. Since the axial allowable stress is 79,200 psi [4], the maximum stress is less than the allowable stress. This panel would weigh 53.9 lb, or 20 percent less than the blade-stiffened DDTA 6 baseline panel. The shortening for the test article which is shown in figure 8 is repeated in figure 12. The shortening for this PRSEUS panel in shown in figure 12 with the long blue dashed lines and is labeled PRSEUS panel A. Reducing the rod radius leads to earlier nonlinear failure, and reducing the web thickness or increasing the web height causes buckling in the web, leading to a reduced failure load.

Alternately, if the skin is designed with a skin that is one stack thinner than baseline DDTA 6, a similar comparison reveals that a rod with a radius of 0.188 inches, a stringer height 2.75 inches, and four stacks in the stringer web, results in a panel with stress of 52,100 psi in the thinnest skin region, again less than the allowable. In this case, the buckling load is 240 kips but nonlinear analysis shows that the panel will continue to support load to 325 kips. This panel weights 49.9 lb, or 26 percent less than the blade-stiffened panel. Reducing the rod radius leads to earlier nonlinear behavior and lower failure load, while reducing the web thickness or increasing the web height causes buckling in the web leading to a reduced failure load. The shortening for this PRSEUS panel is shown in figure 12 with alternating long and short dashed blue lines and is labeled PRSEUS panel B. The displacement and stress for this panel at a load of 325 kips is shown in figure 13. The dimensions

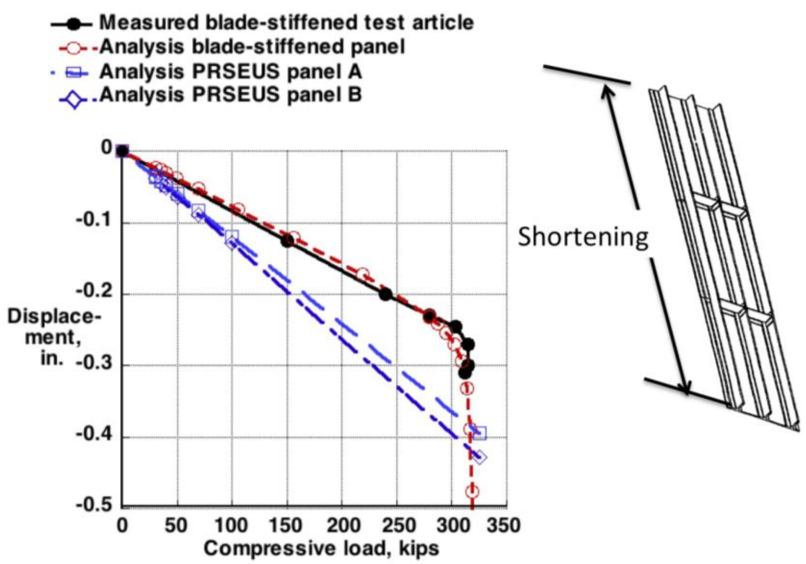

Figure 12. DDTA 6 and PRSEUS panel shortening versus load.

of the stringers of these two PRSEUS designs are shown in Table 3. Further weight savings might result from varying the stringer spacing and more detailed evaluation of the stringer geometry.

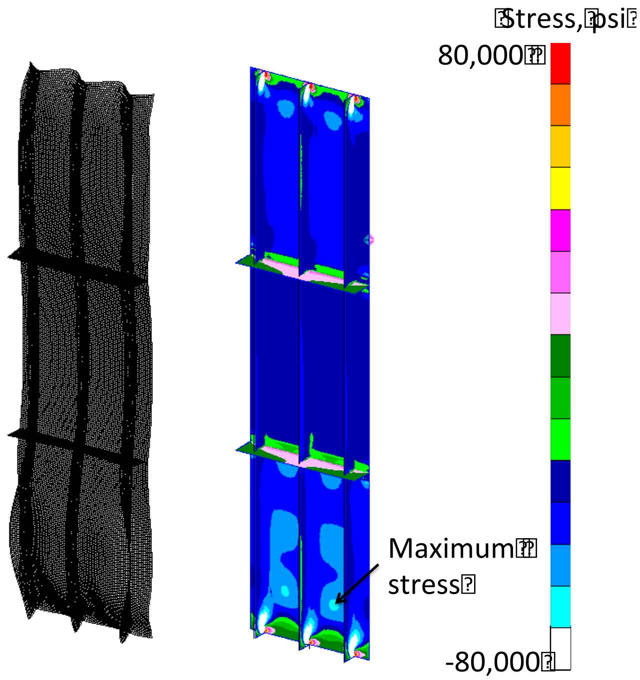

Figure 13. Behavior of PRSEUS panel B at a load of 325 kips.

Table 3. PRSEUS Panel Geometry*

Element+	DDTA 6 A	DDTA 6 B	DDTA D2-1	DDTA D2-4
Skin thickness (ts), in.	0.26 to 0.364	0.208 to 0.312	0.104	0.104
Stiffener height (h), in.	2.75	2.75	2.54	3.24
Flange width, (w), in..	2.0	2.0	2.64	2.64
Web thickness (tb), in	0.208	0.208	0.104	0.104
Tear strap thickness (tR), in.	0.052	0.052	0.104	0.052
Rod radius (R), in.	0.125	0.188	0.475	0.800

*Element nomenclature defined in figure 2.
+Overwrap thickness (to) is always half the thickness of the web; Flange thickness (tf) is always half the thickness of the web

DDTA D2 Panels

The same approach used to evaluate the DDTA 6 panel was used to evaluate the DDTA D2-1 and D2-4 panels. First the test article was modeled and behavior compared to the test data, then models of PRSEUS versions were used to determine if a lighter PRSEUS panel with the same loads and boundary conditions as the test article could be found.

Experimental results for the D2-1 panel are presented in reference 5, showing that it was loaded to failure in axial compression. In the experiment, the DDTA D2-1 test article supported 564 kips, significantly more load than the DDTA 6 test article, due to its clamped boundary conditions (compared to the simply supported conditions of DDTA 6 test article) and the presence of four stringers instead of three. The panel displayed nonlinear strain and displacement behavior as it approached the failure load. Strain gage data and analytical predictions are shown in figure 14 for panel D2-1. Strains are shown on the OML and IML skin midlength in the skin near a stiffener flange. The panel failed through the stringers near the midlength of the panel. End shortening and out-of-plane displacements at the center of the panel are shown in figure 15. Excellent agreement is shown between test and analysis. The initial buckling load of 181 kips, determined by analysis, is in good agreement with experimental data. This buckling load indicates that the panel supported more than three times its buckling load prior to failure.

Even though the test article supported 564 kips, analysis indicates that the allowable stress of 72,900 psi occurs in the skin at 495 kips. So a lighter weight PRSEUS panel needs to support 495 kips without exceeding the allowable stress.

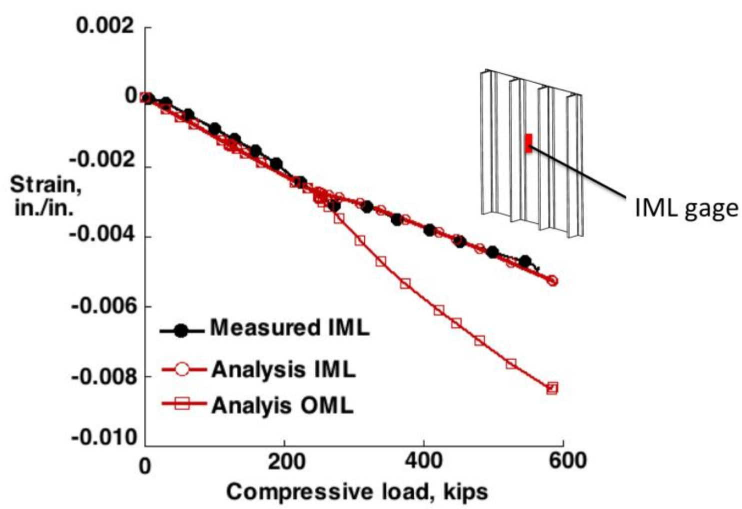

Figure 14. Axial strain versus load in test article DDTA D2-1.

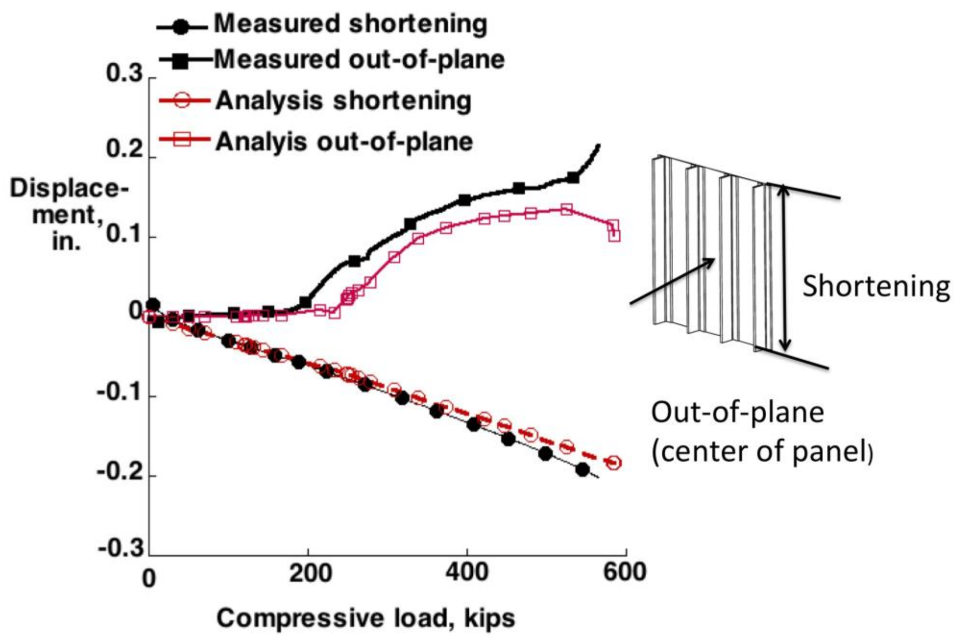

Figure 15. Displacement versus load for test article DDTA D2-1.

Several PRSEUS panels with similar geometry to the baseline D2-1 panel were modeled using the same approach as for the blade-stiffened panel. Initially, the skin of the PRSEUS panel was assumed to have the same number of stacks as the D2-1 test article while the stiffener geometry and the stiffener spacing were varied. Reducing the stiffener spacing and adding an additional stringer with the same panel width did not result in a lighter panel since the two-stack skin buckled and displayed surface stresses in excess of the allowable in compression for either four or five stringers. Increasing the skin by an additional stack caused excessive panel weight unless the rod was virtually eliminated, which put more load into the skin, so this approach was not practical. However, keeping the two-stack skin with four stringers and adding an additional tear strap stabilized the skin and provided a mechanism to get a lighter weight panel. Increasing the stringer height tends to cause premature buckling in the web of the stringer, and therefore either global instability in the panel or excessive stresses in the thin web.

Nonlinear analysis shows that the PRSEUS panel with a 0.475-inch-radius rod, a 2-stack web, a 2-stack tear strap, and a 2-stack skin will support more than the required load of 495 kips without exceeding the allowable stress anywhere in the panel. The surface stresses in the element with the maximum stress (in the skin) is shown for the test article and for the PRSEUS panel in figure 16. The deformation and stresses for this panel are show in figure 17 for a load of 520 kips. The PRSEUS panel would weigh 13.8 lb or 12 percent less than the blade-stiffened panel. The dimensions of the stringers of the PRSEUS design are shown in Table 3. Further weight savings might result from more detailed evaluation of the stringer geometry.

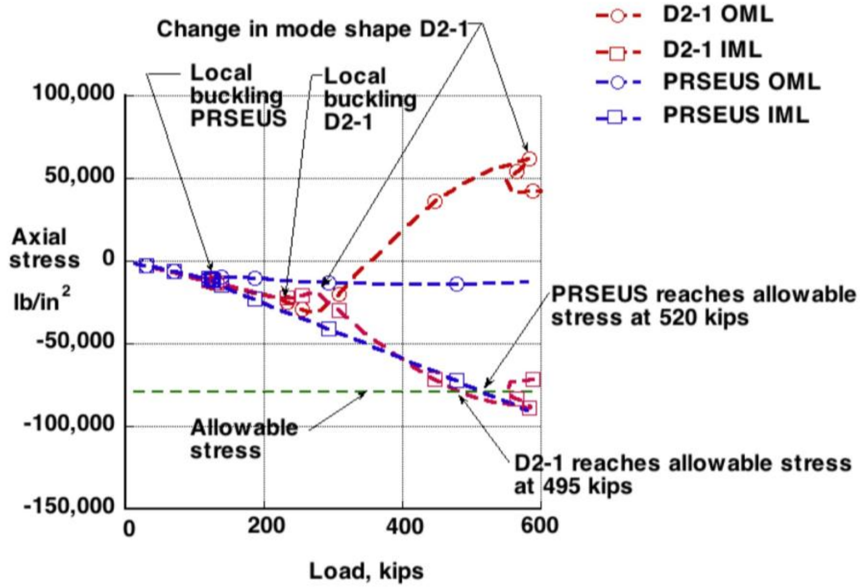

Figure 16. Predicted DDTA D2-1 and PRSEUS stress versus load.

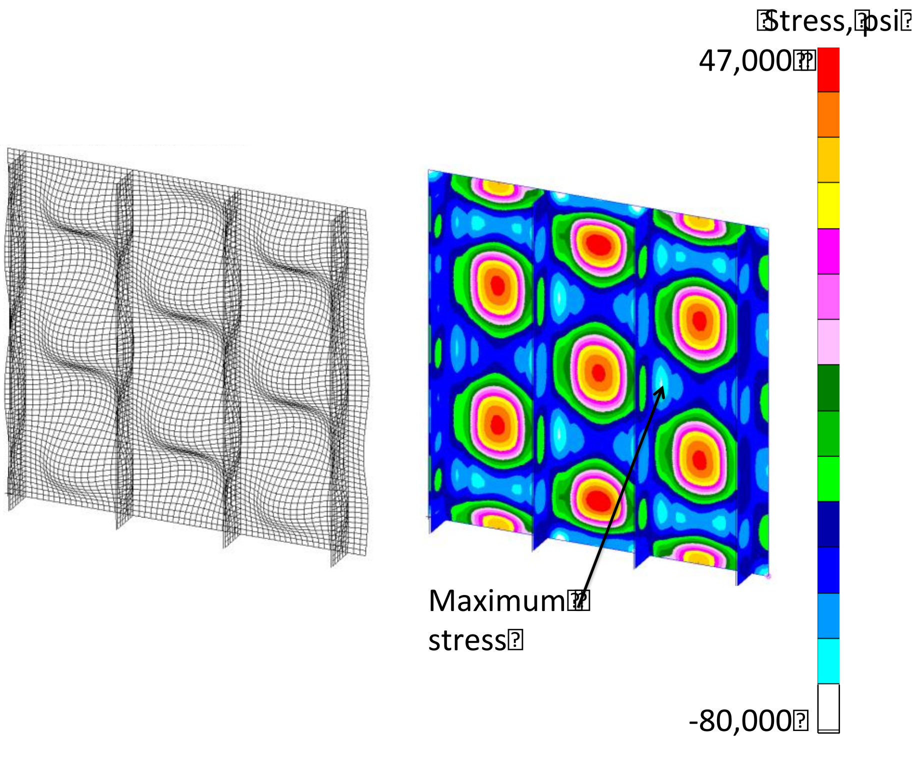

Figure 17. Behavior of PRSEUS replacement for DDTA D2-1 at a load of 520 kips.

Experimental results for panel D2-4 are also presented in reference 5, showing that it was loaded to failure in axial compression. The panel displayed nonlinear strain and displacement behavior as it approached the failure load of 985,550 lb, or over 246 kips/in. Test article D2-4 buckled at approximately 891 kips, or 90% of the failure load. Measured and calculated displacements are shown in figure 18. Based on analysis, the panel skin reached the allowable compressive stress at 970 kips, or 98% of the failure load. Good agreement is seen between the experimental and the analytical results.

The experimental results show that the panel failed with little warning and that the stitching did not arrest damage. The panel failed at the midlength position across the skin and stiffeners. Since the panel displayed relatively little out-of-plane behavior prior to failure, the critical condition inducing failure was the excessive stress. The calculated axial stresses for panel D2-4 are shown in figure 19 at the most critical location, in the skin of the center bay. These results indicate that the panel failed catastrophically when the stress approached the allowable value. The stringers did not buckle prior to this load.

The same stiffener and skin geometry was varied for the PRSEUS replacement for panel D2-4 as for panels DDTA 6 and D2-1, however, this variation did not result in as much weight savings for this heavily loaded panel as for the more lightly loaded panels. Reducing the number of skin stacks while adding increasing rod radius shifts load from the skin to the stiffener and causes the skin to buckle earlier while the stringer still caries load. This approach causes the surface stress in the skin to induce failure at lower load compared to the test article. Alternately, keeping the thick skin causes the web of the stringer to deform, and the surface stress in the web grows and exceeds the allowable stress.

A PRSEUS panel design was identified which carries approximately the same load as the test article and weighs 9% less than the test article is shown in figures 19 and 20. Stress in figure 19 is shown at the location of maximum stress, which is in the web. A failure load of 935 kips corresponds to reaching the allowable stress in the web of the stringer. So the failure location is different than in the test article. So by changing the primary load-carrying element from the skin to the top of the stringer, the primary load-carrying region is moved away from the vulnerable surface but little weight savings may be achieved. The displacement and stress at a load of 962 kips is shown in figure 20 for the PRSEUS panel. The deformation pattern shows deformation in both the skin and in the webs of all stringers, indicating that the panel cannot support load in these elements, therefore only the flange region and the rod could support load. The panel would fail by the time 962 kips is reached either through loss of stability or through exceeding the stress allowable since both occur within a few percent of this load. The dimensions of the stringers of the PRSEUS design are shown in Table 3.

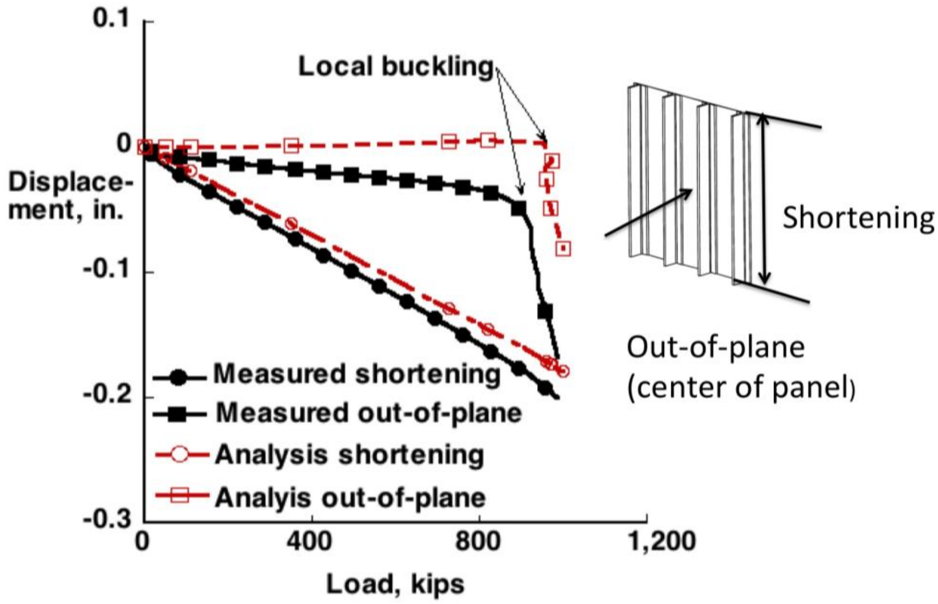

Figure 18. Displacement versus load for test article D2-4.

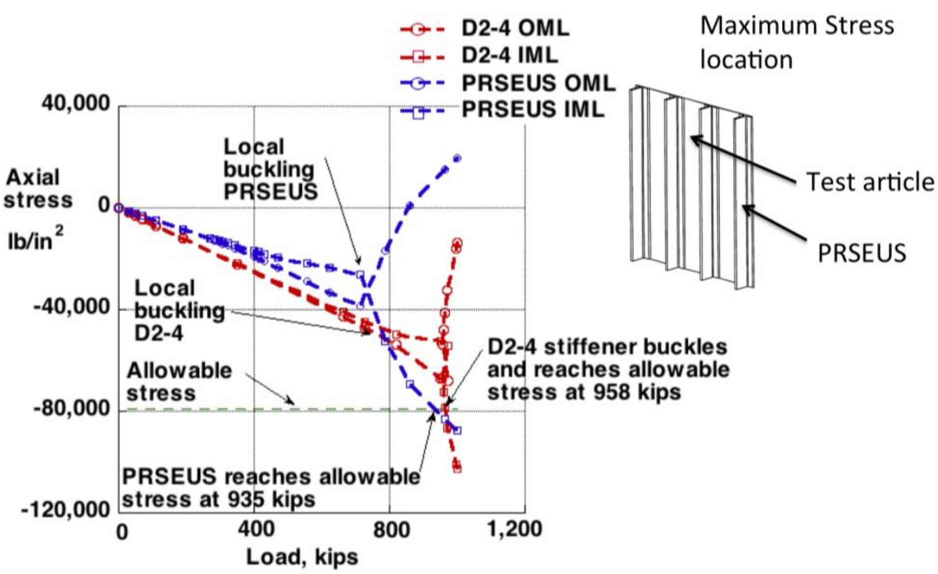

Figure 19. Predicted DDTA D2-4 and PRSEUS stress versus load.

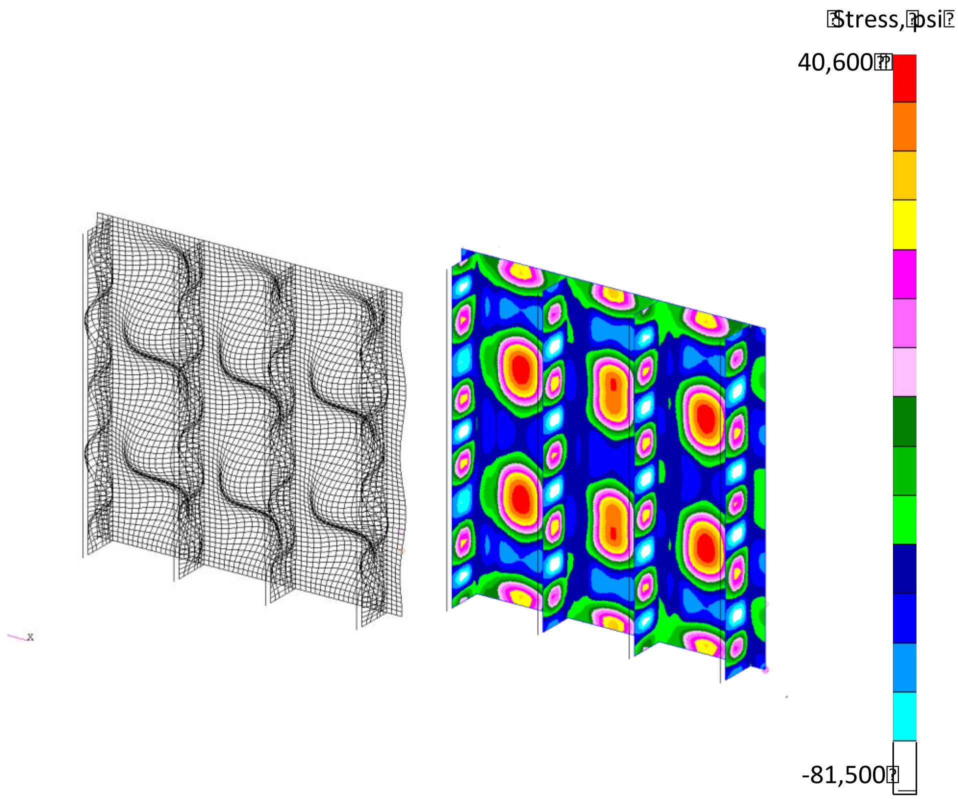

Figure 20. Behavior of PRSEUS replacement for DDTA D2-4 at a load of 962 kips.

Failure and Weight Trends

A summary of the lightest PRESUS replacement panels for the three designs considered herein is shown in Table 4. PRSEUS panels are identified by their corresponding DDTA and by the design load level in terms of load per unit width. The weights presented are the total panel weight divided by the planform area, resulting in a weight per square foot. The weight savings is the percentage of weight reduction determined by comparing the weight of the blade-stiffened and the PRSEUS panel.

Table 4. PRSEUS Panel Summary

Panel type	Design load (kips/in.)	Blade-stiffened weight lb/ft^2	PRSEUS weight lb/ft^2	Weight savings (%)
DDTA 6	14.9	5.08	3.76	26
DDTA D2-1	18.4	3.12	2.74	13
DDTA D2-4	36.1	5.00	4.55	10

In general, the greater the loading, the less weight benefit when switching from stitched blade-stiffened designs to PRSEUS concepts under compressive loading. Stitching offers advantages in damage arrestment and in moving the load-carrying member away from the surface and additional advantages under bending loads and bi-axial loads, as discussed in previous papers, but does not offer as much weight benefit for heavily loaded panels as for more lightly loaded panels previously evaluated in the ERA project.

CONCLUDING REMARKS

Previous studies determined that the use of stitched blade-stiffened carbon-epoxy panels in wing structures could reduce wing weight by 25 percent compared to aluminum wings for large transport aircraft. In the present study, carbon-epoxy panels designed using the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) concept are analytically compared to blade-stiffened stitched panels. Results indicate that weight for some portions of the compression-dominated upper cover panel could be reduced by up to 26 percent by using the PRSEUS concept rather than the simpler blade-stiffeners. However, there may not be as much weight benefit when switching from stitched blade-stiffened to PRSEUS concepts for more heavily loaded portions of the upper cover panel. More detailed studies are needed to determine the overall weight benefit resulting when switching from more conventional blade-stiffened or hat-stiffened designs to PRSEUS.

REFERENCES

1. Karal, M., “AST Composite Wing Study – Executive Summary,” NASA CR-2001-210650, March, 2001.
2. Velicki, A., “Damage Arresting Composites for Shaped Vehicles,” NASA CR-2009-215932 Sep., 2009.
3. Jegley, D. and Velicki, A., “Status of Advanced Stitched Unitized Aircraft Structures” Presented at the 51st AIAA Aerospace Sciences Meeting, Grapevine, TX, January 2013.
4. Hinrichs, S., “DDTA NO. 6 Compression Panels Test Report” Report number MDC98K0324, Report under NASA contract number NAS1-20546, March, 20, 1999, Long Beach, CA.
5. Jegley, D., “ Improving Strength of Post-Buckled Panels Through Stitching,” Journal of Composite Structures. Vol. 80, pp. 298-306, 2007.

6. Rankin, C. C., Loden, W. A., Brogan, F. A., and Cabiness, H. D., "STAGS Users Manual," Rhombus Consultants Group, Inc., Palo Alto, CA 94303, January, 2007.
7. Velicki, A., Yovanof, N., Baraja, J., Linton, K., Li., V., Hawley, A., Thrash, P., DeCoux, S., and Pickell, R., "Damage Arresting Composites for Shaped Vehicles—Phase II Final Report," NASA-CR–2011-216880.
8. Jegley, D., "Structural Efficiency and Behavior of Pristine and Notched Stitched Structure," presented at the annual SAMPE meeting, Oct. 2011, Fort Worth, TX.
9. Yovanof, N., Lovejoy, A., .Baraja, J., and, Gould, K, "Design Analysis and Testing of a PRSEUS Pressure Cube to Investigate Assembly Joints," 2012 Aircraft Airworthiness and Sustainment Conference, April 3, 2012, Baltimore, MD.