DESIGNING PRIMARY STRUCTURES WITH STITCHED COMPOSITES

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Abstract

As the cost of fabricating composite structures becomes better understood, more emphasis is being placed on developing new fabrication techniques that have lower recurring costs. One such method is called the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) concept. It is a highly integrated stiffened panel geometry that is stitched together in the dry fiber state, infused with resin, and then cured in an oven. Although the economics are notable, the most important aspect of this new approach is the use of structural stitching to control damage propagation within the laminate to enable the use of more weight-efficient fail-safe design methodologies. Although this important aspect receives less attention, it is slowly becoming recognized as one of the most important characteristics for developing weight and cost-efficient composite primary structures for large transport aircraft.

1 Rationale for Damage Arrestment Design

The modern era of transport airplane wing and fuselage design was enabled by the development of corrosion-resistant aluminum alloys and the semimonocoque structural design in the mid 1920's. These innovations helped fuel the revolution in modern air travel and nearly 100 years later, those advances have proved to be exceptionally efficient and long-lasting, as they continue to set the standard for modern airplane design. As this progression continues with the introduction of lighter polymer matrix composite materials, further refinements in design criteria have also been instrumental in bridging the differences between aluminum and composite material response. As these dissimilarities become better understood with additional in-service experience, it should be possible to generate further weight-savings by moving beyond the initial conservative no-growth design strategies employed on those first-generation composite structures. (Ref. 1)

Since these initial designs were focused on avoiding resin-dominated failure modes, laminate orientations were precisely constrained to delay the onset of delaminations that would prevent the fibers from working to their full-strength capability. To accomplish this, these designs were typically relegated to strain-limited solutions that would prevent detrimental levels of damage growth up to Design Ultimate Load (DUL) levels. Lacking the plasticity of metals, failures were naturally initiated at local stress concentrations before load redistribution could take place to more lightly-loaded regions of the structure. Such load sharing is a fundamental principle in the fail-safe design regime of primary structures, where local stress concentrations are routinely tolerated in ductile materials, as they locally yield prior to unloading themselves. Because brittle composite materials lack such plasticity, critical crack lengths become so short, that reasonable inspection cycles for safe operation become economically unfeasible.

Brittle material response, coupled with the relative imbalance in fiber-versus-resin strength, makes avoiding delamination-induced failure modes very difficult, resulting in the use of safe-life like design practices where detrimental damage growth is not tolerated below DUL levels. Such necessary design practices erode the material property advantage of composite materials when compared to comparable aluminum designs which can take full advantage of the more favorable fail-safe design practices to garner the intrinsic benefits of damage growth and arrestment design schemes that result in lighter weight designs.

While the fail-safe design approach is an effective strategy in reducing panel weight, the permissible design space is strongly influenced by allowable damage thresholds and relative inspection intervals, so that any new composite fail-safe design scheme must propose practical strategies for addressing these key design parameters; and ultimately test evidence that supports such conclusions. The use of through-thickness structural stitching is one of the few composite technologies that specifically addresses these concerns by providing a structural design feature for confidently controlling damage propagation. This in turn, enables the type of load sharing that is the hallmark of state-of-art damage-arrest design schemes. By exploiting this underlying principle, the PRSEUS structural concept was developed to have greater load path redundancy and tailorability which results in a panel with higher residual strength and improved fail-safety.

2 PRSEUS Structural Concept

2.1 Concept Description

The evolution of stitched structures has led to the highly efficient PRSEUS panel architecture (Fig. 1), which consists of a unique combination of dry carbon warp-knit fabric, pultruded rods, foam core, and stitching threads that are brought together in an innovative manner to create a stiffened-panel geometry that combines resin infusion and out-of-autoclave curing to reduce recurring fabrication costs (Ref. 2). The resulting panels are one-piece assemblies with seamless cocured interfaces reinforced with stitching that fully exploit the highly orthotropic nature and unique processing advantages inherent in carbon fiber material systems.

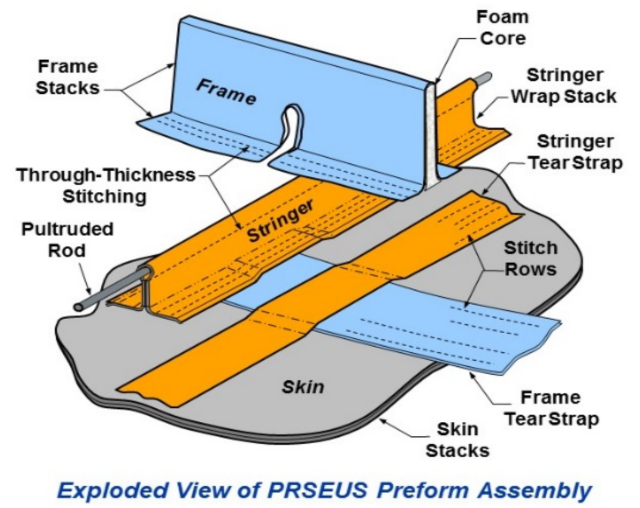

Fig. 1 PRSEUS Structural Concept (Ref. 2)

Additionally, the absence of mechanical attachments, gaps, and stringer pass-through holes results in uninterrupted load paths between the skin, stringer, and frame elements (Fig. 2) to eliminate many of the stress concentrations found in conventional built-up panel designs. Continuity at stringer-to-frame intersections is maintained in both directions by passing the rod-stiffened stringers through small keyholes in the frame webs, while keeping the frame caps continuous. The high-modulus rod embedded in the stringer cap increases local strength and stability of the stringer element, while simultaneously shifting the neutral axis away from the concentrated material near the skin. Frame elements are stitched directly to the skins to eliminate shear tie details, and are designed to

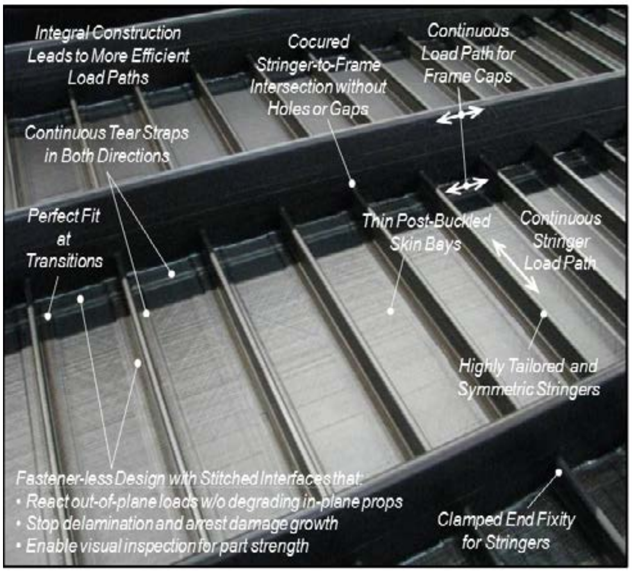

Fig. 2 Summary of PRSEUS Structural Features

take advantage of carbon fiber tailoring by placing bending and shear-conducive lay-ups where they are most effective. Once all of the elements are joined together with stitching, the stitch rows and tear straps constitute a fail-safe design arrangement that can be used to preferentially control damage propagation.

2.2 Use Stitching to Influence Design Criteria

Fail-safe design practices are predicated on creating independent load paths and redundancy to avoid cascading failure modes that prevent load redistribution to undamaged regions of the structure. Creating such a load-sharing arrangement is relatively simple using mechanically-joined structures because local failures are isolated within individual part details. This is characteristically not the case for integral or cocured structures because the monolithic state provides no mechanism for shedding load at the crack tip to slow or stop crack growth as loading increases. Changing this response pattern is imperative for making cocured composite panel designs weight competitive with aluminum structures.

Fortunately, with the addition of stitching, the stitch row now becomes that discrete design feature which can be used to tailor damage patterns in a preferential manner to control delamination at the crack tip and facilitate load redistribution within the panel. This distinctive use of stitching finally creates an opportunity to move beyond conventional No-Growth or Arrested-Growth composite design practices, and begin to incorporate the more aggressive fail-safe design schemes normally reserved for ductile metallic structures.

As important as the physical response of the structural reinforcement is, the other desirable trait necessary to achieve a comprehensive fail-safe design methodology involves in-service inspection. As with mechanical attachments, stitch row structural integrity is readily verified through visual inspection methods that correlate stitch-row appearance directly back to stitch-row strength. Such noninvasive inspection techniques are an especially important element for fail-safe composite design practices that, unlike metals, are prone to fast-fracture between arresting details, and are also time-consuming to inspect using ultrasonic inspection equipment.

2.3 Application to Panel Design Criteria

Conventional composite design practices are thoroughly described in Advisory Circular 20-107B (Ref. 3), but generally fall into two main categories as depicted in Fig. 3, where either a No-Growth or Arrested-Growth design approach is usually selected for composite structures. Early composite designs (Ref. 1) tended to use the more conservative No-Growth philosophy where operating strains are suppressed below levels at which damage grows. This is achieved by limiting maximum allowable damage size below the threshold of detectability, while still maintaining loading capability up through DUL load levels.

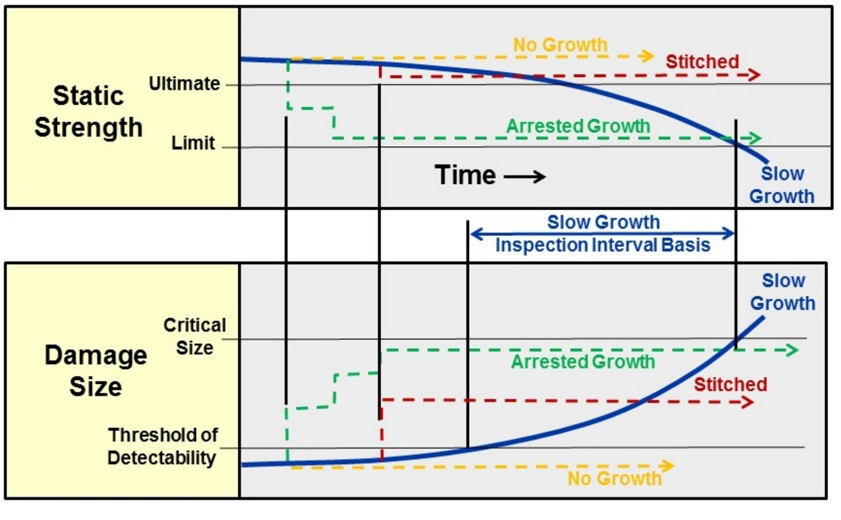

Fig. 3 Comparison of Composite Design Approaches with Conventional Slow

Over time, a more aggressive Arrested-Growth design philosophy was developed where an inspection interval was added to permit allowable damage levels beyond the threshold-of-detectability, but still below the critical damage size that would breach Design Limit Load (DLL) loading capability. The primary concern with this approach, is the large permissible reduction in structural capability (down from DUL to DLL) which is permitted until a repair can be made.

Such a large drop in loading capability is directly attributable to the lack of potential arrestment features that could be used to limit damage size, and in doing so, maintain a higher residual panel strength. A better approach would be to constrain damage size by having more frequent arrestment features, and furthermore, have enough arrestment features to ensure that loading capability never dips below the DUL levels that would trigger the addition of an inspection-and-repair cycle. Such an optimum scenario, which mimics a No-Growth design loading capability, but also allows larger permissible damage sizes prior to repair, is the design approach that becomes possible with the addition of through-thickness stitching. By adding enough stitch row boundaries to restrict damage growth, the remaining panel strength is never compromised below DUL levels – at least until the damage becomes so great as to qualify as a Discrete Source Damage (DSD) load case.

This new “Stitched” design approach for damage arrestment (Refs 4-7), is shown plotted in Fig. 3 relative to the No-Growth and Arrested-Growth design approaches, and in actuality, it captures the best features of each: 1) by maintaining DUL load levels, like the No-Growth approach to eliminate the inspection cycle, and 2) by constraining damage growth between adjacent stitch rows, loading capability can be designed to never drop below DUL. Since this hybrid approach exceeds the limits of the two accepted certification methods, it would not require any additional rule making for certification acceptance.

The premise of using stitching to influence design criteria is predicated on a robust stitch row strength with 100%-reliable crack stopping and turning capabilities, as has been demonstrated in structural testing to date. The other key attribute is that the relative load magnitude of the final panel failure must be substantially greater than the load level at which damage growth is initially arrested. This theoretical difference should be at least 1.5 times greater (ratio of DUL-to-DLL load) for this scheme to work properly. Fortunately, exceeding this ratio is relatively easy with stitching because stitch-row density, strength, and location can easily be adjusted to limit damage size without degrading in-plane laminate properties, in contrast to mainstream mechanically-fastened joints and their characteristically higher stress concentrations. Consequently, by keeping the undamaged structure beyond the stitch row intact and working at its pristine design strength, substantial margin still exists in the structure to carry the load being shed by the damaged region. Thus, by introducing an embedded through-thickness reinforcement feature into the laminate, delamination growth can be confined between adjacent stitch rows to ensure DUL levels of fail-safety are never breached prior to entering DSD loading scenarios.

While achieving this objective generally establishes the minimum stitch density needed to control damage propagation, further benefits can also be derived by delaying the onset of delamination by placing stitch rows at all geometry-induced stress concentrations, like the thickness changes and fillet radii locations. Locating stitching at these critical locations not only increases out-of-plane laminate strength, it also incrementally shrinks potential damage size to further enhance panel structural redundancy and residual strength. Creating this integrated network of highly controllable and reliable damage-arrest features is a fundamental requirement for confidently designing primary structures into the post-damaged nonlinear design space. Without such features, the brittle material response and lack of discrete part boundaries relegates conventional cocured composite concepts to conservative design methodologies.

Putting these principles into practice is outlined in Fig. 4, where a PRSEUS panel design would be loaded in tension parallel to the stringers. In this example, induced Barely Visible Impact Damage (BVID) in the open skin bay (Point A) starts to grow at DLL levels, and then fast fractures until it is arrested at the next stitch row

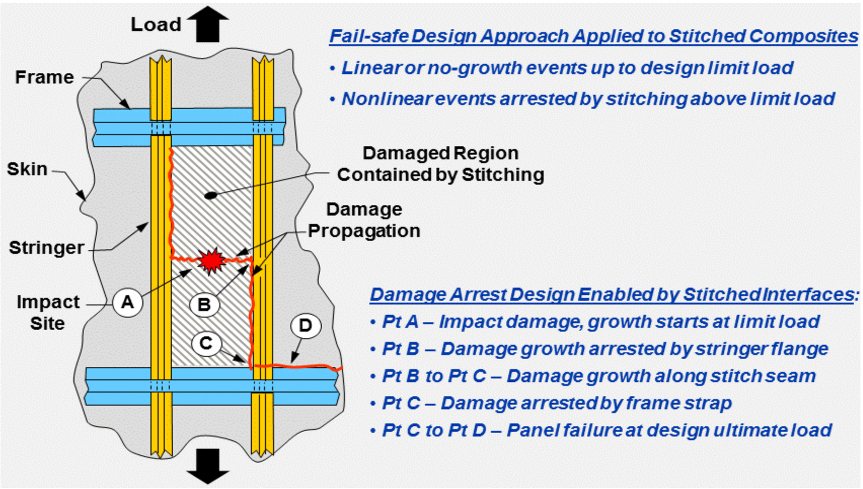

Fig. 4 Stitched Stiffened Panel Damage-Arrest Design Approach

(Point B), under further loading, the crack turns and then runs along the stringer flange before being arrested at next stitch row (Point C). With the damage contained by the stitch rows, further loading takes place until DUL load levels are reached to initiate cracking beyond Point C. Although actively designing within the nonlinear response range is common with metallic structures, where material yielding, cracking, and load redistribution are recognized design variables with a long history of in-service experience, this is not the case with composite structures. To demonstrate these principles, a series of building-block demonstration tests was conducted to explore the notion of using preferential cracking at the stitch row boundaries to permit the application of damage-arrest design principles that could be used to increase operating strain limits for composite structures with stitching, while simultaneously maintaining equivalent levels of safety with aluminum designs.

Demonstrating the characteristic crack-turning and arrest failure modes was the primary objective of a series of flat tension coupons comparing stitched and unstitched laminates (Refs. 8 and 9). As tension loads were increased in the stitched coupons, damage emanating from a centerline slot was first arrested horizontally at the vertical stitch row, right-most photograph in Fig. 5. Then as the crack turned vertically, it easily split the 0-deg fibers before it was arrested again at the horizontal stitch row. Once the damage was stopped in the opposite corners of the skin bay, increasing load levels caused the specimen to fail in the upper corner location (labeled as “Primary Failure” in right-most photograph in Fig. 5). Subsequent testing of unstitched configurations (left-most photograph in Fig. 5) proved that this complex crack-turning failure mode could not be replicated without stitching, as the unstitched specimens failed horizontally across their net sections (labeled as “Primary Failure” in left-most photograph in Fig. 5). Since the only difference between the two specimens was the stitching, it was clear that peak stresses at the crack tip were not capable of advancing the crack front beyond the adjacent stitch row.

This simple test demonstrated that a damage-arrest design approach would be possible using stitching, and that further testing was warranted using larger panels with additional structural members that would be

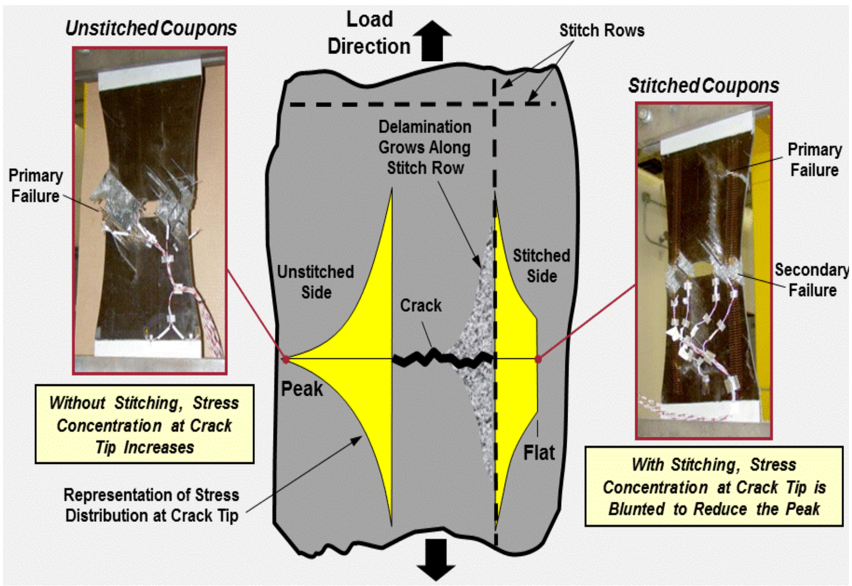

Fig. 5 Flat Laminate Testing With and Without Stitching (Refs. 8 and 9)

capable of carrying additional loading around the damaged regions confined within the stitch row boundaries. Once this basic principle of the damage arrest-and-turn phenomena was demonstrated with coupon-level testing, the same basic design approach was then applied to DSD conditions, where a principal structural element would be severed, and minimum design load levels would be reduced to account for the higher state of damage, commonly referred to as the 2-Bay Crack Criterion depicted in Fig. 6.

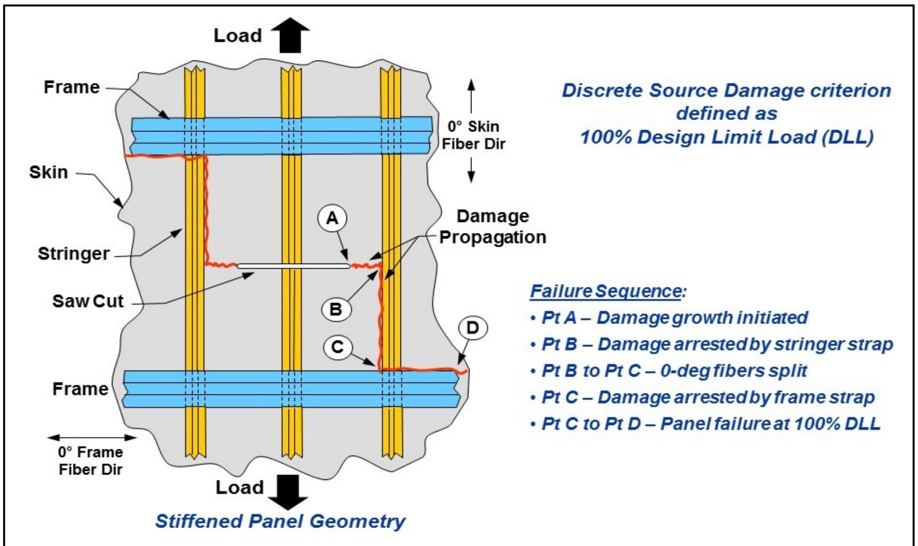

Fig. 6 Discrete Source Damage Design Approach with Stitched Structures

While there is some flexibility in selecting a safe design level for this condition, most transport airplane applications typically select a design load objective ranging from 70% to 100% of DLL loading. In the case of a stitched structure, it made sense to select the highest loading requirement, or most conservative design value, on which to demonstrate the full capability of the stitch row to arrest damage and then redistribute loading within the panel. The other advantage in selecting 100% DLL as the design objective, was that it coincided with the same load level selected to permit BVID growth. Although the two conditions are not explicitly linked, it did help simplify the damage arrestment discussion regarding which load cases would be critical during each step of the progressive failure analyses because the minimum loading capability would never be permitted to drop below DLL regardless of the level of induced damage being assessed. Putting these principles into practice for a 2-bay damage loading scenario is outlined in Fig. 6. In this example, a PRSEUS panel would be loaded in tension parallel to the stringers, where damage would start at the edge of the induced damage site (Point A), at well below DLL levels, and then fast fracture until it is arrested at the next adjacent stitch row (Point B), and finally under further loading, the crack turns and runs along the adjacent stringer tear strap stitch row, before being arrested at frame tear strap stitch row (Point C). Once the damage is contained by the adjacent stitch rows, within the two-bay damage zone, further loading takes place until DLL levels are reached where cracking beyond Point C is initiated, and at that point, failing the adjacent stringer and most likely leading to panel failure. This unique approach to fail-safe design was tested in a series progressively larger built-up PRSEUS test specimens and is described in the following sections.

3 Discrete Source Damage Testing

3.1 3-Stringer Panel Test

The stitched damage-arrest design philosophy for discrete source damage loading was first demonstrated using the 3-stringer tension panel with 6-inch stringer spacing and 20-inch frame pitch pictured in Fig. 7 (Refs. 8 and 9). The goal of this test was to show that damage would be arrested and that panel residual strength would exceed 100% DLL. The tension specimen was statically loaded to failure and was able to arrest damage in both the horizontal and vertical directions as the damage propagated from the saw-cut edges. With the damage fully contained within the 2-bay damage zone bordered by adjacent stringer and frame elements, the panel was able to continue carrying load well beyond 100% DLL. With the undamaged regions of the panel working to their full capability, the final failure occurred near the frame location at

132% DLL (labeled "Primary Failure Site" in Fig. 7). Without stitching, load levels would not have advanced much beyond 82% DLL, the load level at which cracking reached the stringer flange. Such a large increase in panel residual strength was achieved by unloading the crack tip until the adjacent undamaged fibers beyond the stitch row could be loaded to failure. This test demonstrated the fundamental principle of using preferential cracking, in a manner similar to yielding in metals, to alleviate local stress concentrations at the crack tip long enough to enable load redistribution to the undamaged elements in the panel.

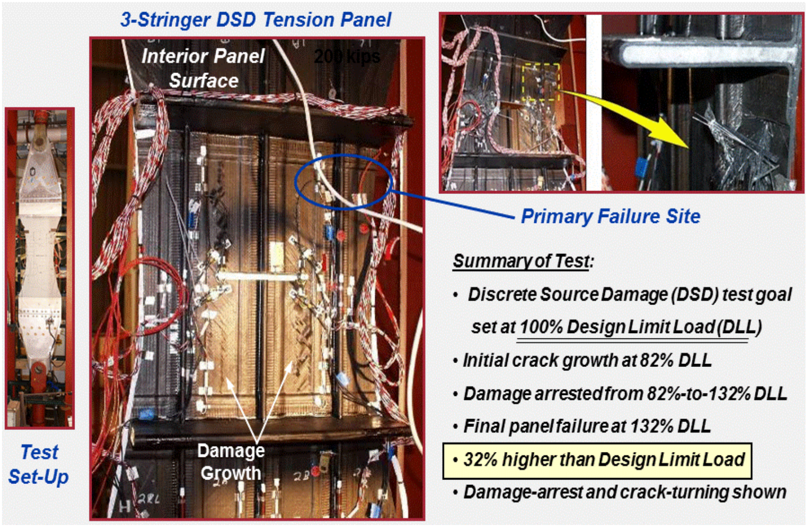

Fig. 7 Tension Loaded 3-Stringer PRSEUS Panel Test (Ref. 8 and 9)

3.2 7-Stringer Panel Test

After the success of the 3-stringer specimens, a larger, curved, 7-stringer, 5-frame specimen (Fig. 8) was fabricated and tested under more representative bi-axial fuselage loading conditions (Ref. 10). This combination of internal pressure and tension loading (parallel to stringers) was believed to be particularly challenging for arresting damage growth due to the normal forces that would more directly exercise the out-of-plane capability of the stitched interfaces to resist both delamination and pull-off failure modes. But even with the addition of complex loading and panel curvature, the classic damage-arrest and crack-turning response was replicated again, before the specimen finally failed at 185% DLL in the end grip region. The specimen failed in three distinct stages as summarized in Fig. 8.

Initially at 55% DLL, when laminate cracking started at the slot edges, splitting fibers along the 45-deg axis, before it was arrested by the stringer stitch rows, labeled as Location 2 in Fig. 8. In the next phase of loading up to 120% DLL, cracking in the skin continued along the stitch row and then fractured across the open skin bay to the next adjacent stringer where it was arrested at the stitch row, labeled as Location 3. Loading was then increased to 185% DDL when the Stringer 5 rod failed outside the test region, causing asymmetrical loading in the panel, which led to the final failure across the net-section, labeled as Location 3. By demonstrating an unprecedented level of fail-safety in a composite structure, this test continued to provide quantifiable evidence that large-notch load cases will no longer be critical design drivers for composite structures that are reinforced with stitching.

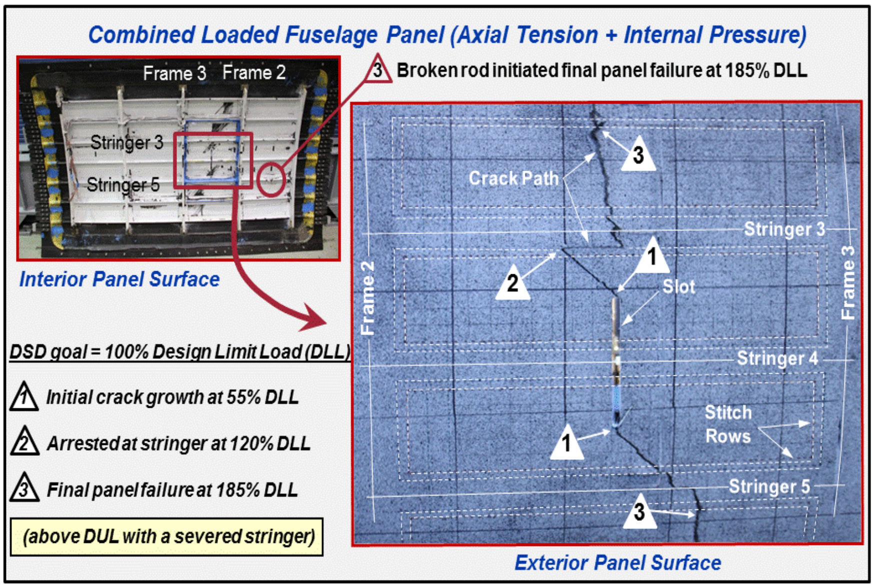

Fig. 8 Tension Loaded Curved 7-Stringer PRSEUS Panel Test (Ref. 10)

3.3 Large Component Damage Arrestment

An increasingly more difficult loading environment was encountered for the large-scale, closed-box Blend Wing Body (BWB) test article (Fig. 9) that was built and tested under the NASA Environmentally Responsible Aviation Program (Ref. 11). The primary purpose of this activity was to demonstrate the feasibility of achieving a weight-competitive solution for the challenging flat-sided pressure vessel design of the BWB configuration. The predominant goal of this work was to demonstrate that the aggressive use of stitched composite fail-safe design techniques,

Fig. 9 BWB Test Set-up at NASA-LaRC COLTS Test Facility (Refs. 11-16)

i.e. those validated in prior testing, could be strategically deployed to counteract the BWB noncircular fuselage weight penalty. Because the thin-gauge PRSEUS panels would be exposed to extreme secondary-bending and pull-off loads that are unique to the pressurization of flat panels, the challenge of designing a damage-arrest network using a layered material system becomes even more difficult, even given the enormous advantage of deploying through-thickness reinforcements, like stitching.

To assess this premise, the specimen was tested at room temperature and subjected to a series of combined bending and internal pressure load cases in the NASA-LaRC COLTS (Combined Loads Test System) test facility pictured in Fig. 9. The specimen was positioned between two pivoting load platens to induce bending loads into the structure, while simultaneously being pressurized to simulate cabin pressure. After successfully completing all of the critical DLL maneuver and pressure load cases at 2.5-g, 2.5-g+1P, -1.0-g, and -1.0-g+1P, BVID damage was introduced at several key locations, loading was increased to DUL levels, and then the loading sequence was successfully repeated. Additionally, a DUL static 2P (18.4 psi) pressure-only load case was also successfully completed without incidence. After meeting all of the DUL load cases, the center frame element on the upper crown panel was cut to simulate a two-bay crack criterion and the specimen was tested to failure in bending to maximize the compressive running loads across the damaged center-bay section - center photograph in Fig. 10.

The final failure occurred at 151% DLL, slightly above DUL even with the severed frame, but more importantly, well beyond the 100% DLL goal established for the Discrete Source Damage load case. Although the specimen failure(s) occurred in rapid succession near the final failure load, the mode of failure clearly exhibited the load redistribution patterns witnessed in prior subcomponent tests - the failure sequence is summarized in relative order

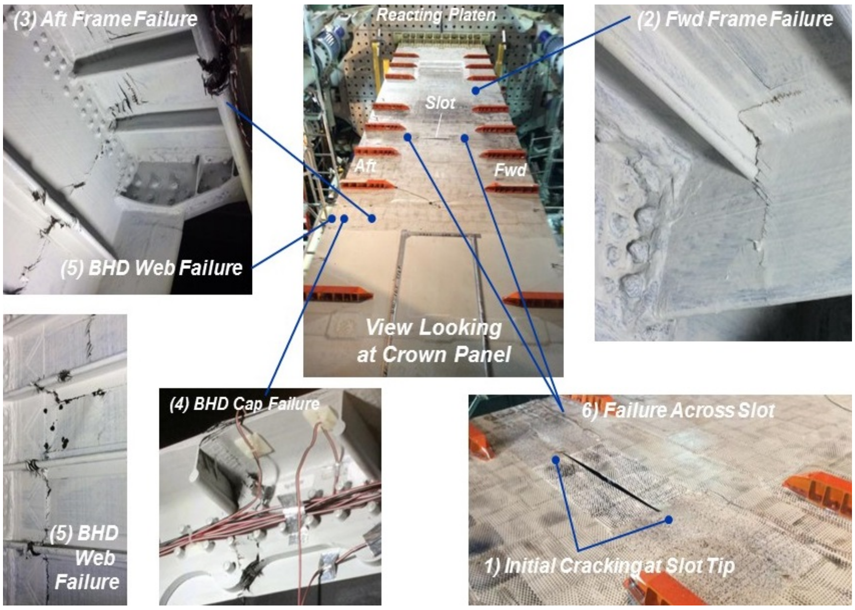

Fig. 10 Summary of Progressive Failure Sites on BWB Specimen (Refs. 11-16)

in Fig. 10. Starting with the initial damage growth at the slot edge that was immediately arrested at the adjacent frame stitching, to the subsequent sequential failures of the individual principal structural members, the damage-arrest capability of the structure was clearly evident as the predominant loading shifted from right-to-left across the specimen, as the damage growth was contained at each new failure site, and then loading was shifted from the softened damaged areas to the stiffer undamaged structural load paths before finally failing at 151% DLL. After successfully completing all of the DUL test cases, and then breaking the specimen after exceeding the final DSD loading goal, what becomes abundantly clear, is that constraining damage growth is a very effective strategy, and in fact, does lead to substantially higher achievable load levels, that ultimately result in lighter structures that can be worked to consistently higher strains levels than conventional No-Growth or Arrest-Growth composite designs.

4 Benefits of Damage-Arrest Design

4.1 Applicability to Transport Aircraft

Creating a more robust structural architecture is the key to reducing the weight and cost of composite primary structures. The limited out-of-plane capability of the resin matrix leads to the excessive use of mechanical attachments and over-sized structural members designed to shift load away from the potential delamination failures that are very difficult to predict, inspect, and ultimately arrest. While the other critical missing element for composite design is the in-service inspection piece, made infinitely more difficult to achieve with a fast-fracture material response that renders traditional time-to-failure inspection programs unusable – resulting in critical crack lengths and damage sizes that must be set at maximum values and assumed to traverse the entire distance between arresting features. Robbed of two fundamental aspects of fail-safe design theory, time-to-failure and visual-inspection-of-strength, unreinforced composite designs will continue to be more conservatively designed and expensive to certify. Fortunately, this is a critical area where stitching can readily be used to transform the fail-safe design methodology typically used for composite structures. By defining ever-smaller damage regions, bounded by stitching, slow-growth inspection requirements could be eliminated because critical damage sizes would never be allowed to violate DUL-loading capability. In-service confirmation would readily be accomplished using simple visual detection methods that would then be used to verify that detrimental damage growth, in excess of BVID levels, had not violated stitch row boundaries that would have been designed and demonstrated to stop damage propagation prior to affecting DUL-loading capability. Such a revolutionary new approach to fail-safe design theory for composite structures only becomes possible when damage-arrest features are easily added to the laminate without degrading in-plane properties. Additionally those features must also provide visual cues that relate appearance back to residual strength to maintain the basic tenants of fail-safe design theory, redundancy and inspectability.

4.2 Summary

The PRSEUS panel architecture was conceived to address the weight and cost short-comings inherent in conventional layered material systems. By replacing pre-impregnated materials with dry fabric, and fasteners with stitching, a highly engineered structural solution becomes possible that moves beyond traditional No-Growth and Arrested-Growth fail-safe design practices. The result is a highly unitized panel design with integral crack-stopping capabilities provided by through-thickness structural stitching that results in unprecedented levels of fail-safety. This is the primary reason to use stitching, and it has been demonstrated in a series of static structural tests (Refs. 17-24) that substantiated the robust nature of this new design approach to operate efficiently and economically, within the design space of future large transport aircraft wing and fuselage applications.

References

[1] Fawcett, A. J., Trostle, J. and Ward, S., "777 Empennage Certification Approach," Proceedings of the 11th International Conference on Composite Materials, Gold Coast, Australia (1997).

[2] Velicki A., and Thrash P.J., 2008. "Advanced Structural Concept Development Using Stitched Composites," presented at the 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April, 2008.

[3] FAA Advisory Circular 20-107B, COMPOSITE AIRCRAFT STRUCTURE, issued September 2009.

[4] Velicki, A., and Thrash, P.J., 2010. "Damage Arrest Design Approach Using Stitched Composites," 2nd Aircraft Structural Design Conf, Oct 26–28. 2010.

[5] Velicki, A., and Thrash, P.J., 2011. "Damage Arrest Design Approach Using Stitched Composites," *The Aeronautical Journal*, 115(1174): 789-795.

[6] Velicki, A., 2009. "Damage Arresting Composites for Shaped Vehicles," NASA CR-2009-215932.

[7] Velicki, A., Yovanof, N., Baraja, J., Linton, K., Li, V., Hawley, A., Thrash, P., DeCoux, S., and Pickell, R., 2011. "Damage Arresting Composites for Shaped Vehicles—Ph II Final Report," NASA-CR–2011-216880.

[8] Air Vehicle Technology Integration Program (AVTIP), Delivery Order 0059: Multi-role Bomber Structural Analysis, AFRL-VA-WP-TR-2006-3067, K. Hoffman, MAY 2006, Final Report for Dec 2004 – 2006, AFRL-VA-WP-TR-2006-3067.

[9] Air Vehicle Technology Integration Program (AVTIP), Multi-role Transport Structural Analysis, AFRL-VA-WP-TR-2008-3063, Kim Linton, SEPT 2005, Final Report for 12 September 2005 – 15 February 2008, AFRL-VA-WP-TR-2008-3067.

[10] Gould, K., Lovejoy, A., Neal, A., Linton, K., Bergan, A., and Bakuckas Jr, J., 2013. "Nonlinear Analysis and Post-Test Correlation for a Curved PRSEUS Panel," presented at the 54th AIAA Structures, Structural Dynamics, and Materials Conference, April, 2013.

[11] Velicki, A., Hoffman, K., Linton, K.A., Baraja, J., Wu, H.T., Thrash, P.J., 2017, "Hybrid Wing Body Multi-Bay Test Article Analysis and Assembly Final Report", NASA/CR–2017-219668, prepared for NASA-LaRC under contract NNL10AA05B and NNL11AA68T.

[12] Wu, H.T., Shaw, P., and Przekop, A., 2013. "Analysis of a Hybrid Wing Body Center Section Test Article," presented at the 54th AIAA Structures, Structural Dynamics, and Materials Conference, April, 2013.

[13] Przekop, A., Wu, H.T., and Shaw, P., 2014. "Nonlinear Finite Element Analysis of a Composite Non-Cylindrical Pressurized Aircraft Fuselage Structure," presented at the 55th AIAA Structures, Structural Dynamics, and Materials Conference, January, 2014.

[14] Rouse, M., and Jegley, D., 2015. "Preparation for Testing a Multi-Bay Box Subjected to Combined Loads," presented at the Society for Experimental Mechanics meeting, June, 2015.

[15] Przekop, A., Wu, H.T., Jegley, D., Rouse, M., and Lovejoy, A., 2015. "Nonlinear Analysis and Preliminary Testing Results of a Hybrid-Wing Body Center Section Test Article," presented at the American Society for Composites Meeting, Sept 2015.

[16] Thrash, P., 2014. "Manufacturing of a Stitched Resin Infused Fuselage Test Article," presented at SAMPE Fall Technical Conference, October, 2014.

[17] Jegley, D., 2011. "Structural Efficiency and Behavior of Pristine and Notched Stitched Structure," presented at the annual SAMPE meeting October 17-20, 2011.

[18] Yovanof, N., and Jegley, D., 2011. "Compressive Behavior of Frame-Stiffened Composite Panels," presented at the 52nd AIAA Structures Dynamics and Materials Conference, April, 2011.

[19] Jegley, D., 2013. "Behavior of Frame-Stiffened Composite Panels with Damage," presented at the 54th AIAA Structures, Structural Dynamics, and Materials Conference, April, 2013.

[20] Allen, A., and Przekop, A., 2012. "Vibroacoustic Characterization of a New Hybrid Wing-Body Fuselage Concept," presented at the INTER-NOISE 2012 Conference, August, 2012.

[21] Yovanof, N., Lovejoy, A., Baraja, J., and Gould, K., 2012. "Design Analysis and Testing of a PRSEUS Pressure Cube to Investigate Assembly Joints," Aircraft Airworthiness and Sustainment Conf, 2012.

[22] Przekop, A., Jegley, D., Rouse, M., and Lovejoy, A., 2014. "Analysis and Testing of a Metallic Repair Applicable to Pressurized Composite Aircraft Structure," presented at the SAMPE Technical Conference, June, 2014.

[23] Jegley, D., 2009. "Experimental Behavior of Fatigued Single Stiffener PRSEUS Specimens," NASA-CR–2009-215595.

[24] Linton, K., Velicki, A., Hoffman, K., Thrash, P., Pickell, R., and Turley, R., 2014. "PRSEUS Panel Fabrication Final Report," NASA-CR-2014-218149.