OVERVIEW AND STATUS OF "COMPOSITE JOINTS WITH INHERENT DISBOND ARREST CAPABILITY (COJAC)" PROGRAM

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ABSTRACT

In the design and development of future naval air systems, several challenges exist in meeting acquisition and operational cost and performance goals. Many of these challenges can be addressed using bonded composite structures technology, provided structural integrity/reliability concerns are addressed. Bonding enables low cost but high composite content airframes that reduce 1) aircraft structural weight fraction and 2) maintenance cost associated with fatigue, corrosion, and survivability. However, widespread use of primary bonded composite airframe structures is currently constrained by structural integrity and reliability concerns. These concerns are reflected in the JSSG-2006 guidelines which states that primary bonded structures must sustain a residual strength capability at limit load or better "without a safety of flight failure with a complete bond line failure or disbond". One way to address this criterion is to use Z-pinning as a disbond arrestment feature in the bondline. Under the "Composite Joints with Inherent Disbond Arrest Capability (CoJAC)" program, Z-pin technology in the form of "stubble" concept will be applied to co-bonded joints based on 3D woven Pi preforms. Funded by the Office of Naval Research (ONR) and led by Northrop Grumman Aerospace Systems (NGAS), the goal of the CoJAC program is to assess the feasibility of the Z-pin stubble-based co-bonded Pi joints to meet the JSSG requirement by combination of automated Z-pin insertion technique and autoclave-based co-bonding. This paper will provide an overview and current status of the program.

1. INTRODUCTION

Bonded assembly enables low cost but high composite content airframes that reduce 1) aircraft structural weight fraction and 2) maintenance cost associated with fatigue, corrosion, and survivability. However, the prevalent use of bonding in primary structures remains elusive due to structural integrity and reliability concerns. While 3D Pi preforms have enabled high-strength bonded joints, particularly under out-of-plane loading (such as those found in pressurized bays), questions remain on the quality and damage tolerance of the bondline. Such concerns are reflected in the JSSG-2006 guidelines which states that primary bonded structures must sustain

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residual strength capability at limit load or better "without a safety of flight failure with a complete bond line failure or disbond." One way to address this criterion is to incorporate disbond arrestment features into the bondline. Z-pin technology is such an arrestment approach and NGAS has successfully implemented it on F/A-18E/F on cocured hat stiffeners [1]. Moreover, under an ongoing independent research and development (IRAD) funded activity, NGAS has applied Z-pins to co-bonded Pi-joints using a "stubble" concept developed by AFRL [2], in conjunction with out-of-autocalve (OOA) Pi-preforms as illustrated in Figure 1. While the consolidation of the OOA Pi over the Z-pin stubble fields on the precured laminates have been challenging due to the use of vacuum bag pressure only, static tests at element and subcomponent levels have shown considerable improvements in residual strength capability (up to 23%) in presence of defects over conventional Pi-joints, indicating that the Z-pins by themselves contribute to a good portion of the joint strength. Recent fatigue tests of Z-pinned Pi-joint elements has shown robust fatigue performance – no visible degradation was observed during constant amplitude fatigue at limit load and while sustaining several hundred cycles at 90% of ultimate static strength with one side fully disbonded and held only by the Z-pins.

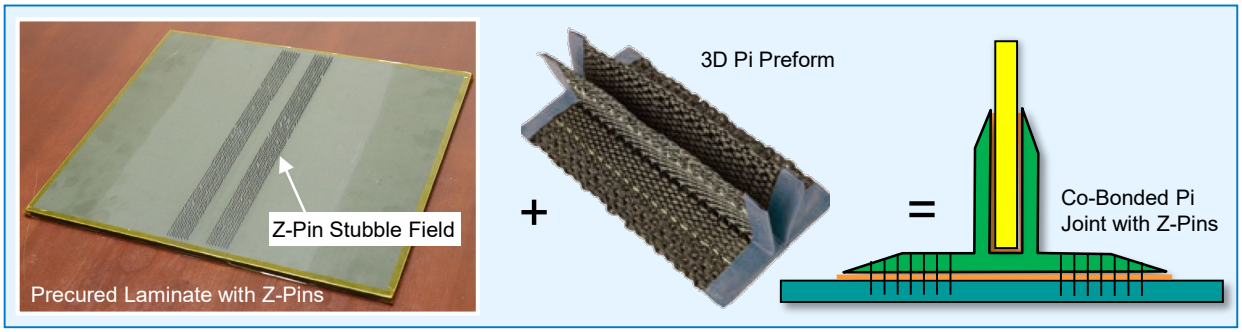


Figure 1. Co-Bonded Pi Joint with Z-Pin Stubble Concept

Based on the results of the IRAD study on the OOA-based Pi joints, a potential exists for a JSSG-2006 compliant bonded assembly using Pi preforms with Z-pin technology. Under ONR's CoJAC program, NGAS will assess the feasibility of such a JSSG-compliant bonded assembly by expanding on the IRAD approach through 1) use of autoclave cure for improved Pi preform compaction over the Z-pin stubble field, 2) use of automated Z-pin insertion process to improve residual strength performance including scatter, and 3) tailoring/design of Z-pin field for increased Z-pin retention strength. As shown in Figure 2, these expansions will occur over 5-year period of performance through three coupon/element-level tasks in the Base period, followed by two optional subcomponent-level tasks. The basic technical approach is to 1) verify the three expansions through fabrication and testing of coupons and Pi-joint elements in three basic tasks and 2) apply and verify the optimized processing and structural design parameters through design, build, and testing of subcomponents in the two optional tasks. The program has just completed its first year, with near completion of Task 1 and starting on Task 2.

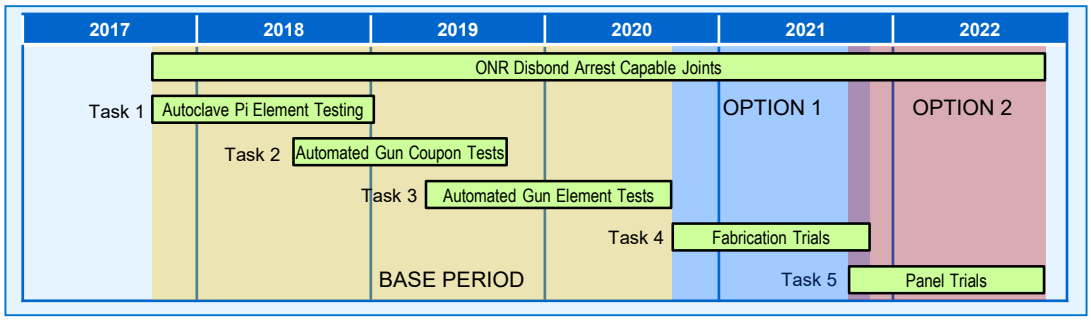


Figure 2. CoJAC Program Plan

2. BACKGROUND

2.1 Z-Pin Technology & Stubble-Based Pi Joint

NGAS has a unique background in Z-pin technology as the only aerospace company currently using Z-pin reinforcements in production. The technology has been developed and implemented on the F/A-18E/F program, resulting in an elimination of over 4,800 fasteners in each aircraft and cost saving of $84,000 per shipset. In the past, the Z-pin technology has been applied to making co-cured Pi joints. Under an IRAD project, a co-bonded version was developed using the Z-pin stubble concept per Clay et al [3]. The procedure is shown in Figure 3. Starting with an uncured composite skin laminate, a neoprene carrier is installed on top of the laminate. This carrier provides a means to achieve a desired height of the Z-pin stubble field and also helps to support the Z-pins during autoclave cure. Z-pins are inserted through the neoprene carrier and into the uncured laminate using a handheld ultrasonic insertion gun and then trimmed to the desired stubble height as dictated by the neoprene carrier. After the Z-pinned panel is autoclave cured, the neoprene carrier is removed, leaving two rows of Z-pin stubbles. Prepregged pi-preforms, film adhesive, and spar web are then assembled and seated onto the stubble field. The complete assembly then vacuumed bagged and goes through a final out of autoclave cure and afterwards, is machined into elements for testing.

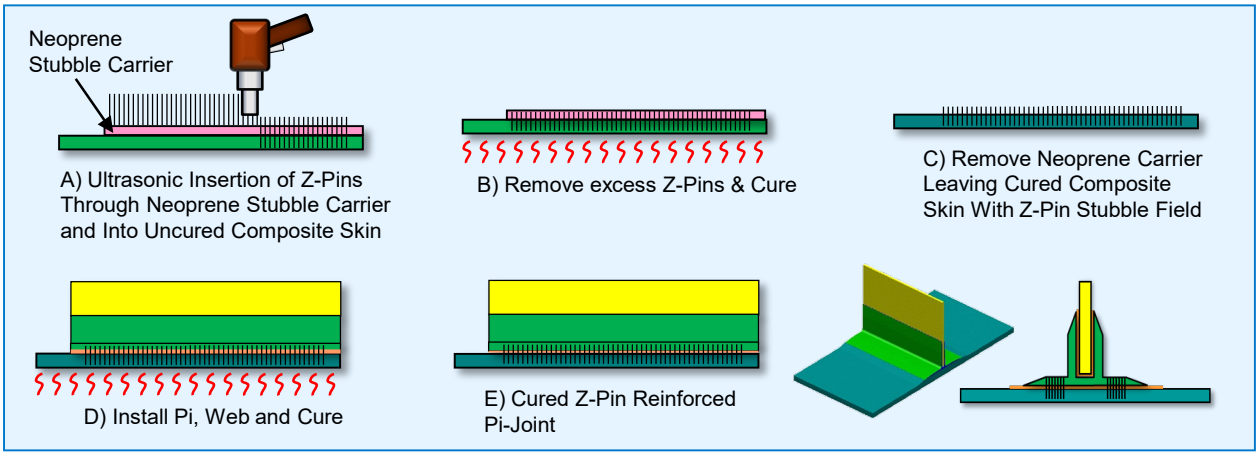


Figure 3. Fabrication Process for Protruding Z-pin Stubble Insertion and Production

2.2 Potential Benefit of Z-Pin Stubble Co-bonded Pi Joint

The ability to enhance the damage tolerance of bonded joint with stubble-based co-bonded Pi joints were demonstrated through both element-level and subcomponent-level tests. In particular, two tests showed the potential benefits in damage tolerance / residual strength capabilities. In the first test, a large composite skin/spar assemblies were tested in a pressure box fixture. Five of these subcomponent level tests were performed with two assemblies having Z-pin reinforced Pi-joints. One of the two Z-pinned panels contained multiple controlled defects along the bondline. This test panel failed at a pressure 23% higher than the non-Z-pinned *pristine* version—i.e., without defect. Post failure inspection of the panel showed that the Z-pins were retained evenly between the skin and the Pi.

In the second test, fatigue performance was assessed with three element level specimens in pull-off configuration. The fatigue load profile was a R=0.1 constant amplitude block loading, with maximum fatigue load of each block increasing from previous block at 5% increment of static ultimate strength (UTS). Each block typically contained 1,000 cycles. During fatigue testing, incremental C-scans were performed to provide visual indication of damage at the bondline. All three fatigue tests showed that even with a complete disbond of one side of the Pi flange, the joint still retained significant residual strength (load carrying capability up to 90% of ultimate load for a limited number of cycles) due simply to the presence of Z-pins. A typical failure behavior is shown for one of the fatigue specimens in Figure 4. For this specimen, a visible disbond developed at the clevis and both tips of the Pi-joint during the 85% UTS block. These disbonds continued to grow and propagate and as shown in Figure 5, the left side of the Pi-joint came completely unbonded at around 70 cycles into the 90% UTS block but the Z-pins still allowed load carrying capability at 90% of ultimate load for over 20 additional load cycles before final failure.



Figure 4. Fatigue Test Results Emphasize Outstanding Residual Strength of CoJAC Approach

2.3 CoJAC Problem Statement / Goals

The IRAD studies showed a potential for improving the reliability of co-bonded assembly with Z-pins. The articles fabricated and tested were based on Z-pin stubbles with manual Z-pin insertion and fixed Z-pin pattern, cured under vacuum bag pressure only. The goal of the CoJAC program is to assess if the structural performance (both strength/toughness and scatter) can be further improved with 1) automation of Z-pin insertion and 2) cure/consolidation with autoclave pressure. The program will assess the improvement approaches through five major tasks described in Table 1, following the schedule shown in Figure 2.

Table 1. CoJAC Task Description

Task 1: Autoclave Pi-Joint Element Testing	• Develop baseline mechanical test data for unpinned Pi joint and Z-pin stubble Pi joint using autoclave pressure • Modify/update existing analytical models for prediction of unpinned and Z-pinned Pi joint performance
Task 2: Automated Process Coupon Trials and Tests	• Develop stubble panel cure processing approach that is compatible with Z-pin automation • Develop strength and toughness mechanical database from at coupon-level for various Z-pin patterns created using automated insertion machine • Update Z-pin predictive methods with test data to enable tailoring of Z-pin pattern
Task 3: Automated Process Element Trials and Tests	• Fabricate and test Z-pin stubble Pi joints based on best pattern and process from Task 2 • Predict auto-Z-pinned Pi joint performance
Task 4: Subcomponent Panels – Option 1	• Validate performance improvement with 2-bay pressure box testing simulating pure pull-off loading
Task 5: Subcomponent Panels – Option 2	• Validate performance improvement with 2-bay pressure box simulating combined pull-off and side bend loading

3. CURRENT STATUS

The CoJAC program is currently finishing up Task 1. The goal of Task 1 is to develop a set of test data for unpinned and manually Z-pinned co-bonded Pi joints, following the test matrix shown in Table 2. The test data will serve as reference to compare against the Z-pin stubble Pi joints made with Z-pin insertion machine developed under IRAD.

Table 2. Task 1 Test Matrix (Total Specimen Count: 58)

Z-Pin	ID	Skin Laminate	Defect Type	Static			Fatigue
				Pull-Off, 2-Point	Pull-Off, 4-Point	Side Bend	Pull-Off, 4-Point
Un-Pinned	1	L1	N/A	3	3		
	2	L2	N/A	3	4	3	1
	3	L2	ES1: Straight Under Tip		3		
	4	L2	EC1: Semi-Circle Under Tip		4		1
	5	L3	N/A		4		1
	6	L3	CS1: Straight Under Throat		3		
	7	L3	CC1: Circular Under Throat		4		1
Z-Pinned	8	L2	N/A		4		1
	9	L2	EC1: Semi-Circle Under Tip		4		1
	10	L3	N/A		4		1
	11	L3	CC1: Circular Under Throat		4		1

The three test loading configurations—i.e., 2-point pull-off, 4-point pull-off, and side bend—are shown in Figure 5. The specimens with four defect types, as shown in Figure 6, were also tested. The defect locations, whether Pi tip or Pi throat (see Figure 5 for definition), were determined based on the location of the predicted peak peel stress in the bondline.

For unpinned joints, all static tests have been completed and fatigue tests remain. For Z-pinned joints, specimen fabrication is in progress, after having determined the best way to seat the Pi preform over the stubble field through a number of trials.

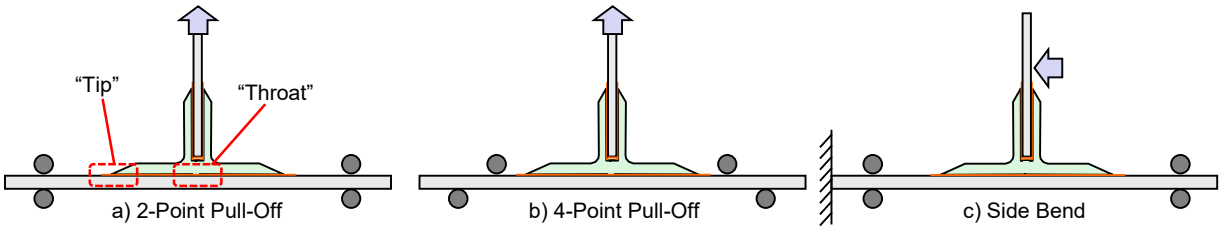


Figure 5. Joint Test Configurations

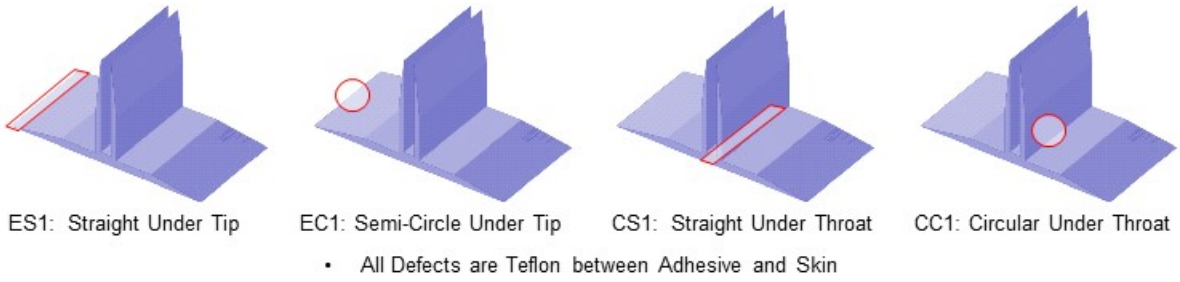


Figure 6. Defect Types

Prior to starting the fabrication of Z-pin stubble based Pi joint specimen for database generation, three process trials were performed to improve the seating of the B-staged Pi preform over the stubble field and onto the skin laminate with the film adhesive. The distortion in the Pi base and bondline thickness uniformity improved over successive trials. Pull-off and side-bend tests were performed to assess various seating procedure. The load-displacement test results are shown in Figures 7 and 8 for pull-off and side-bend tests, respectively, comparing the unpinned and Z-pinned specimen responses.

In assessing the goodness of the Z-pin seating process trials, the initial significant load drop level for both unpinned and Z-pinned specimens were compared. Ideally, the initial significant load drop level for the Z-pinned specimens should not be differentiable from the initial and only load drop (i.e., maximum load) observed for the unpinned specimens. As can be seen for both loading cases, the initial load drops observed in the Z-pinned specimens were approximately 30% lower than the unpinned cases. In addition, for side-bend loading, the scatter in the initial load drop for Z-pinned specimens were rather large compared to the unpinned specimens.

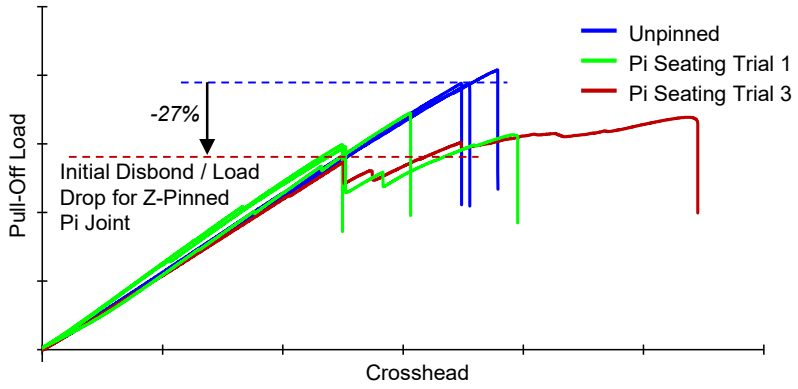


Figure 7. Z-Pin Stubble Pi Joint Trial Results: 4-Point Pull-Off, L2 Skin Laminate

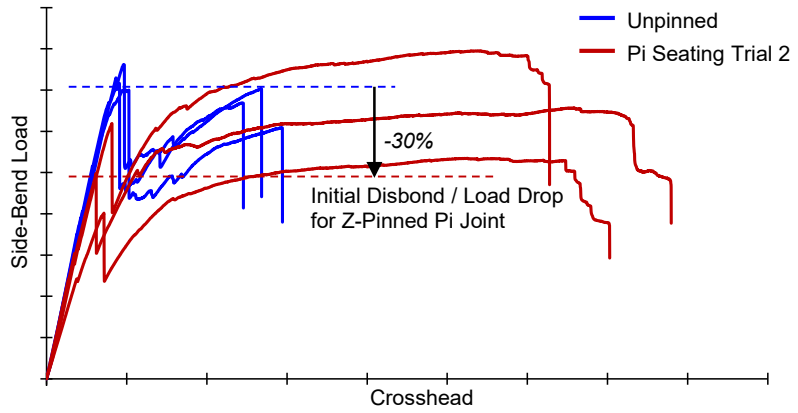


Figure 8. Z-Pin Stubble Pi Joint Trial Results: Side-Bend, L2 Skin Laminate

These tests indicate that factors other than bondline quality may be affecting the initial load drop level in the Z-pinned joints. Potential factors may include contamination of the skin due to neoprene residue on the Z-pins and premature ply cracking in the skin ply on the joint side. The neoprene rubber is a release material and hence the Z-pins could pick up the release while penetrating through the rubber layer. Once driven into the skin, the neoprene residue on the Z-pin surface may spread into the skin and reduce its interlaminar properties. In addition to neoprene contamination, ply cracks could initiate disbond at either the Pi tip or the Pi throat. When Z-pins are driven in through the skin, the plies split locally, as shown in Figure 9. These splits are essentially initiators for ply cracks. For those splits near the free edge of the specimens, the ply cracks should form much earlier than for unpinned cases, and subsequently lead to premature disbond between the Pi and the skin. During Task 2, causes for the reduced initial load drop in the Z-pinned specimens will be determined.

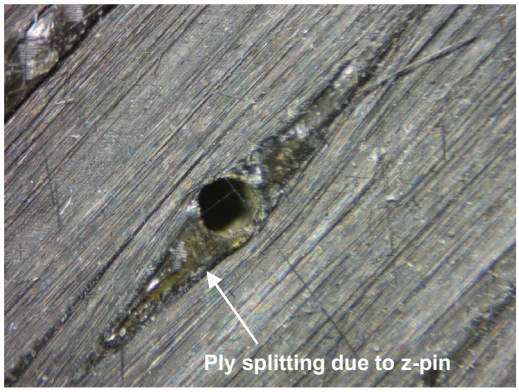


Figure 9. Ply Damage Due to Z-Pin Insertion

4. SUMMARY

Internal studies by NGAS have shown great potential for increasing the reliability of co-bonded assemblies through the use stubble-based Z-pins in the Pi joints despite being fabricated with vacuum pressure only. The CoJAC program was initiated to assess whether further improvements in residual strength capability can be achieved by incorporating 1) autoclave pressure in the joint co-bond cure cycle, 2) controlled Z-pin insertion via automation, and 3) tailoring of Z-pin pattern for optimal performance. The program just completed the 1st year of the 3 year basic program with reference test database generated for unpinned joints made with autoclave pressure. Reference database for stubble-based Pi joint specimens is currently in work. The stubble field in these joints were made using manual Z-pin insertion procedure and is meant to provide baseline against the automated insertion process. Concurrently, coupon-level assessment of stubble patterns created using z-pin insertion machine will begin.

5. REFERENCES

1. Mouritz, A.P., "Design Dilemma for Z-Pinned Composite Structures", 27th International Congress of the Aeronautical Sciences, 2010
2. Stephen B. Clay and Amanda K. Pommer, "Z-Pin Stubble Technology Advanced Research (ZSTAR)", April 2008, Final Report, AFRL-RB-WP-TR-2008-3017