Reducing Unscheduled Maintenance with Terminating Structural Repair Solutions

Len Reid, Vice President Research & Development
Fatigue Technology Inc.
401 Andover Park East
Seattle, Washington 98188 USA

lreid@fatiguetech.com

ABSTRACT

Unscheduled maintenance and recurring inspections are the largest cost drivers when it comes to aircraft maintenance, especially when applied to an aging aircraft fleet. Non-permanent repairs can have a huge impact on military platform availability. The advent of a "Conditioned Based Maintenance" philosophy for long-term fleet management require engineering staff to seek more permanent or terminating repair methods to extend or eliminate ongoing structural inspections which are often the cause of increased downtime. This paper reviews some innovative terminating repair concepts and ideas using different cold expansion processes and products such as, ForceMate expanded bushings, ForceTec rivetless nut plates, and TukLoc blind installed threaded nuts. These are all derived from the split sleeve cold expansion process used extensively to prevent structural fatigue cracking from holes. The paper will discuss the different repair technologies and include a number of specific repair applications to show the ongoing maintenance cost savings benefits to the operators. These significant savings aid sustainment efforts and the ongoing quest to eliminate unscheduled maintenance and its impact on aircraft availability and fleet operations. Incorporation of these technologies into structural repairs reduces operational costs and also has the added advantage of increasing structural integrity and continuing airworthiness in aging fleets.

1.0 INTRODUCTION

It is common knowledge that the average age of military aircraft fleets are increasing rapidly. Replacement aircraft are not as readily available and some types are being extended beyond their originally defined economic life; albeit after being subjected to a substantial structural audit. As the lives increase so does the cost of maintenance increase commensurately and is often at a much faster rate than the earlier stages of design life. The maintenance cost drivers are typically:

- Structural inspections
- Fatigue crack removal/repair
- Corrosion abatement
- Fuel leaks
- Lug durability/bushing migration
- Component repair/replacement
- Major structural life improvement programs (SLIPs)

Unscheduled maintenance further exacerbates the maintenance cycle and severely impacts availability of aircraft for their design or operational mission. Condition based maintenance plans were introduced for long-term fleet management to increase aircraft availability by managing individual aircraft based on usage and not routine calendar based servicing, which tends to "over-service" many aircraft in the fleet. For this program to be effective it is essential that structural repairs carried out are permanent and do not require ongoing inspection. These can further add to ongoing sustainment costs and fleet management.

The USAF and US Navy have different approaches when it comes to structural integrity. Fleets are managed based on damage tolerance/inspection or safe life supplemented with on-condition inspection. Most military fleets would fall into either group with some combining both philosophies based on indigenous requirements. The aircraft are designed with the same or similar materials and to comparable stress levels; they are essentially the same airplane. Operational differences drive the Navy emphasis on individual aircraft tracking as compared to the Air Force using recurring inspections for structural integrity monitoring. As Navy aircraft approach/exceed original design lives, dependence on damage tolerance increases. Basically the fleet is managed based on a safe life, no maintenance actions for fatigue, to "On Condition" with recurring inspections, if possible. Widespread cracking would lead to service life termination. The Air Force life management is essentially a "Damage Tolerance" approach with continuous inspection of increasing locations and frequency. Which ever structural maintenance philosophy is used, the cost of maintenance will increase as the fleet ages. Keeping these costs down is imperative for economical sustainment of the fleet.

This paper discusses some innovative terminating repair concepts and ideas using the different cold expansion processes and products that have normally been associated with aircraft production. Derivative cold expansion technologies have been used in a number of unique and cost effective repairs carried out on military and commercial aircraft including:

a. Fatigue crack mitigation using hole cold expansion
b. Hole resizing resulting from fatigue or corrosion
c. Elimination of hole damage or ovalization problems by using expanded bushings and the bushing style rivetless nut plates
d. Replacement of worn or migrating bushings or incipient fretting damage in lugs with a high interference fit expanded bushing
e. Restoration of static and fatigue strength problems when repairing corrosion problems with hole cold expansion or rivetless nut plates and bushings

2.0 COLD EXPANSION PHILOSOPHY

Aircraft and rotorcraft are designed using good safety, durability and structural integrity principles. They are also required to have long fatigue lives and low operating and maintenance costs. Good detail design of joints is necessary to achieve the required fatigue life and structural endurance under expected in-service loads. The installation of light interference fit fasteners can improve joint fatigue life by inducing a tensile pre-load around the hole. High-interference fasteners may compressively pre-load the hole, however, it is highly dependent on the fit of the fastener. Alternatively, pre-stressing to induce residual compressive stresses around the hole prior to installing the fastener can greatly enhance the fatigue resistance of the joint by preventing cracks from growing from the hole. Split-sleeve hole cold expansion is the most widely used and cost effective method of pre-stressing holes. The zone of residual compressive hoop stress effectively shields the hole from the cyclic tensile stresses that cause cracks to grow. Furthermore, when used on older aircraft structure, these beneficial stresses retard crack growth by reducing the stress intensity factor associated with a pre-existing crack. The resultant overall fatigue life and damage tolerance of the structure is greatly enhanced by using this technology.

2.1 Split Sleeve Cold Expansion Process

The Split Sleeve Cold Expansion process, shown in Figure 1, was discussed at the 2001 NATO RTO Task Group AVT-085 conference [1]. It improves the fatigue life of holes in metallic structure by generating a large, controllable zone of permanent residual compressive hoop stress around the hole. It is a one sided process accomplished by pulling a tapered solid mandrel, pre-fitted with a split sleeve, through a hole with approximately 4% interference as shown in Figure 1.

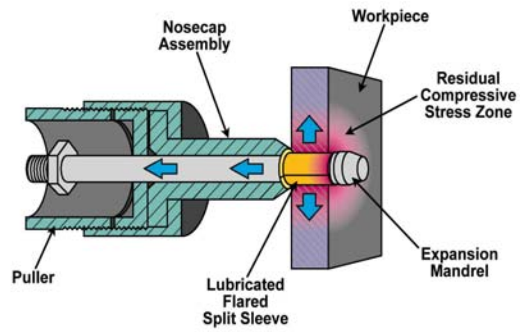

Figure 1: Split Sleeve Cold Expansion Process

The magnitude of the peak residual compressive hoop stress is about equal to the compressive yield stress of the material and the zone of compression typically spans one radius to one diameter from the edge of the hole as shown in Figure 2. Fatigue life improvement from this process usually ranges from 3 to 10 times in typical aircraft structures for aluminum alloy and also titanium [2].

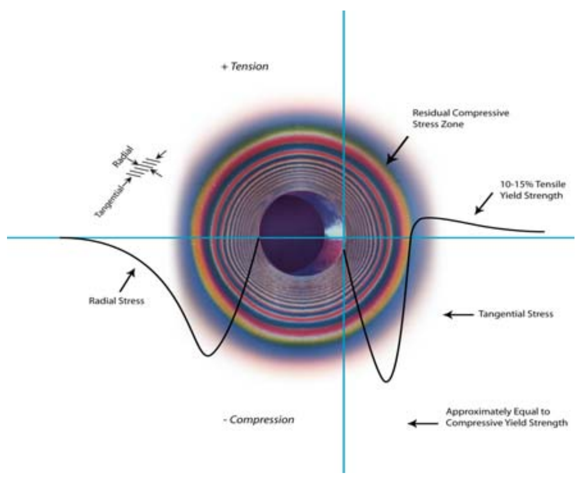

Figure 2: Typical Residual Stress Distribution Around a Cold Expanded Hole

2.2 Enhanced Durability and Damage Tolerance

The cold expansion residual stresses reduce crack growth rates by reducing the stress intensity factor range (ΔK) and the stress ratio (R, min. stress/max. stress) [3]. The stress intensity factor is a measure of the stresses acting at the crack tip. Additionally, the presence of residual stresses may change the critical crack length for unstable fracture, because it reduces the static stress intensity factor. The reduction in crack growth rate and the increased critical crack length significantly improves the damage tolerance of the structure [4].

What this means to the operator is that most airworthiness authorities require inspection thresholds be established for single-load path structures based on crack propagation analysis assuming a small manufacturing flaw exists at critical holes. In the past, particularly on military aircraft, initial manufacturing damage was simulated by a 0.050-inch radius corner crack or "rogue flaw." In addition, 0.005-inch cracks were assumed to exist at each fastener hole, representative of equivalent initial quality, for continuing damage calculations.

When fatigue-enhancing systems such as hole cold expansion are used, the rogue flaw (0.050-inch crack) has been simulated by a smaller crack to determine the residual crack growth life. The United States Air Force (USAF) damage tolerance specifications (USAF specification, MIL-A-87221) allow the design of a cold expanded (Cx) hole to be based on analysis for the same size non-cold expanded (NCx) hole with a reduced initial assumed flaw. In this case it is typically a 0.005-inch radius corner flaw. The result is a very conservative approach, as shown in the example at Figure 3 based on FTI test data for 2024-T3-aluminum alloy.

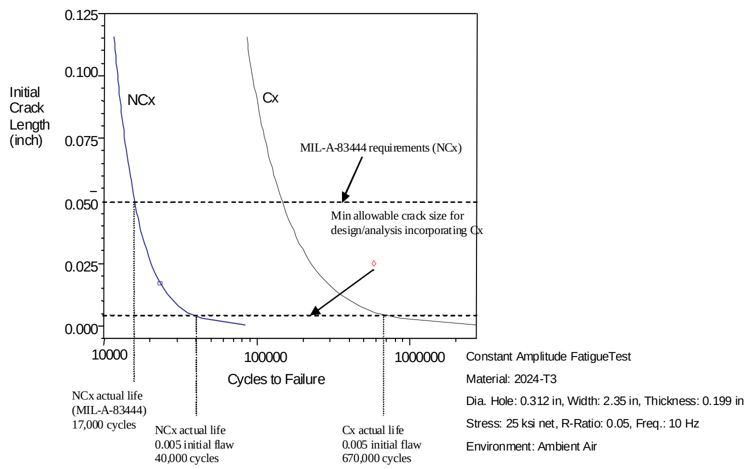

Figure 3: Reduced Initial Flaw Assumption Versus Test for Pre-Cracked Cold Expanded Holes

2.3 Cold Expansion Applications

Hole cold expansion is used in major fatigue prone locations such as the lower wing skin attachment, leading edge attachment, fuselage joints, critical sub-assembly attachments and anywhere where cyclic fatigue loading occurs. It is also used extensively in structural repairs and service life upgrade programs to extend structural inspection intervals, as terminating repair action and to mitigate the effects of fatigue or corrosion damage. Examples of these were presented at the previous conference [1]. By way of example, when the KC-135 had the wing skins replaced due to fatigue and corrosion problems, the new material skins were installed with all the lower wing skin holes cold expanded to ensure fatigue at the joints and attachment holes would not be a recurring problem. In the twenty years hence there have been no reported cracks at these locations. For most military aircraft now, whenever fatigue cracking in tension joints is found the subsequent repair invariably calls for cold expansion of the repaired holes, even when reinforcing doublers are installed.

2.3.1 Cold Expansion in Compressive Dominated Load Environment

As previously discussed, split sleeve cold expansion is commonly used to enhance the fatigue life of holes subjected to cyclic tensile loads. However, more recently the use of cold expansion in holes subjected to compressive loading has increased. Typical areas would be upper wing surfaces where ground taxi loads induce high cyclic tensile stresses leading to long term tensile fatigue cracks. These locations are typically under compressive load in flight. As aircraft are aging, and in many cases exceeding their original design life, the structure is accumulating many more fatigue cycles and therefore exposing certain locations to the onset of fatigue cracks. The concern is that the interaction of the compression loads would be compounded by the induced compressive residual stresses from cold expansion and therefore the cumulative compressive stresses may exacerbate the situation leading to premature tensile or compressive yielding around the hole.

A number of studies [5, 6] were conducted to investigate the effect of compression load spectrum on the residual stress field. While a reduction in overall fatigue life was shown the residual stress field from cold expansion increased the overall compression spectrum fatigue life; even in filled hole coupons tested with pre-flaws of 0.050”. An application where it is used is in the B-52 upper inboard wing where the upper tensile stresses reach +25 ksi during ground maneuver and compression stresses of -20 ksi in flight.

3.0 DERIVATIVE PROCESSES

In the previous paper [1], derivative cold expansion processes were introduced. These included ForceMate® (FmCx™) developed by FTI [7], which radially expands an initially clearance fit bushing into the hole using a tapered mandrel as shown in Figure 4. The process simultaneously installs the bushing with a high interference fit, up to 0.25 mm (0.01 inch) and in most cases imparts beneficial residual compressive hoop stresses to the material surrounding the bushing.

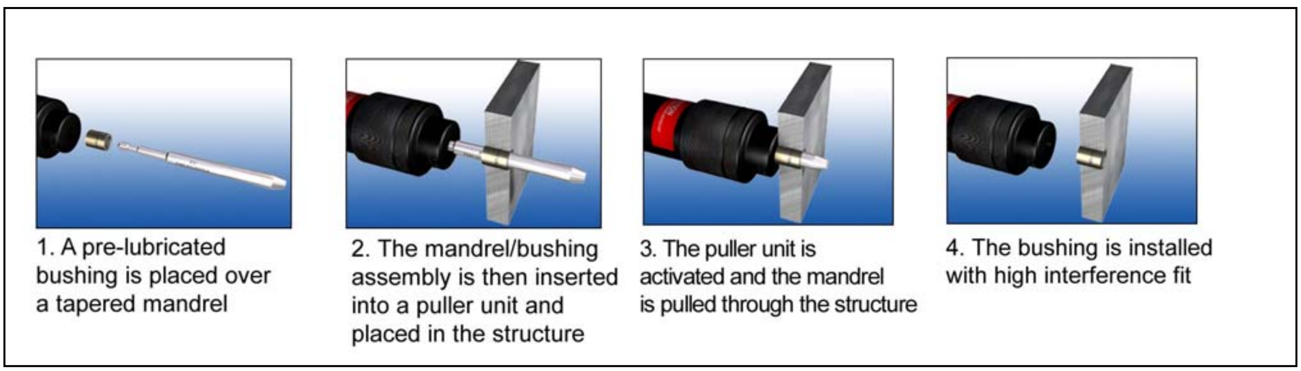

Figure 4: The ForceMate Bushing Installation Process

The other process was a cold-expanded rivetless style nut plate, adapted from the previous bushing installation method that utilizes a nut retainer that is cold expanded into the fastener hole. This fastener system, known as ForceTec® (FtCx™), is shown in Figure 5. The retainer has an integral “basket” and clip that retains a standard nut that is inserted after the retainer is installed. The combined effect of the high interference and residual compressive stresses from cold expansion, prevent rotation of the retainer and also provide significant fatigue and crack growth life improvement of the structure.

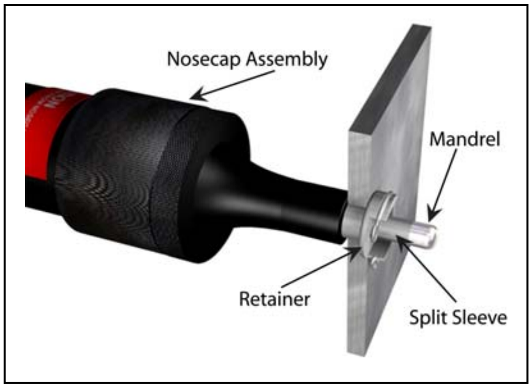

Figure 5: Schematic of ForceTec Retainer Expansion

Both of these processes provide significant improvement in fatigue and damage tolerance of the installation, whether it is for a bushed hole in a lug or fitting or a structural or access panel attachment. They greatly enhance the integrity of the installation and have been shown to be particularly effective in providing permanent repair methods in a number of aging aircraft applications.

3.1 ForceMate Bushing Applications

The ForceMate method has become the industry standard for attaining the maximum structural benefits and performance of bushing installations. In the aerospace industry, ForceMate bushings are used in attachment of aircraft wing and tail planes, engine and weapons pylons, landing gear, wing fold fittings and rotating components in helicopters. In helicopter rotor systems, ForceMate bushings have facilitated attainment of the flaw tolerant requirement imposed by the regulatory authorities without increasing the size of the rotor and therefore did not change the dynamics of the system [8].

3.1.1 Life Extension Using ForceMate in Engine Pylon Attachment

ForceMate bushings are used to replace migrating bushing in highly loaded engine, weapons pylons and landing gear pylons. In one particular commercial aircraft engine pylon attachment the use of the expanded bushing resulted in an almost five fold extension of the inspection cycle, as illustrated in Figure 6, as well as a significant reduction in the downtime to incorporate the upgraded ForceMate bushing repair. This extension of the inspection cycle provides significant maintenance cost savings to the operator.

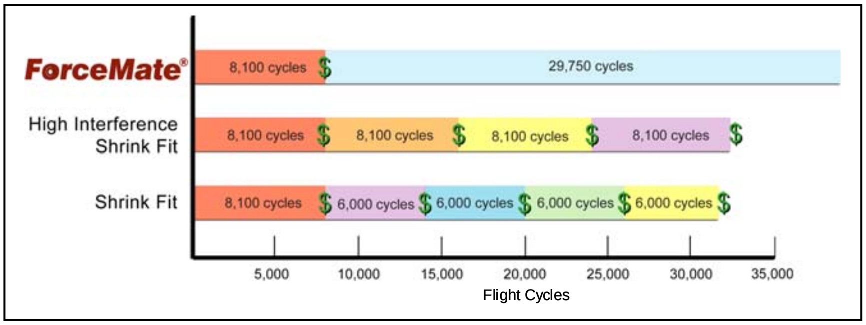

Figure 6: Increase in Re-Inspection Interval after Installation of ForceMate Bushing in B-767 RB211 Engine Pylon

3.1.2 C-130 ForceMate Repairs

The C-130 has benefitted from a number of insitu ForceMate bushing repairs that have avoided major structural replacements. The most significant is the inner to outer wing joint “Rainbow” fitting. Originally, very minimal or no repairs were allowed to the holes in the joint fitting shown in Figure 7 which led to many fittings being replaced when corrosion pits were found. USAF evaluation showed that damaged or corroded attachment holes could be cleaned up and re-sized back to the nominal fastener size using ForceMate expanded bushings. The study showed that installation of ForceMate did not compromise the static strength of the fitting. Besides the considerable maintenance time saving by being able to rework the damaged holes with the fitting left in place, the cost of the repairs was significantly less. Furthermore, it precluded the possibility of causing secondary damage to the wing in the process of removing this critical fitting.

Figure 7: C-130 Rainbow Fitting

Again on the C-130, the engine support structure includes left and right truss mounts connected with a diagonal brace assembly. Both the truss mount and braces comprise bushed lugs. Fatigue failures of the truss lugs necessitated either repair or truss replacement, requiring additional depot level maintenance. Analysis of this application showed the improved fatigue life with ForceMate over press fit bushings was “many times greater” and with increased allowable rework limits from 0.63 inch to 0.75 inch. The only challenge was that the bushed hole is a stepped configuration and the bushing sits on a bottom land. This poses problems in bushing removal/installation and was not ideally suited for a ForceMate bushing repair. Utilizing a unique expanding inner sleeve to install the ForceMate bushing overcame the problem and it is being used extensively in repairs to these lugs.

3.1.3 Corrosion Repair on F-15 Weapons Pylon Attachment

Corrosion repairs are common on most aircraft and there are a number of repairs where use of ForceMate expanded bushing have allowed major repairs to lugs and pylon fittings. As mentioned previously, this invariably has permitted larger repair rework limits, thereby saving major structural replacement. One such example is the F-15 weapons pylon where a large 5.5 inch (140 mm) diameter ForceMate installed bushing facilitates repair and resizing of the hole back to nominal as shown in Figure 8. The high interference fit also eliminated the potential for fretting fatigue failure of the pylon itself. The bushings are manufactured with a thermosetting epoxy resin (Bluecoat©) on the outer diameter as an effective anti-fretting coating.

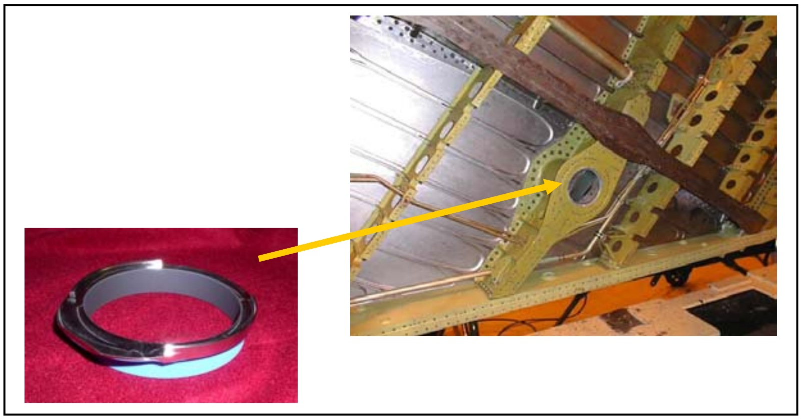

Figure 8: F-15 Weapons Pylon ForceMate Bushing Repair

3.1.4 F-16 Wing Rib Pylon Attachment ForceMate Repair

On the F-16 wing rib pylon attachment, the current bushed hole has a severe pitting/galvanic corrosion problem because it is on the upper wing surface. The upper facing “cup” bushing retains water and it cannot drain or allow the water to evaporate. Current inspection of this pylon is every 300 hours. Primers and coatings and sealants have not corrected the problem which, if it gets serious enough, necessitates wing removal and a 6 weeks overhaul, at considerable cost and loss of aircraft availability. After significant engineering effort, FTI was able to design a ForceMate bushing and hole cold expansion repair solution that could be incorporated with the wing on the aircraft. It can also be incorporated in three days. Because of the initial clearance fit of the ForceMate installation the necessary protective coatings on the bushing and the hole are more effective and eliminate the galvanic corrosion potential. Not only is the repair less costly and increases aircraft availability there is also a reduced recurring maintenance cost because the 300 hour inspection of this fitting is eliminated.

3.1.5 Commercial Aircraft Bushing Migration/Corrosion Repair

In another application on a commercial aircraft horizontal stabilizer attachment, where in-service migration of the bushings had allowed moisture ingress and corrosion of the attaching lugs, ForceMate was thoroughly tested as a means of preventing bushing movement. The high interference fit, in combination with the induced residual compressive stresses, produced a repair that not only eliminated bushing migration but also extended the life of the fitting by a factor of over 10:1 by eliminating fretting induced fatigue of the lugs. Furthermore, a unique “double flanged nested bushing” configuration of the ForceMate method was used in the repair that further improved corrosion resistance and showed it to be a superior method of installing the bushings in the lugs. The results of the installation under qualifying testing including fatigue, torque, pushout and vibration, qualified the installation for production as well as fleet retrofit.

3.1.6 Upper Wing Surface Compression Load ForceMate Repair

Installation of ForceMate bushings is also an excellent way to support open holes subjected to high compressive loads such as those in upper wing surfaces. An application on the center wing upper skins of the A-10 was reported at the 2005 USAF ASIP conference [9]. Cracks had initiated on the upper and lower sides of the fuel vent holes of the upper integral stiffeners of the wing skin. The magnitude of the compressive cyclic loads produced localized yielding at the top and bottom of the holes, which resulted in residual tensile stresses at these critical points. The magnitude of the loads and the fact that they were open holes precluded cold expansion of the holes as a repair option. ForceMate bushings provided reinforcement around the holes, prevented localized yielding and enabled the holes to be cleaned up and resized back to the original 0.375-inch holes. Rework bushings up to 0.625-inch diameter were shown to be effective in coupon tests. Using inconnel bushings enabled NDI re-inspection of the holes through the bushings. Estimated cost savings were $13,584 per aircraft (over $3M for the fleet) and inspection intervals for this location were extended to 8000 hours.

3.2 ForceTec Rivetless Nut Plate Applications

The ForceTec rivetless nut plates have been used to prevent and repair cracking associated with traditional riveted style nut plates on a number of military aircraft. As aircraft have been extended beyond their original design life or through increased service loading, cracking of otherwise non-life limiting attaching structure is now becoming an issue. Incorporation of these bushing style expanded nut plates have not only economically facilitated repair of existing structure but have eliminated the need for ongoing inspection of many critical locations. They have also been used to avoid major structural replacement as a result of damaged and/or ovalized riveted nut plate holes.

3.2.1 F-15 Ovalized Rivet Hole Repair

An example of this was on a vertical tail leading edge spar where damage had necessitated replacement of the spar before a new leading edge could be installed. The bushing nature of the ForceTec nut plate allowed the holes to be resized back to a nominal fastener hole (Figure 9). The cost saving in avoiding the leading edge spar replacement, with the additional substantial maintenance downtime, increased aircraft availability without compromising performance or safety.

Figure 9: Use of ForceTec to Resize Ovalized Holes in a Leading Edge Spar

3.2.2 F-16 Fuselage Access Panel Nut Plate Cracking

The previous paper [1] also discussed the use of ForceTec to repair fuselage access panel holes on the F-16. Cracks originating at the fastener hole under the riveted nut plate had limited the life of the fuselage. Removal of the riveted nut plates, cold expansion of the satellite rivet holes and plugging them with a sold rivet, then opening up the fastener hole and expanding a sealed ForceTec nut plate corrected the problem.

Full scale coupon testing showed the repaired life was extended from around 3000 flight hours to over 13,000 hours. Most F-16s have been reworked and all new production aircraft incorporate ForceTec in this location.

3.2.3 P-3 Orion Engine Nacelle Nut Plate Cracking

During full scale testing of the P-3 aircraft cracking was found in the lower wing skin initiating from satellite rivet holes used to attach riveted nut plates in the location of the under wing fillet fairing attachment. This area was not currently inspected and no cracking had been reported in the fleet. Initial fleet inspection found 9 of 10 aircraft with cracks. The proposed repair method was to install large doublers in the region. Replacing the riveted nut plates with ForceTec was introduced as a solution because they would effectively remove the incipient cracks from the fastener hole with the bushing like retainer. This ForceTec repair was incorporated at all the cracking locations on the full scale fatigue test article. A series of parallel coupon tests were conducted using baseline configuration nut plates and representative edge margin geometries. Crack detection began at around 6000 hours, similar to the full-scale test. These coupons were repaired, as were others with short e/D (0.9) at 9000 hours, using ForceTec by cold expanding the rivet holes and installing the ForceTec retainer, simulating the test article repair. Testing continued to 45,000 hours (three lifetimes), with no further cracks. In the full scale test, the repairs using ForceTec were cycled to more than 28,000 additional hours without cracking [10]. Subsequently a fleet wide replacement of the riveted nut plates in these and many other locations on the P-3 aircraft is on-going as a preventative measure to avoid major doubler repairs in the future. It is deemed to be terminating repair action with no further inspections required.

3.2.4 Other Nut Plate Repairs

There are many other locations on military aircraft where riveted nut plates have been replaced with the ForceTec rivetless nut plate to correct corrosion problems such as discussed in Section 3.1.3 on the F-15 wing leading edge as shown in Figure 10. On the H-60 helicopter main floor beam, corrosion from the riveted nut plate holes had exceeded rework limits. By opening the fastener holes to accommodate the ForceTec nut plate retainer it removed the damage and saved replacement of the beam and an additional two weeks unscheduled maintenance. ForceTec nut plates have also been used for field and depot repair where adhesively bonded nut plates have dis-bonded under in-service loads or when tightening the nut on assembly. To eliminate future repair down time that does not include time consuming preparation and re-bonding of nut plates, they are being permanently replaced with ForceTec.

Figure 10: ForceTec Nut Plate Retainers on F-15 Outboard Leading Edge

3.3 Blind Fastener Repairs

A further derivation of the expanded fastener concept is a blind installed nut element. The TukLoc system was developed, again using the proven cold expansion technology. A lightly countersunk hole is used and TukLoc is installed in the structure by radially expanding the nut body into the hole. Simultaneous collapse of the back of the nut and the expansion creates an interference fit that is resistant to torque and pushout. The fit is fuel tight when the sealed nut version is used as shown in Figure 11.

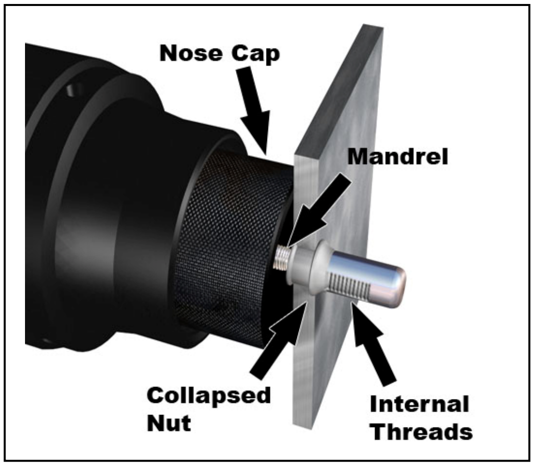

Figure 11: Schematic of Sealed TukLoc Installation

The high interference fit and hole resizing capability of the TukLoc installation facilitates field repair of blind holes and can significantly improve aircraft availability by eliminating fuel leaking as a major cause of unscheduled maintenance when the sealed version is used.

3.3.1 F-16 Wing Fuel Leak Repair Solution

TukLoc has replaced NAS1734 elliptical press nuts used to attach the inboard wing attach fittings on the USAF F-16 fighter aircraft that had notoriously been a source of fuel leakage. Additionally, fatigue cracks had developed from these NAS1734 holes during full scale fatigue testing. In coupon testing, the combination of cold expansion and the interference fit of the TukLoc installation showed a life improvement over the NAS1734 nuts. TukLoc provided a fuel tight blind fastener for this F-16 application, and some incorporation in the USAF fleet wing fuel leaks have been eliminated. On-going studies to further improve the fatigue life by possibly installing an intermediate ForceMate bushing into the hole before installing the TukLoc nut also has shown a significant life improvement.

The results from the previous evaluations, as well as other load transfer tests, have shown that TukLoc can be an effective repair solution for “blind” joints when the hole or the attaching fastener is damaged. Oversizing of the hole to install TukLoc removes any incipient damage from the hole and if necessary a specially designed TukLoc nut that accommodates a countersunk fastener effectively replaces the original joint fastener. This again provides an option for field repairs or provision of a blind threaded structural attachment.

4.0 SUMMARY

Split Sleeve Cold Expansion has successfully eliminated fatigue failure as a structural life-limiting characteristic in numerous aerospace applications. Many years of testing and in-service experience have shown that the compressive residual stresses imparted in the material surrounding holes by the split sleeve cold expansion method have extended the fatigue and crack growth lives of numerous aging military and commercial aircraft.

Benefits derived from use of this process include: (1) added safety and operational assurance through improved structural integrity, both in production and repair; (2) reduced maintenance costs by eliminating fatigue problems associated with fastened joints; (3) reduced inspection costs, by extending inspection intervals resulting from the enhanced durability and damage tolerance of the structure; (4) providing terminating repair action, and (5) possible structural weight savings.

Derivative processes such as ForceMate high interference bushing installation use the cold expansion principle to prevent bushing migration, fretting and corrosion and enhance the overall durability and damage tolerance of bushed installations and assemblies. The ForceTec rivetless nut plate system uses the beneficial residual stresses to improve nut plate installations and remove a potential source of structural fatigue failure. These expanded bushings and rivetless nut plates can be used to repair damaged or defective holes in existing structures to generate terminating repairs, and thereby avoid costly structural replacements. The cold expansion processes can effectively and economically be used to sustain an aging aircraft fleet by extending the fatigue life and damage tolerance of the structure without compromising structural integrity, airworthiness or the operational role of the aircraft.

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