Enhanced technology repair for corrosion and fatigue damage in hybrid aerostructure

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Abstract: The cold expansion method has been successfully used in aerospace structures to repair and prevent fatigue damage for more than 50 years. In 2022, PartWorks completed the first part of an innovative program for the United States Air Force using a new process incorporating cold expansion to repair corroded fastener holes (U.S. Patent 11,255,371) on aerostructures. This paper summarizes the experimental and analytical results of that development and demonstration program. In addition to addressing the corrosion issue, another critical goal of this program is to find ways for OEMS and operators to take credit for the compressive Engineering Residual Stress (ERS) imparted during the process. A part of getting life credit from ERS requires documenting that each fastener hole is processed correctly and ensuring the correct holes were processed. A data record with process data that shows this should be captured and included in the digital thread of that aircraft.

Locations in aerospace structures that have composite and metallic interfaces have demonstrated some of the highest levels of corrosion when compared to all-metal structures due to galvanic corrosion between metal and carbon fiber composites. The existing repair methods for these metal/carbon fiber composite skin bolt hole/fastener sites usually involves extensive removal of corrosion resulting in non-standard or oversized holes and extensive modeling/validation to prove repair effectiveness. The existing repairs can also lead to premature structural component replacement. This new repair method uses cold expansion with thin wall bushings and/or a rivetless nut plate (RNP) to restore fatigue life to the metal bolt hole even if some corrosion damage is missed and has the potential to expand to applications where corrosion is minimally removed.

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Keywords: Cold Expansion, Engineering Residual Stress, corrosion, hybrid

BACKGROUND

The repair of highly corroded fastener holes is an urgent problem as the US Department of Defense (DOD's) fleet of aircraft with hybrid airframes ages. Between FY17 and FY20, corrosion costs for the US Navy F-18 fleet accounted for $2,086,796,55, which is 29.4 percent of the total maintenance cost for [F-18C-G] aircraft (1).

Corrosion of fastener holes is commonly caused by aluminum coming into electrical contact with carbon fiber composite skins, which creates a galvanic reaction that corrodes the metal. Past experience with the F/A-18 found that this type of galvanic corrosion of fastener holes is more severe than the corrosion experienced by all-metal aircraft in maritime environments. Work on this process began with a development and demonstration program for the ONR to show the potential for the repair.
USAF fixed wing and rotary wing aircraft that use fasteners to attach composite skins to metal substructures, such as the F-22, F-35A/B/C, V-22, and RQ-4, experience the same galvanic corrosion issues as the F/A-18 and require similar repair solutions. In 2021, the USAF awarded its first contract to PartWorks to further develop and demonstrate a repair system. The repair process is designed to, lower the repair/sustainment costs for USAF by increasing the fatigue life of corroded parts. This first phase of work was accomplished via eight tasks over a two-year effort and subsequent projects are planned to further refine and qualify the new process.

The first task that PartWorks performed was to survey the USAF fleet and repair depots to determine the requirements for the program, including the level of corrosion damage that should be included in the test program. Then a corrosion protocol was developed to corrode specimens in the lab to simulate damage found in the fleet. PartWorks used digital image correlation (DIC) adn X-ray diffraction (XRD) to measure the residual stress imparted into the structure during the cold expansion process. The residual stress measurements were correlated to analysis predictions using Finite Element Analysis (FEA). The validated FEA model could then be used to predict residual stresses across multiple tests without experimental data. Partworks also developed an improved adhesive/sealant to limit further corrosion.

From an operational level, the process that PartWorks is developing is intended to be less expensive and faster than conventional repair methods. The process utilizes standardized and easy-to-use tools and supported by modeling and fatigue data to result in sped up repairs and provide confidence to those responsible for aircraft structural integrity about the viability of the repaired corroded fastener hole. Partworks is also making progress capturing process data in-situ and post-intall which could allow for life extension credit to be taken for the repair.

TECHNICAL APPROACH

As mentioned, metal frame to carbon fiber skin airframe design is inherently susceptible to galvanic corrosion as the carbon fiber in the composite skin come into electrical contact with the metal substructure and cause galvanic corrosion around and down the bore of the fastener hole. As the corrosion damage accumulates, it can originate fatigue cracks and compromises the strength of the substructure.

Modern aircraft use thousands of fasteners, which makes the detection and repair of corroded fastener holes a costly and time consuming effort. See Figure 1 for an example of the galvanic corrosion found at fastener holes in aluminum alloy substructures after the carbon fiber skins are removed.

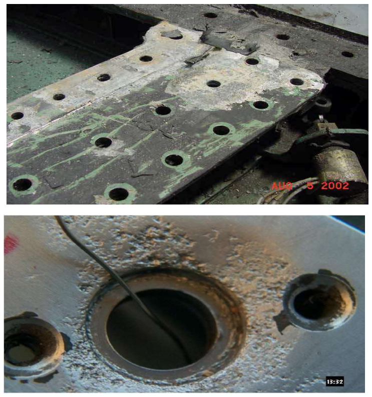

Figure 1. Fastener Hole Corrosion

EXISTING REPAIR APPROACH

The current practice for repairing corroded fastener holes involves removing the surface corrosion via grinding and repeatedly reaming the fastener hole (i.e. increasing the hole's diameter) until corrosion pits or cracks in the bore are no longer detected. An additional 0.03" is then typically reamed from the fastener hole as insurance against undetected damage. Once the diameter of the reamed fastener hole is determined, a very high tolerance custom designed bushing is fabricated with the necessary wall thickness required to restore the fastener hole's diameter to its original dimensions. A shrink or thermal fit process is used to install this bushing which involves soaking the close tolerance bushing in liquid nitrogen (approx. -320F) to thermally "shrink" the bushing prior to being inserted or pressed into the close tolerance hole. As the bushing warms to room temperature, it expands to create a very low interference fit with the bore of the fastener hole. It does not expand sufficiently to permanently cold expand the surrounding metal (i.e., no yielding of the surrounding metal) resulting in a limited and unreliable fatigue life benefit. For example, in the case of a standard NAS75, 1/4" ID bushing (0.3761+.000/-.001" OD after plating) installed into a 0.3750 +.0005/-.0000" hole, could result in a diametral interference as low as 0.0001". The interference may also include any sacrificial bushing OD plating. This low of an interference does not introduce cold working (i.e. cause the surrounding metal to yield) and no reliable fatigue life benefit is expected. The introduction of condensate into the structure may also act as a source of corrosion.

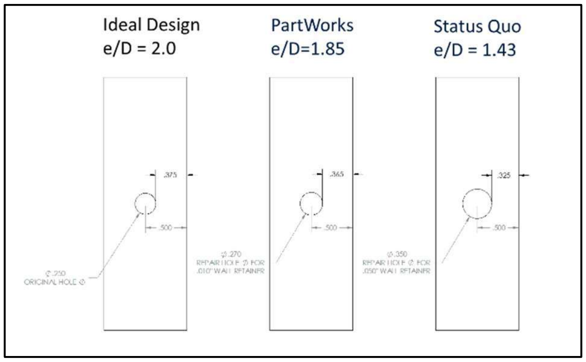

Figure 2. Demonstrating e/D distance for a typical repair

One of the disadvantages of the current repair process to the parent structure is that the reaming process may significantly decreases the hole edge distance (e/D), where e is the distance from the center of the fastener hole to the edge of the part and D is the hole diameter (

Figure **2**). In most cases decreasing e/D reduces the fatigue life of the aircraft structure. Typical aircraft design guidelines recommend that the hole edge distance be 2.0 or greater for new structures and at least 1.5 for repaired structures. Shrink fit bushing repairs can reduce the edge distance below 1.5 (a e/D below 1.5 is referred to as a short e/D condition) and hence reduce the fatigue life of the aluminum alloy substructure, especially for smaller holes. For example, if you have 1/4" hole with e/D=2 , and ream to 0.375" for a standard NAS75 (1/16" wall), the e/D goes from 2.0 to 1.33.

Because short e/D conditions are a common result of the currently used process for repairing fastener holes, a detailed analysis is then required for each corroded fastener hole repair. This process can take weeks or maybe even months of analysis time and enormous cost. For the F/A-18, the Navy found that repair and analysis can cost as much as $140K per fastener hole. The costs and time spent in a non-flyable state increase as the aircraft ages as more of repairs are needed. For the F/A-18, which was the first aircraft with hybrid airframe to be widely deployed in a corrosive environment (at sea), a substantial number of the F/A-18 A-D models have been scrapped because of the time and high cost of repairing galvanic corrosion of the aluminum alloy substructure. The F/A-18 can be viewed as the “canary in the coal mine” for galvanic corrosion of fastener holes. This represents a threat to the readiness of any USAF aircraft with hybrid airframes and to a lesser extent, all aluminum airframes, as the fleet ages.

NEW REPAIR TECHNIQUE

PartWorks has spent the last several years developing a fast, low cost and standardized process for repairing fastener holes as shown in Figure 3. The steps for repairing the fastener hole with the PartWorks process are:

(1) Ream out a small portion of the inner surface of the fastener hole to remove some of the pitting that results from galvanic corrosion and begin with a standard hole size
(2) Insert a thin-walled bushing into the fastener hole that will restore the inner diameter to the desired size
(3) Insert a mandrel though the bushing and fastener hole
(4) Cold expand the bushing into the inner surface of the fastener hole with the mandrel, introducing a high interference fit and inducing plastic strain around the hole.

As the mandrel is removed, the hole and bushing contract elastically which puts the volume around the fastener hole under compressive residual stress.

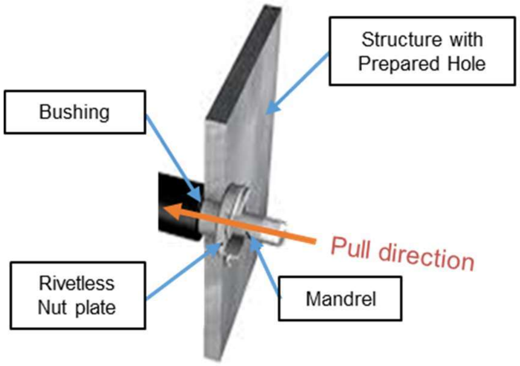

Figure 3. Repair of a corroded fastener hole

For this most current program for the USAF, PartWorks is developing the process to meet airworthiness requirements and confirm that it will be significantly faster and cheaper than current repair processes. Further development of the process and the associated tooling will result in a more automated process of caturing the necessary data to certify that each fastener hole has been properly repaired in order to receive credit for service life extension for the aircraft.

TECHNICAL DISCUSSION

The cold expansion process has been used by the aerospace industry for over 50 years to enhance the fatigue life of aircraft structures (2) by imparting compressive Engineering Residual Stress (ERS) around fastener holes. This compressive stress delays formation of fatigue cracks and retards the growth of existing cracks (3, 4) if they do develop. The fatigue life improvement from ERS has been shown to provide a three to greater-than-tenfold improvement over non-cold expanded repairs. However there is little data to show that cold expanding corroded fastener holes improves the fatigue life of the aircraft structure (5).

Given the challenges associated with galvanic corrosion of metal to composite fastened interfaces, this USAF project tested the fatigue life improvement of corroded vs. uncorroded holes with and without a thin-wall rivetless nut plate cold expanded into the hole. Test specimens were fabricated as follows:

Table 1. Specimen Configurations

	Corrosion	Clean up Ream to Size	Nut Plate
Bare Hole	No	No	No
Corroded Bare Hole	Yes	No	No
Baseline Repair	No	Yes	Yes
Corrosion Repair	Yes	Yes	Yes
Pre and Post Corrosion Repair	Before and After Repair	Yes	Yes
Fast Corrosion Repair	Yes	No	Yes

The test specimens were fatigue tested under a constant amplitude with different load levels representing worst cases (high load) and for F-35, F-22 fatigue load spectrums with various scaling.

The cold work process and the resulting benefits must be proven to be stable, reproducible, have characterized properties, demonstrate predictable performance and support a method for fatigue life extension credit. The latter is a particular difficult challenge as predicting the fatigue life benefit of the process requires accurately quantifying the level of residual compressive stress in the structure.

The cold-work process of PartWorks ensures a stable result with consistent and repeatable quality and predictable costs for implementation. For this project, the mandrel pull force is recorded by the puller and correlated to the level of expansion and hence the expected compressive ERS around the fastener hole. This is the first of many possible quantifications of the process validation that will be explored. By establishing a method to validate the level of ERS using process parameters, the need for complex systems to measure the residual stress (e.g. x-ray diffraction) can be avoided as they are impractical for production. This project also included a non-destructive evaluation method using Digital Image Correlation (DIC) to verify a suitable ERS field has been established. A method of recording the hole location to indicate to QA that the fastener hole was properly processed was also developed and implemented by using Augmented Reality (AR).

In order to ensure the thin-walled bushing and rivetless nut plate met the torque and pushout requirements, an adhesive/sealant can be applied. The adhesive properties are especially important in scenarios where the thin-walls of the bushing and nut plates are installed into thin parts of structures such as large sections of airplane skins. The adhesive improves the ability of the rivetless nut plate to resist torque and pushout. In addition, a suitable adhesive will also act as a sealant to prevent moisture ingress to prevent further corrosion. This project developed a prototype of an easy to apply adhesive that required no extraordinary surface cleaning or preparation, cured at room-temperature and demonstated a high shelf life.

The process of installing a thin-wall rivetless nut plate involves an oversized mandrel being pulled through the the inside diameter to impart a large residual radial interference and impart the beneficial ERS in the parent material. High friction forces from this process are mitigated with the use of dry film lubricant on the inside of the thin-wall bushing. The PartWorks process uses a dry film lubricant with a very high, one-time lubricity to reduce the pull force required to pull the mandrel thru the hole.

Requirements Determination

In an effort to emulate the extent of the problem in the USAF fleet, PartWorks coordinated with the USAF to try and quantify the corrosion and fatigue problems in locations where composite and metallic structure are bolted together. This level of damage found in the USAF fleet was then replicated in this test program.

Corrosion Protocol

A critical part of this program was the development of a corrosion protocol that allowed fatigue specimens to be corroded to match the most severe level of damage identified in the fleet in a practical time frame. This protocol was developed by the University of Dayton Research Institute (UDRI) based on the prior work by Kelly & Burns at the University of Virginia. The severe corrosion that resulted is shown in Figure 4.

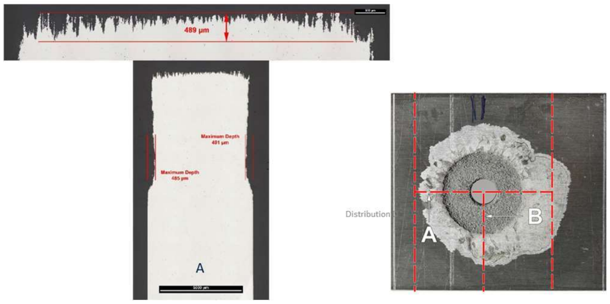

Figure 4. Corroded specimen

Engineering Analysis and Modeling

Finite Element Analysis (FEA) simulations of the nutplate were performed to predict the residual strain and stress generated during the cold-work process. The model consisted of the bushing, specimen, nosecap from the puller unit and mandrel as shown in Figure 5. A closeup of the finite element discretization is shown in Figure 6. The model was run in Abaqus® FEA software using the explicit method.

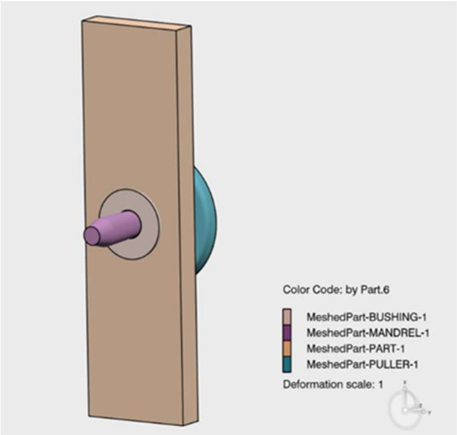

Figure 5. FEA Model

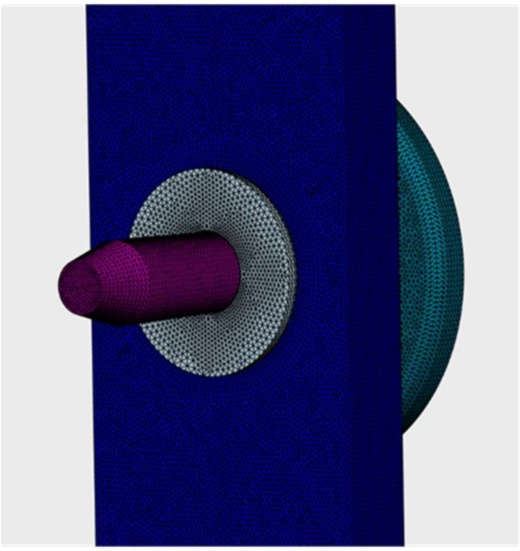

Figure 6. FEA Model Closeup

Contour plots of the residual hoop plastic strain and stress after the mandrel pull through are shown in Figure 7 and 8. The residual hoop plastic strain was tension as expected from the expansion due to the expansion of the mandre. The associated residual hoop stress was in compression near the hole and transitioned to tension away from the hole which is consistent with general understanding of the cold expansion process.

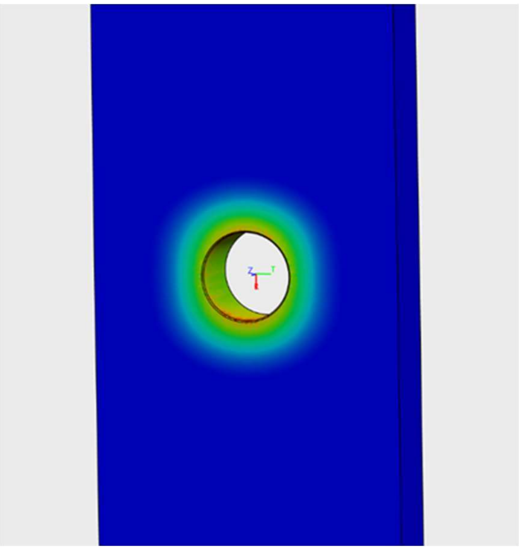

Figure 7. FEA Residual Hoop Strain

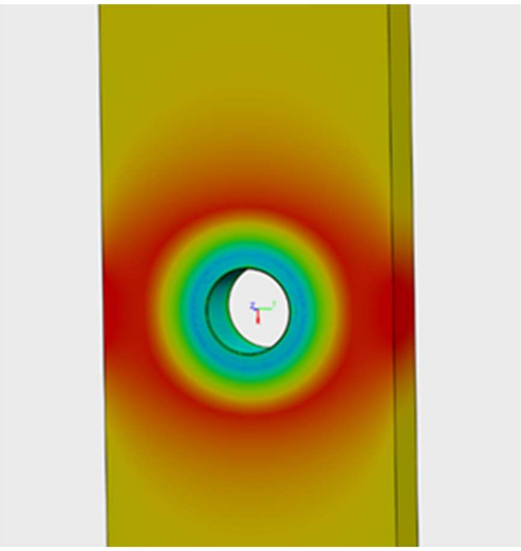

Figure 8. FEA Model Residual Hoop Stress

Digital Image Correlation

Digital Image Correlation (DIC) was used to capture the residual strain imparted during the cold expansion process. The DIC process is in widespread use in experimental mechanics where high sensitivity and non-contact are required. As a result it does not affect testing or influence the cold expansion processing. Results of the DIC method showing the measurements of the residual hoop strain during and after installation are shown in Figure 9 and 10.

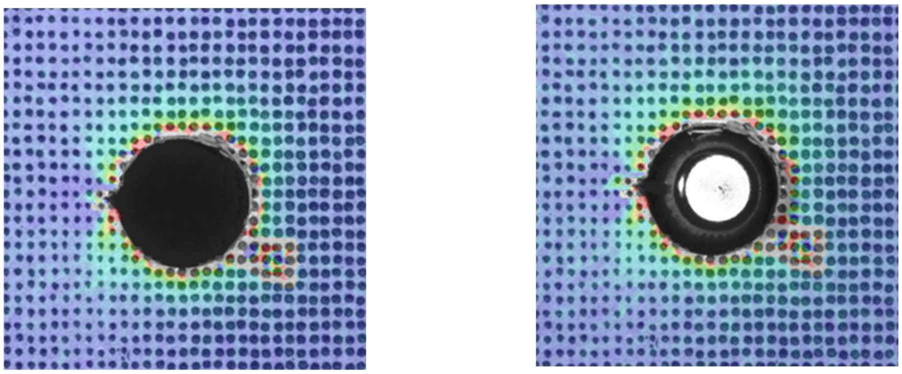

Figure 9. DIC Showing Strain During Expansion (left) and Residual Strain After Processing (right)

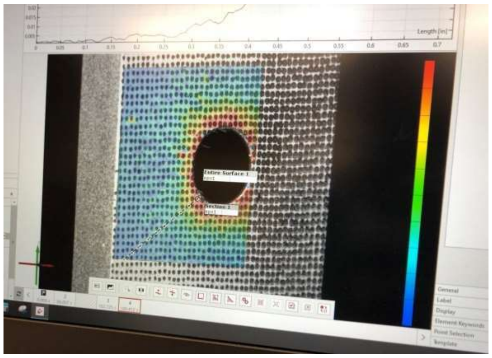

Figure 10. Residual strain visualization using DIC

Analysis

DIC measurements and FEA results along radial lines from the center of the hole were compared to validate the model as shown in Figure 11 and 12. The measured and predicted strain values showed good agreement. As expected, the residual hoop strain was highest at the edge of the hole and decreased quickly with radial distance. In the short edge margin direction, as shown in Figure 11, both the FEA and the DIC measured strains showed a fall off to a level of residual strain that was consistent all the way to the free edge indicating that the ligament was permanently stretched. The results in Figure 12 along the very large edge margin do not show this since there is more surrounding material to resist a permanent stretching of the ligament.

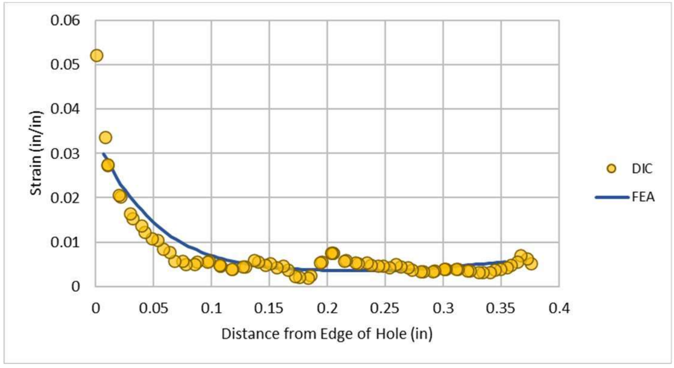

Figure 11. DIC Comparison with FEA Hoop Strain on Short Edge Margin

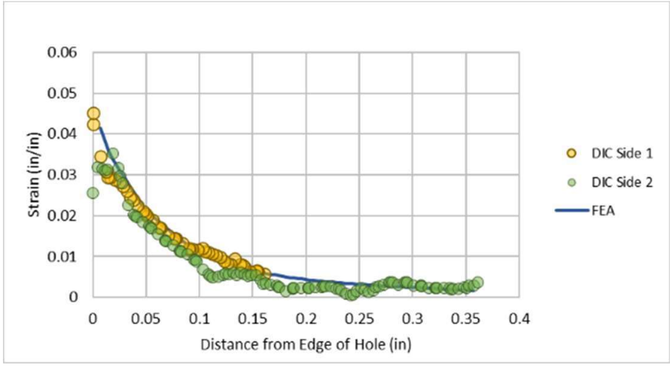

Figure 12. DIC Comparison with FEA Hoop Strain on Vertical

X-Ray Diffraction (XRD) was used to measure the residual hoop stress in the specimen after installation and compared with the FEA results to validate the model as shown in Figure 14. A good correlation was found away from the hole. The correlation closer to the hole was less consistent and indicate the possibility of the need for a more accurate material behavior model and study of other features that affect the residual stress at the surface in the model.

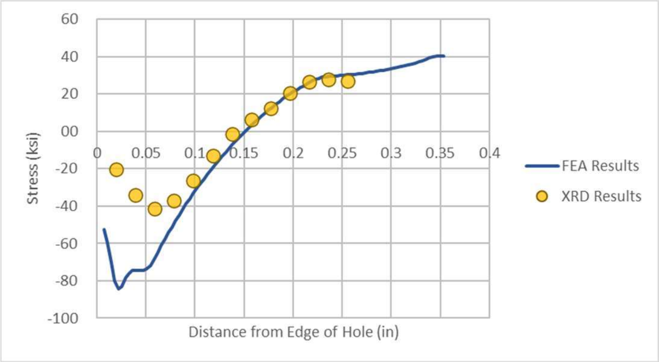

Figure 13. XRD Measurement Comparison with FEA Hoop Stress

The comparisons of the experimentally determined strain and stress showed good correlation with the FEA simulation but additional work is needed for correlating the surface stress measurements.

Fatigue Testing & Life Assessment of PartWorks Repair for Corroded Fastener Holes

To quantify the level of fatigue life improvement of PartWorks standardized repairs, test specimens were fabricated that replicate the material and fastener configurations for USAF aircraft of interest. Test specimens were purposefully corroded to mimic the types and ranges of corrosion per the protocol identified earlier. Specimens were fatigue tested with both constant amplitude loading and figher spectrum loading (Figure 15) to obtain the fatigue life of the configurations in Table 1 previously shown.

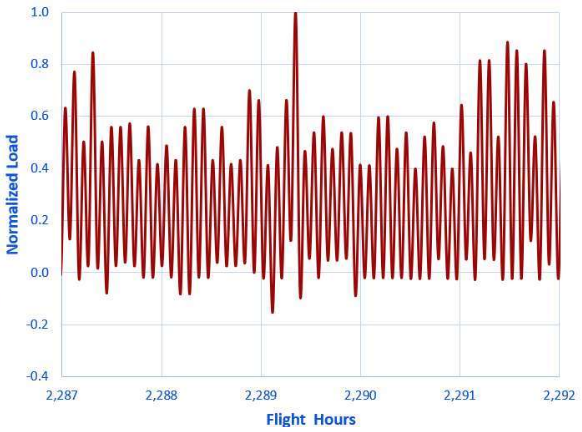

Figure 14. Typical fatigue test spectrum for fighter aircraft

Figure 15 shows fatigue data generated by PartWorks as part of this program. This figure compares the specimens outlined in Table 1 previously.

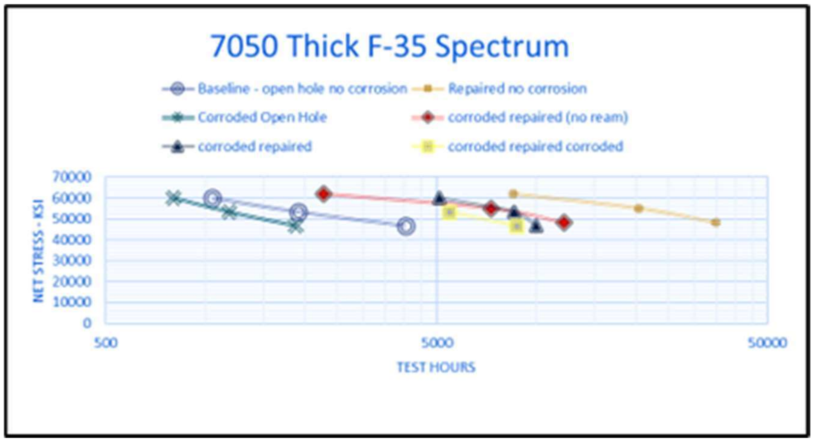

Figure 15. Fatigue Test Results for Repaired specimens – Corroded and Baseline

The PartWorks process increased the fatigue life for all specimens, regardless of whether it was corroded or how whether a ream of the corroded hole was performed. To better compare the fatigue life benefit across all specimen configurations, the open hole test specimen was chosen as a baseline to compare to as shown in Figure 16. As expected, an open hole subjected to corrosion showed a signficant drop in fatigue life. The hole with a nut plate without corrosion represents both a repaired hole without corrosion and a hole with an expanded nut plate during production. This demonstrated a very high life improvement over the open hole. All repairs with corrosion demonstrated very good life improvements, even if corrosion took place after the repair took place.

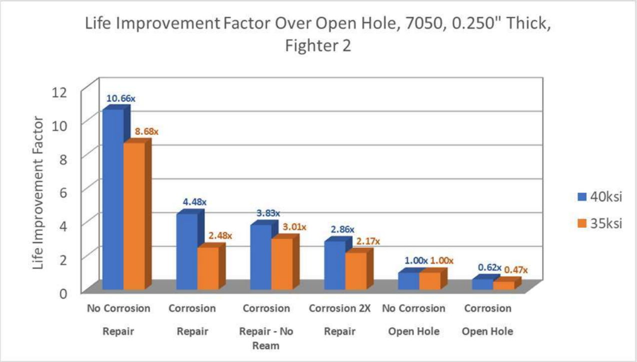

Figure 16. Fatigue Test Results for Repaired specimens – corroded and baseline

Adhesives and Lubricants

Standard practice in many cases is to apply a polysulfide sealant to a bushing or fastener when installed and hope that some is retained in the joint. Despite this, it has been shown over time that significant corrosion still occurs. As a result, one can conclude that the application of polysulfide is not sufficient for sealing in order to prevent corrosion.

In order to ensure the nut plate achieved the required resistance to torque and pushout forces for very thin gages of structures and to prevent moisture ingress post-repair, the thin walled bushing were coated with adhesive on the OD prior to install. This had the additional beneft of sealing the bore in the case of incidental pitting or corrosion defects being left inadvertently in the hole beyond the mechanical seal from the interference. More importantly, the area under the flange/nut plate head is sealed from further corrosion as it is not mechanically sealed like the bore of the hole due to the high inteference fit.

A test was performed to evaluate the ability of the adhesive/sealant to prevent moisture ingress post repair in-service. This phase of the program involved incorporating the PartWorks repair in a new part including adhesive/sealant on the OD of the repair bushing. The part was then fatigue cycled for 10,000 flights to explore the durability of the repair and bond. Then the part was put subjected to the severe corrosion protocol to evaluate if moisture or corrosion by-products would be exhibited down the bore of the hole or if the adhesive would act as a sealant. To check, the part was sectioned to look at the cross section of the bore afterwards. As seen in Figure 17, the unprotected portions of the part were severely corroded. However, even though the corrosion protocol affected the exposed surfaces of the part, the surfaces with adhesive under the flange and the bore of the hole were protected from corrosion.

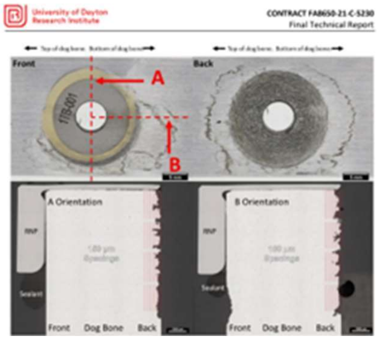
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Figure 17. Results of severe corrosion tests on the bore of a fastener hole.

Augmented Reality (AR)

Part of this project included research and development focused on using AR to record and document the repair for QA, maintenance and inspection of aircraft. Partworks demonstrated the use of extended reality (XR) interfaces (e.g. head-mounted visual displays, tablet-based AR, speech/gestural input, and/or body mounted touch interfaces) coupled with existing software and tools to enhance training, provide real-time job aids, aid in decision support, and provide automatic data collection for integrating into the digital thread.

Partworks and Georgia Tech (GTRC) developed the first phase of a maintenance aid AR system. For the first mode of selecting holes to be repaired, a manual operation can be conducted that allows an operator to prescribe which holes are to be repaired on screen, see **Error! Reference source not found.**18. Once the holes are selected, the operator or mechanic can proceed to install parts and the subsequent actions will be tracked and recorded by the tool.

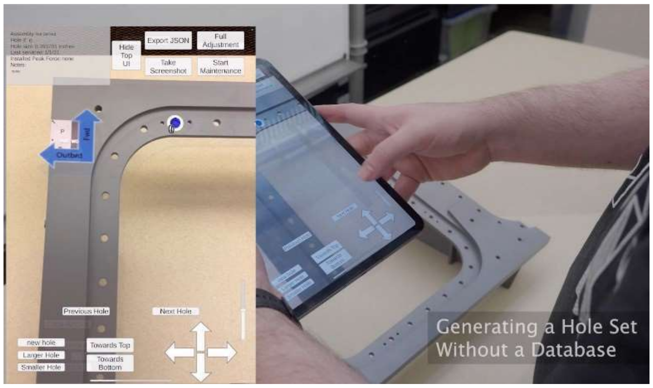
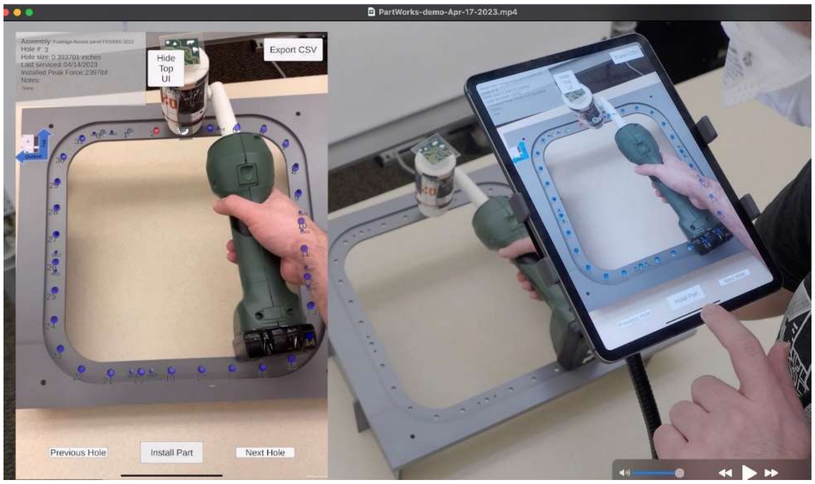


Figure 18. Manually Selecting the Holes to be Processed using AR

For the a second, more automated mode of operation, as seen in Figure 19 below, the system can read a data file or CAD model and pre-populatd the hole locations to be processed on the screen. The operator has an opportunity to correct any hole locations that may not have matched the database. The operator or mechanic can then continue with the repairs with the system tracking the processing of each hole and providing feedback for pass/fail to the operator.

Figure 19. Auotmatic Selection of Holes to be Processed using AR

Figure 20 below shows the feedback to the operator from the AR system that a hole had an issue with the installation as indicated by the red dot on the screen. The operator can then review discrepancies, open the datasheet on the table and comment regarding the hole flagged with the error indicator.



Assembly: Fuselage Access panel FS10000 3222
Hole #: 3
Hole size: 0.393701 inches
Last serviced: 04/14/2023
Installed Peak Force:2397lbf
Notes:
None

Figure 20. Error Notice of an Issue during Hole Processing

CONCLUSIONS

The results of the first phase of this project for the USAF found that thin walled rivetless nut plate / thin wall bushing repairs improved fatigue life, even for severely corroded specimens. Even in the worst-case scenario where corrosion damage is not removed from the fastener hole, the repair extended the fatigue life of the structure. The results also showed that capturing installation parameters (e.g. puller force) is possible and can be connected to the aircraft digital thread via AR. Work continues to evaluate other structural configurations but the results of this program indicate that there are significant benefits for this application of the technology.

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