THE INHERENT NEED FOR HOLISTIC STRUCTURAL INTEGRITY APPLICATION AND PROGRESS

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Abstract: The holistic structural integrity process (HOLSIP) has been gaining attention within structural integrity communities worldwide in recent years. HOLSIP involves accounting for elements beyond the safe-life and damage tolerance design paradigms, including physics-based and probabilistic model creation, as well as use of advanced non-destructive inspection techniques. Material microstructure, crack growth phases, Initial Discontinuity States (IDS), residual stresses, and environmental considerations are incorporated within this paradigm. Maintenance and unintentional damage also are a factor within the holistic framework. The end goal of HOLSIP is to maintain structural integrity by accounting for these factors and predict potential failures, including environmental impacts and time-based degradation, throughout the useful life of a system and is applicable to many industries, not just aerospace applications.
HOLSIP's practices are becoming accepted as problem solving methodologies to many of the aging issues affecting United States Air Force legacy aircraft fleets. This paper will detail some of the holistic approach advances used in the Aircraft Structural Integrity Program (ASIP) and other structural integrity organizations and focus on the progress which has been made in these efforts over the past 50+ years. Examples from the authors' experiences in F-16 sustainment will be used to explain how time-based degradation and failure modes must be accounted for throughout the life of the aircraft**.**

Keywords: Structural integrity, fatigue, aircraft sustainment, corrosion

INTRODUCTION

The word "holistic" is used frequently in many different settings, including in a structural integrity context, with all references indicating an overall view of a whole system, not just component parts. Understanding of the complete system and its varied interactions with itself and its environment should be accounted for as a critical part of the system design and sustainment. The holistic structural integrity process, or HOLSIP, is a physics-based, whole life structural design approach that considers all failure modes or mechanisms to be interconnected. This includes accounting for elements beyond the typical safe-life and damage tolerance paradigms. The process includes all aspects of the life cycle, including design, manufacturing, usage, and retirement. The intrinsic nature of materials, as well as extrinsic issues, such as loads, temperature, time dependent degradation, environment, contact, etc. are all considered within the HOLSIP paradigm.

Describing HOLSIP in terms of crack propagation is helpful for comprehension of what makes this paradigm different. The purpose of HOLSIP is to improve upon safe-life and damage tolerance through advanced physics-based and probabilistic modelling, as well as innovative non-destructive inspection (NDI). The process includes the whole life cycle including design, manufacturing, operations, retirement, as well as ethics. Figure 1 illustrates the various stages of fatigue crack growth (degradation) accounted for within HOLSIP, where modelling and crack detection capabilities become very important to understanding when, where, and how to inspect. Note that cracks can propagate from either an intrinsic initial discontinuity state (IDS) or form by a pure fatigue mechanism or other related process that may act concomitantly or sequentially with fatigue. Continuum mechanics continue to be used, but the limits of applicability are defined and are material and process specific. Discontinuities and heterogeneity in materials are key concepts.

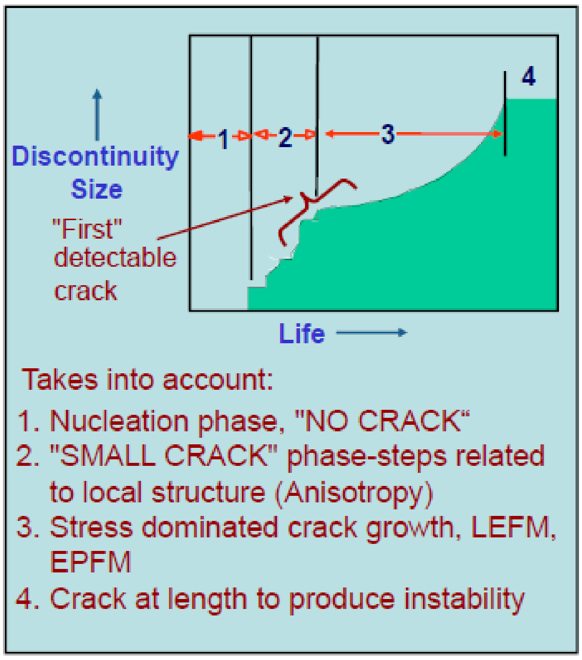

Figure 1: Depiction of the Degradation Process

Many HOLSIP practitioners are in the aircraft sustainment and related research fields, but HOLSIP can be applied to almost any system. Because of the physics-based modelling requirements, aircraft are a natural fit due to the significant amount of research that has been performed in related areas. Some of that research was performed by holistic minded individuals, ever working to advance HOLSIP into more applications.

HISTORY OF HOLSIP: OVER 50 YEARS AND COUNTING

The concepts of HOLSIP came about from many contributors for over 100 years, including many of the early fatigue and fracture mechanics pioneers. Griffith [1] noted that discontinuities existed in solids, which is a critical concept for holistic structural integrity. Many others, including Irwin [2], Orowan [3], Peterson [4], Neuber [5], Hartman [6], Crichlow [7] have also contributed to the HOLSIP framework through their research.

Dr. David W. Hoeppner, after giving a briefing to the Lockheed board of directors in 1971, was, as he put it, “fortunate to be taken aside after part of it and one of the corporate legal counsels suggested that I NOT use the word or concept of a crack or an intrinsic discontinuity as a defect or flaw.” The attorney later met Dr. Hoeppner and introduced him to a defect-based design in a legal context, which led to Dr.

Hoeppner pursuing the topic and doing all the research he could on the term and the concept. Dr. Hoeppner, as well as several others, have been proponents for the correct use of terminology. HOLSIP has its own list of terms and definitions, and Steve Swift [8] and Dr. Hoeppner [9-10] have various papers on the topic.

In 1971, Dr. Hoeppner spoke at the first International Symposium on Corrosion Fatigue where the keynote paper, "Corrosion Fatigue Considerations in Materials Selection and Engineering Design" [11], introduced corrosion, corrosion fatigue, creep fatigue, and fretting fatigue into engineering design. Figure 2 illustrates this use of a systems approach to design for corrosion and corrosion fatigue. This paper formed many of the initial HOLSIP concepts which would later be more formalized.

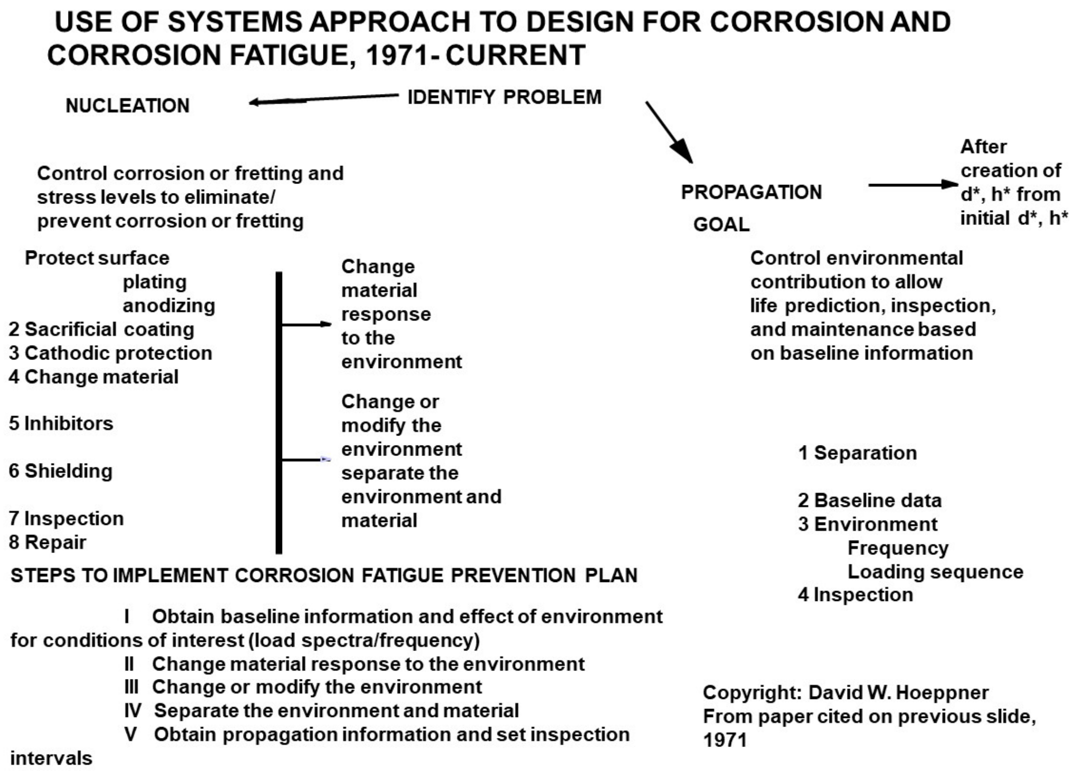

Figure 2: Hoeppner Systems Approach for Corrosion and Corrosion Fatigue

Significant research has been performed on IDS of aluminum alloys during the United States Air Force funded Corrosion Fatigue Structural Demonstration Program (CFSD) in the early 2000s, with Lockheed Martin Aeronautics as the prime contractor, and sub-contractors National Research Council – Canada (NRC), the University of Utah, and Analytical Processes/Engineered Solutions (APES), Inc. Much of this work focused on understanding basic fatigue research related to IDS, corrosion fatigue, and associated physics-based modeling. During the CFSD program, several individuals from these organizations (see Figure 3) began meeting to discuss holistic structural integrity concepts, and it was so successful and beneficial, that they expanded it to small workshop forum in 2002. These workshops have been held continuously for over 20 years, including virtually through the COVID pandemic. The group membership has changed over the years with several of the original core group retiring or passing away, but the HOLSIP workshop continues to flourish, adapt, and extend its reach to new attendees.

Figure 3: HOLSIP Founding Fathers (L-R: David Hoeppner (University of Utah), Jerzy Komorowski (NRC-Canada), Craig Brooks (APES, Inc.), Nick Bellinger (NRC-Canada)

20+ YEARS OF HOLSIP ADVANCEMENT

Holistic ideas and concepts have been presented widely in journal articles, at various conferences and other meetings over the past twenty years. With the overall world situation as it currently stands, aging aircraft continue to be flown well past their design lives, requiring more than the standard damage tolerance approaches to ensure structural integrity and safety. HOLSIP presentations and papers have not always been well-received by the masses, but the successes have been shown in various forums and continue to be used by organizations all over the world, with growing numbers of supporters. A few key papers/presentations are summarized briefly in this section; this is not meant to be an all-encompassing list, but to provide a guide for some important holistic structural integrity contributions.

Walter Shütz presented the 1995 Plantema Memorial Lecture on “Corrosion Fatigue – The Forgotten Factor in Assessing Durability” [12]. He pointed out the variability of corrosion’s influence on fatigue life and stated the opinion that researchers have focused too much on “electrochemical reactions between the corrosion agent and the material of unnotched specimens (or at the crack tip of cracked specimens); however the corrosion fatigue performance of actual components and structures up to now has almost been neglected.” His concern was for the behaviour of the structure under actual in-service corrosion fatigue conditions. These conditions should be approximated, with the appropriate corrosion protection system in place, as closely as possible. This includes leaving the component in the corrosive solution the entire time, even when not actively running fatigue cycles. If the full scale fatigue test is run under corrosion fatigue conditions, many of these concerns would be mitigated.

Nick Bellinger created a presentation entitled “The Age for Reason” in 2005, which was subsequently presented to various organizations in Canada, to the HOLSIP workshop, and to a University of Utah Mechanical Engineering 7070 class by Dr. David Hoeppner [13]. In the presentation, safe-life and damage tolerance paradigms are discussed, with failure examples. Issues related to the current design paradigms were discussed, with often unexpected failure complications from interaction of time-based failure modes, repair, new materials, and overall design. The Holistic Structural Integrity Process was introduced, with examples of success from its use.

Dr. Joseph P. Gallagher gave the 2007 ICAF Plantema Memorial Lecture on “A Review of Philosophies, Processes, Methods and Approaches that Protect In-Service Aircraft from the Scourge of Fatigue Failures” in May 2007 [14]. The irony in this presentation was that the F-15 canopy sill longeron failure-caused mid-air break-up occurred just a few months later in November 2007, an event that changed the course of the United States Air Force Aircraft Structural Integrity Program (ASIP). The ASIP Review process was described, which started in 1997, added engineering process reviews in 2004 and ASIP management process scrutiny in 2006. These improvements were identified as a need due to the conclusion “that the health of aging aircraft was significantly being underestimated by the lack of execution of ASIP requirements." Figure 4 shows the evolution of the historical ASIP approach and timeline of adoption by United States Air Force (USAF). Dr. Gallagher proposed various approaches for "protecting structural integrity for aging fleets" through evolving ASIP processes, including, a recent addition at the time, risk assessment and management for structural failure prevention, necessitating robust methods for capturing inspection data.

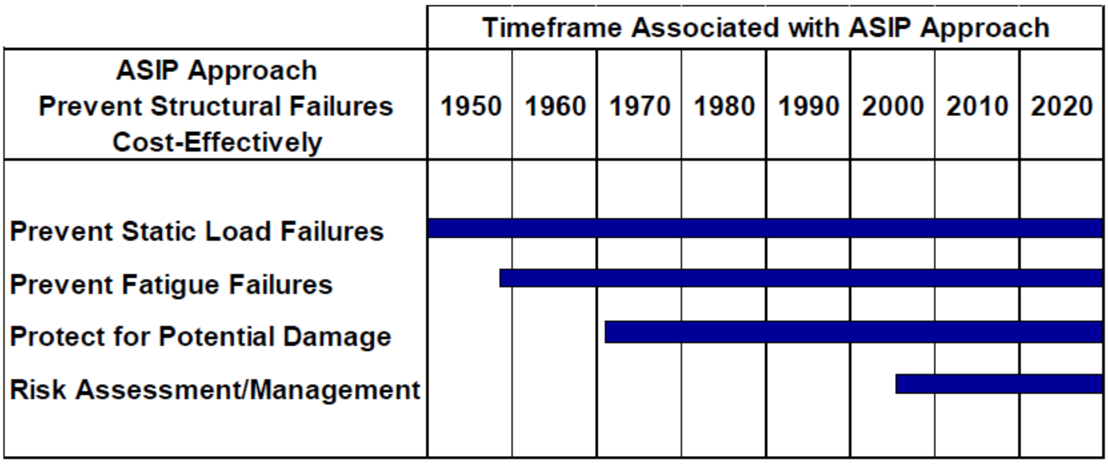

Figure 4: Evolution of the USAF's ASIP Philosophies and Approaches Illustrated as a Function of Time [14]

One of the earliest larger conference audiences for an official holistic structural integrity presentation was by Jerzy Komorowski at the 2007 Aircraft Structural Integrity Program Conference as one of the group lunch speakers [15]. Mr. Komorowski presented an application of HOLSIP to Canadian Forces challenges, while stating that HOLSIP tools were new and used in parallel with existing tools for this study. Various aircraft structural integrity applications were evaluated for corrosion fatigue, multiple site damage (MSD) and widespread fatigue damage (WFD). HOLSIP tools generated life estimates that were very close to test lives and were better than the damage tolerance and safe life calculated predictions. HOLSIP related tools have the potential to provide more information for decision making in the future.

Fretting fatigue, in relation to HOLSIP, was addressed by Hoeppner in an article titled, "Fretting Fatigue Considerations in Holistic Structural Integrity Based Design Processes (HOLSIP) – A Continuing Evolution" [16]. Since fretting fatigue is a common failure mechanism in joined components, there has been a substantial amount of work in the area, with standards for testing and terminology created internationally. Fretting fatigue design directives are fairly limited for the safe life and damage tolerance paradigms, but HOLSIP provides methods and lifing estimations that consider IDS and other conditions produced by or involved with fretting/corrosion mechanisms.

Professor Graham Clark gave the 2011 Plantema Memorial Lecture at ICAF on "Fleet recovery and life extension – some lessons learned" [17]. Professor Clark discussed risks associated with aircraft life extension but noted that there must be an awareness of how "good" the data is and if risks are well understood to determine if a risk is at an acceptable level. Unknowns will drive the risk of failure and other "surprises." He questioned if the current SI management framework can deal with the possible unknown risk of failure. Current tools, including full scale tests, and paradigms are not perfect, but they can minimize the risk of failure. Mechanical/systems failures were noted as causes of accidents, along with maintenance and organizational issues; Professor Clark suspects that organizational failures may be a larger threat to safety than structural integrity issues and cited examples where this occurred, with suggestions for improvement.

During the 2011 ICAF Symposium, Dr. David W. Hoeppner discussed the need to understand the early stages of crack formation/nucleation and propagation to accurately assess fatigue life [9]. Significant research has been performed in these areas, including with environmental degradation effects such as corrosion and fretting, with recommendations to explore the microstructurally short crack regime more thoroughly. Techniques such as in situ fatigue systems within a Scanning Electron Microscope (SEM) and Orientation Imaging Microscopy are promising tools to advance the suggested efforts.

At the 2015 ICAF in Helsinki, Finland, Dr. Paul Clark presented “Is the World Ready For HOLSIP?” [18]. This paper and presentation described HOLSIP and its evolution and cited examples of past structural failures that show gaps in current approaches of traditional design paradigms. Ongoing work in HOLSIP related fields was cited to indicate that people are ready to move past using only safe life and damage tolerance design paradigms.

Jerzy Komorowski gave the 2015 Plantema Memorial Lecture at ICAF on “Structural Integrity – the unfinished business” [19]. He focused on structural integrity, major influencers in the field, and many of the areas in which NRC and Mr. Komorowski specifically have worked over the years, indicating topics that still need further effort as not all problems have been solved. He has worked on various projects involving strain analysis, composites, NDI, structural health monitoring, and corrosion. His experience over many decades has led him to HOLSIP as a solution for many of these unresolved structural integrity concerns, and NRC has been pioneering many analysis methods that incorporate holistic structural integrity principles. There is still much structural integrity related unfinished business and collaboration is key to making progress in these areas.

Larrosa, Akid, and Ainsworth reviewed damage tolerance models in 2017 for corrosion fatigue, acknowledging that current information on the subject is “insufficient to address life estimation with a sound physical basis from the initiation of localised corrosion (such as pitting) to the estimation of crack propagation” [20]. This paper also discussed the need for corrosion fatigue physics-based models that consider the dependence of the fatigue process on the interaction of environmental, metallurgical, and mechanical features to provide more realistic life estimates. Damage tolerance initial flaw size assumptions could then be modified appropriately for a given situation.

At ICAF 2019, the Plantema Memorial Lecture titled “Last Diamond: An Appeal for Holistic Regulatory Leadership” was given by Steve Swift [21]. He focused on more holistic guidance for the various regulatory agencies around the world in order to define acceptable standards that can be implemented across various aircraft types. These efforts are typically met with many roadblocks. Mr. Swift reiterated the importance of language, including grammar, echoing the message from his 2011 ICAF paper. All aspects of structural integrity could use a thorough look through a more holistic lens to improve how they are accomplished and understood. Human character also needs to exhibit holistic traits, including competence, integrity, imagination, wisdom, and courage.

Craig Brooks presented “Holistic Approach for Determining a Helicopter’s Airframe Interval for Depot Induction” at ICAF 2019 [22]. A study was conducted to program maintenance intervals of United States Coast Guard MH-65 helicopters based on structure criticality, corrosion damage tolerance assessment, usage, corrosion history, and design procedures. By taking a holistic approach to the program that included time-based degradation and advanced modelling, the maintenance induction interval was extended while maintaining airworthiness.

Molent and Dixon [23] discussed the key factors that influence why fatigue cracks cannot be well accounted for in their 2020 paper and suggested many areas for future research and study to move past current fatigue prediction limitations. Topics such as crack nucleation, defects/discontinuities, design paradigms, and short crack regime were addressed. A suggestion also was made to apply machine learning (ML) and artificial intelligence (AI) to the abundance of data collected during aircraft sustainment.

Dr. Eric Lindgren presented "Intelligence Augmentation for Aviation-based NDE Data" at the 2022 ASIP Conference [24]. He warned of the limitations currently with AI/ML to detect nuances and outliers, which for aircraft structures, are typically what is required to be identified when in the fatigue crack inspection realm. Data quantity, quality, noise, and variability are important factors that need to be accounted for within the AI/ML framework. With the push to wield AI/ML technologies broadly for many applications, the large amount and quality of data necessary for successful implementation cannot be ignored.

DIGITAL ENGINEERING/DIGITAL TRANSFORMATION AS A PART OF HOLSIP

The United States Air Force has been pushing efforts towards a digital campaign, moving to more advanced digital engineering, and released a 'Guidebook for Digital engineering and e-Series' [25]. Mr. Thomas Fischer gave a lunchtime presentation at the 2021 ASIP Conference and discussed the USAF digital campaign drive [26]. The digital campaign involves the entire product lifecycle, with the objective to "Deliver capabilities at ever increasing speed and efficiency by designing, sustaining, and modernizing them in an integrated digital environment." Mr. Fischer cited the importance of data and seamless data sharing in this transformation as drivers to speed and agility. Mr. Chuck Babish wrote a "White Paper on Digital Engineering (DE) for Aircraft Structural Integrity Program (ASIP) Execution" in response to Mr. Fischer's ASIP presentation [27]. Digital engineering has been defined multiple ways, with Mr. Babish's definition being "the use of models and data for design, analysis, structural certification, and sustainment to enable informed decision making over the entire life cycle". These digital engineering efforts are not new within ASIP for many USAF weapon systems and have been practiced within the HOLSIP community to have the necessary data and analysis capabilities for whole life modelling concepts. Robust risk assessments require significant amounts of data to support the analysis, and many USAF fleets, including the F-16, have been gathering increasing amounts of data in digital formats for decades.

For over 20 years, the USAF F-16 System Program Office (SPO) has developed and maintained the F-16 ASIP Portal website for data and lifecycle management purposes [28]. Engineering dispositions, detailed inspection data, flight data recorder files, and service life information are all stored in a centralized database that is easily leveraged for risk analyses, updated fatigue crack modelling, and maintenance planning. This data, when combined with F-16 Original Equipment Manufacturer (OEM) full scale test results, fatigue crack correlation (including Foreign Military Sales (FMS) F-16 fleet data), fine grid finite element analyses, and leveraging new techniques such as accounting for engineered residual stresses, create a powerful tool in the push toward applying HOLSIP principles to improve aircraft inspection intervals and better manage aircraft life. Figure 5 illustrates how these various F-16 data "threads" interact and inform each other.

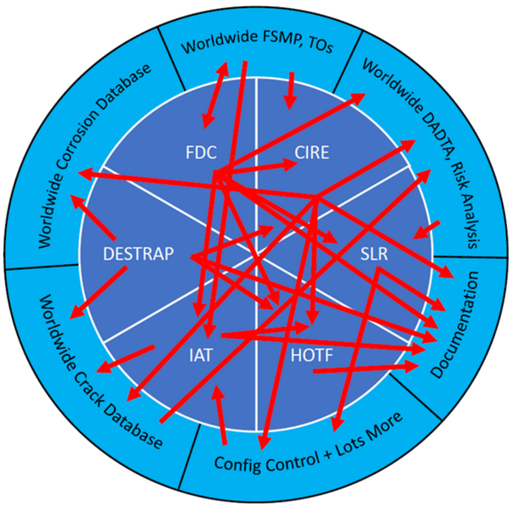

Figure 5: F-16 ASIP Engineering Threads [28]

F-16 EXAMPLES RELATED TO HOLSIP PRINCIPLES

Corrosion

MIL-STD-1530 is the regulation for ASIP regarding structural integrity through damage tolerance. Corrosion and other time-based degradation need to be accounted for, but the guidance on how to incorporate these factors is limited [29]. Some areas of concern for the USAF F-16 fleet are corrosion within the F-1 fuel cell and around the lower longerons and frames beneath the cockpit area. These are difficult areas to inspect and repair, but cases of heavy corrosion have been found, including perforations through structure; an example is shown in Figure 6. Due to the complex nature and variability of corrosion in these areas, analysis is more difficult and has much more variability than traditional fatigue cracking. Much of this unpredictability can be human caused; maintenance practices and culture, interpretation of the technical orders, and rushed maintenance have all influenced corrosion issues over time. Additional corrosion concerns include changes in corrosion prevention systems due to environmental hazards and deployment location environments. All these factors contribute to the complexity of the problem.

Figure 6: Corrosion Damage and Perforation

Finding and mitigating corrosion is insufficient for the USAF F-16 fleet. Many of the corrosion problem areas cannot be addressed at the field level and require induction into a depot for repair. It is already known that there may be major corrosion in problem areas on a significant percentage of F-16 aircraft. There are several depot repair programs in place that include corrosion mitigation/repair, but it will be years before the entire fleet is through these programs. Fail safe analyses of problem areas were conducted to determine the urgency of fixing the corrosion. The results were favourable, allowing aircraft to be triaged and inducted into a depot over the multiple year spans of the repair programs.

Fracture critical parts

One of the major concerns for F-16s currently involves a fracture critical part, part condition, and surface preparation for eddy current inspection. From a damage tolerance and HOLSIP perspective, gouges in a fracture critical part are clearly not acceptable without characterization and subsequent analysis, so part condition, not surprisingly, has shown its importance as far as a crack nucleation mechanism. Figure 7 shows an example of this fracture critical part with a 6.35 mm crack propagating from a gouge, which was found using eddy current and confirmed using fluorescent penetrant inspection. Other evidence of gouges and rough polishing can be seen.

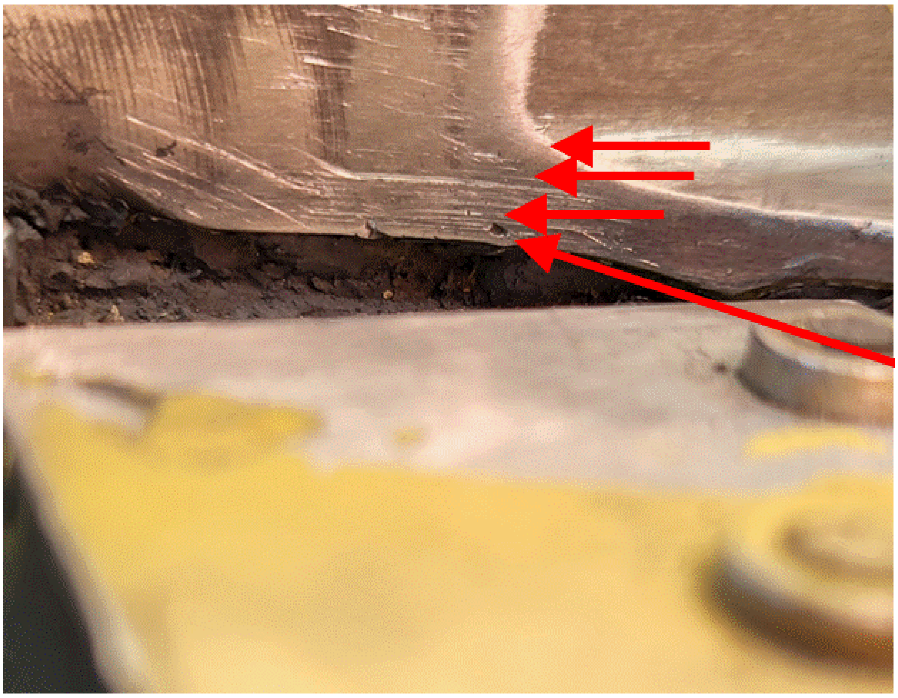

Figure 7: Crack From a Gouge in a Fracture Critical Part

Practical Risk Analysis

The prioritization of depot inductions for the F-16 fleet is vital, due to limited depot capacity. Multiple risk analyses have been considered in order to maximize depot induction intervals for applicable USAF F-16 aircraft. The primary risk driver in this scenario has been the lower end pad radii on the center fuselage bulkheads near where the wing bolts attach the wings to the fuselage structure. Multiple Time Compliance Technical Orders (TCTOs) have been issued to drive inspections at these radii. Data collection of the findings, and blend depths when cracks have been found, have been vital to perform the risk assessments and re-evaluate aircraft as needed. Large amounts of robust flight data recorder and inspection data collection, combined with the updated risk assessments, have provided each aircraft a specific inspection interval and individual aircraft tracking capability.

CONCLUSIONS

HOLSIP can be applied throughout the entire lifecycle for engineered structures design, manufacturing, operations, retirement, and ethics. Over the past 50 years of HOLSIP development and more than 20 years of intentional practice, significant strides have been made to move past some of the limitations of traditional design paradigms and linear elastic fracture mechanics. These principles are not restricted to aircraft structural integrity and can be applied to any industry; examples of other areas where HOLSIP has been applied include oil pipelines, the mining industry, and artwork transportation. With the propagation of HOLSIP concepts to additional industries, researchers, and practitioners, progress for this effort continues to advance. Further development and use of physics and time-based degradation models need to gain traction to improve aging related safety, reliability, and availability issues within USAF and worldwide fleets.

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