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DIGITAL ENGINEERING FOR IMPROVED AIRCRAFT STRUCTURAL INTEGRITY PROGRAM EXECUTION

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Abstract: The United States Air Force (USAF) has spent considerable effort describing a Digital Transformation vision and establishing initiatives to implement the key tenets for all programs. One of the key tenets is developing a Digital Engineering (DE) capability with the purpose of "*achieving a measure of authoritative virtualization that replaces, automates, or truncates formerly real-world activities*" as stated in official correspondence to all USAF members. The USAF strategy to implement DE in programs was further defined as seven discrete efforts ranging from developing digital models and threads to ensuring organization readiness to implement DE. DE is not a new concept for Aircraft Structural Integrity Program (ASIP) execution as defined in MIL-STD-1530. The ASIP has always embraced, utilized, and relied upon models and data to conduct and continuously update the structural analyses used as the primary basis for structural certification throughout the entire aircraft life cycle. However, there is more work to be accomplished to continue the journey toward a comprehensive DE environment for proper ASIP execution and the Digital Transformation initiative is an excellent opportunity to significantly advance the state-of-the-art. This paper defines terms such as DE, Digital Thread, and Digital Twin as they relate to ASIP execution and describes the considerations, key models, data, and tools commonly used by aircraft programs. The paper presents some use case and benefit examples for expanding the use of DE for ASIP execution as well as some challenges that must be overcome. Finally, the paper presents the path forward to improve DE for ASIP execution including competencies and personnel required, priorities for aircraft in development, and priorities for aircraft in sustainment.

Keywords: Digital Engineering, Aircraft Structural Integrity Program, Digital Thread

INTRODUCTION

The United States Air Force (USAF) has spent considerable effort describing the Digital Transformation (DT) vision and establishing initiatives to implement the key tenets for all programs. One of the key tenets is developing a Digital Engineering capability with the purpose of "*achieving a measure of authoritative virtualization that replaces, automates, or truncates formerly real-world activities*" as stated in official correspondence to all USAF members. The correspondence provides guidance to implement DE to include developing digital models of systems, developing a digital twin and digital thread, linking models and digital artifacts to create an authoritative source of truth, implementing an integrated digital environment, implementing digital acquisition, ensuring organizational readiness for DE, and tracking digital maturity metrics. There is similar and perhaps confusing terminology in use associated with the USAF's DT initiative and the following key terms are defined below as they apply to Aircraft Structural Integrity Program (ASIP) execution.

Key Digital Transformation Terms

Digital Engineering (DE). DE is the use of models and data for structural design, analysis, certification, and sustainment to enable informed decision making over the entire life cycle. The models must represent the physics and chemistry correctly (or sufficiently vetted surrogate models) and be verified and validated. The data must come from authoritative sources and be accurate. Examples of DE models include Model Based Definition (3-dimensional representation of the air vehicle structure, subsystems and their routing, etc.) and Air Vehicle Finite Element Model (AV-FEM).

Digital Thread. Digital Thread is the digital linkage of requirements, data, models, etc. As one example, the Digital Thread should enable the tracing of requirements (explicit, derived, and self-imposed) to: (1) verification/certification data and results, (2) Technical Orders that define the aircraft limitations, restrictions, and maintenance requirements, and (3) airworthiness and system safety hazards, and their associated risks.

Digital Twin. Digital Twin is the aggregate of the models and data used to capture the as-designed, as-built, as-certified, as-operated, as-maintained, as-repaired, and as-modified configuration of each aircraft produced. ASIP requirements such as Individual Aircraft Tracking (IAT), Loads/Environment Spectra Survey (L/ESS), and structural management databases (executed by 3-Dimensional Computer Aided Design (3D CAD) models) are examples of Digital Twin efforts.

ASIP Background

The USAF established the ASIP in November 1958, in response to five B-47 aircraft losses in the span of one month due to in-flight structural failures [1,2]. Four of the B-47 losses were attributed to fatigue, which led to a probabilistic approach for establishing the aircraft service life capability. This approach was called “safe life” and it relied upon the results of a laboratory test of a full-scale airframe subjected to loading that simulated the operational service environment of the aircraft. The USAF established the safe-life of the aircraft by dividing the number of successfully test simulated flight hours by a scatter factor. The intent of the factor was to account for aircraft-to-aircraft variation in materials and manufacturing quality. The USAF believed the process was sufficient to preclude in-service structural failures attributable to fatigue. The safe-life approach was the basis for all new designs during the 1960s and was used to establish the safe life of earlier designs that were subjected to a fatigue test.

Losses of an F-111 in December 1969 and an F-5 in April 1970, each far short of their qualified safe-life, demonstrated that the safe-life approach had shortcomings [2]. The safe-life approach allowed the use of low ductility materials operating at high stresses which resulted in designs that were intolerant to manufacturing and service-induced defects. The aircraft failures arising from the deficiencies of the safe-life approach demanded a fundamental change in the design, qualification, and inspection of aircraft. The damage tolerance approach emerged as the candidate chosen for this change.

Developers of the damage tolerance approach recognized that an aircraft’s structure is subject to a wide range of initial quality from both manufacturing processes and service induced damage. They also recognized that the aircraft structure had to be inspectable. To ensure the aircraft operates safely in the presence of anomalies, the USAF requires the structure to tolerate “damage” for some inspection-free period of service usage. The damage tolerance approach provides the USAF a safety limit for each critical area in the aircraft. The safety limit is the time, in flight hours, required for a crack to grow from either an assumed initial flaw size, or the inspectable flaw size, to a critical size. Inspections are scheduled to occur at a time equal to one-half the determined safety limit. The USAF used the damage tolerance approach to upgrade the structural integrity of several operational aircraft in the early 1970s, including the F 111, C-5A, and F-4. The success of these endeavors convinced the USAF that damage tolerance should be the structural safety basis for all future designs. In December 1975, the USAF formally integrated the damage tolerance approach into the ASIP.

During the 1970s and 1980s, the USAF performed a damage tolerance assessment on every major aircraft weapon system to develop inspection or modification programs necessary to maintain operational safety [3]. The results of the damage tolerance assessments were incorporated into USAF

Technical Orders, which established maintenance requirements to maintain structural integrity and to control risk at an acceptable level. As one measure of success for the USAF implementation of the damage tolerance approach, the USAF destroyed aircraft rate due to structural reasons is approximately three destroyed aircraft per ten million flight hours accumulated in the fleet (dashed line in Figure 1). This is approximately ten times lower than the overall USAF destroyed aircraft rate due to all causes, except combat related (solid line in Figure 1). Accordingly, the USAF believes the damage tolerance approach incorporated into the ASIP in the 1970s continues to be the cornerstone for protecting the safety of the USAF fleet.

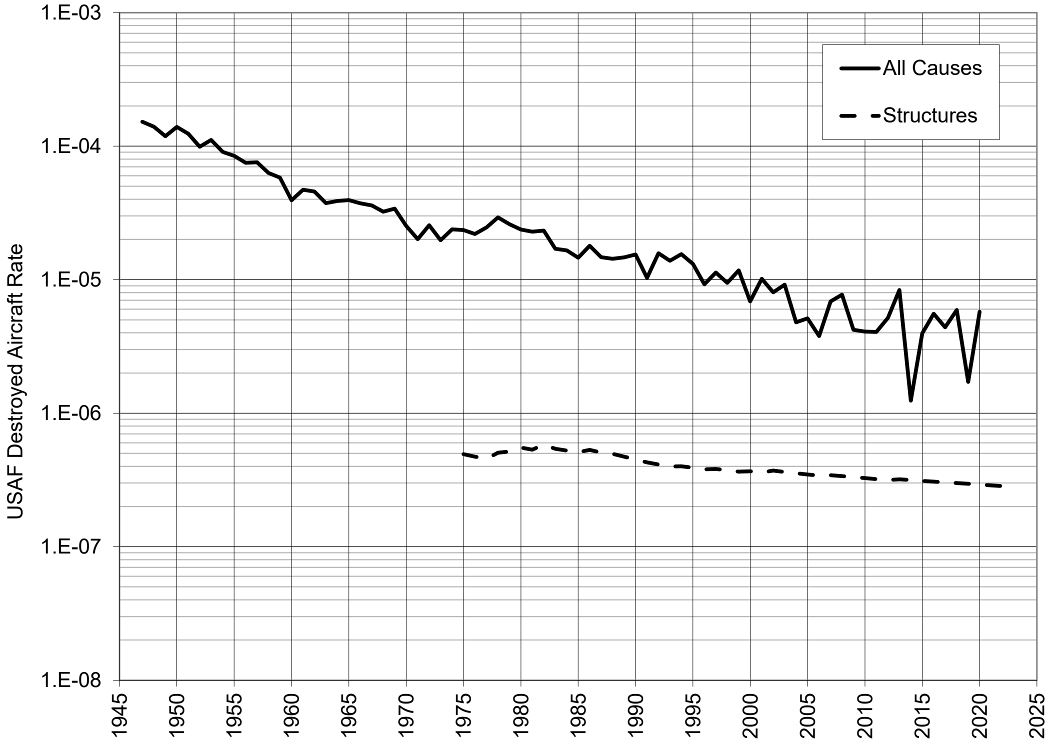

Figure 1: USAF Destroyed Aircraft Rates.

ASIP AND DE

The ASIP has always embraced, utilized, and relied upon models and data to their fullest extent to conduct and continuously update the structural analyses used as the primary basis for structural certification throughout the entire aircraft life cycle. That fact is evident in ASIP MIL-STD-1530 [4] where these requirements and interactions are established within each of the five major ASIP tasks: design information, design analyses and development testing, full-scale testing, certification and force management development, and force management.

The scope and fidelity of the structural models developed and used during ASIP execution have improved as model capabilities and computing resources have enabled it. These improved structural models reduce the structural testing required to demonstrate structural integrity attributes (strength, rigidity, durability, and damage tolerance) by obtaining data for model correlation/correction/validation, versus conducting additional testing. The primary basis for structural certification has been and continues to be structural analyses validated through a building-block structural test program. The structural testing results over the past five decades to include those from the most recent programs indicates structural analyses cannot replace most of the full-scale structural ground and flight testing (highest tier in the building-block test program) in the mid-term. However, recent full-scale static testing programs indicate static strength analyses coupled with lower tier building block testing may be sufficient in the near-term, especially for attritable or expendable aircraft that accept higher risk.

DE Considerations for ASIP Execution

Decisions related to the DE environment during aircraft development should consider all potential needs and uses during the aircraft sustainment phase. Therefore, the types of decisions required throughout the entire acquisition and sustainment phases must be determined so that the proper models, tools, and data capture requirements are established. Examples of decision topics that should influence DE model and data development as well as preservation include: reference data architecture definition/selection, Product Life-Cycle Management (PLM) system definition/selection, digital deliverable requirements definition, IAT system architecture and methodology, maintenance and usage data collection, and fleet management system architecture and methodology (structural risk, force structure projection, aircraft capability, aircraft availability, and sustainment cost).

DE should not necessarily focus on retaining all or most models because they may become obsolete, or advanced techniques may warrant replacing them with improved versions. For example, it may not make sense to retain each AV-FEM iteration used during the design analysis phase when an AV-FEM with an element representation of 6 inches by 6 inches of structure (therefore no stiffeners or shear web penetration holes are included) can be replaced with a new AV-FEM with element representation of 1 inch by 1 inch that includes discrete modeling of key features for improved accuracy as needed. However, the static test data used to correlate/correct/validate the original AV-FEM must be captured so that it can be used for any future AV-FEM update that is performed to avoid the cost of repeating structural testing to obtain the necessary data. In addition, officially released versions of the AV-FEM such as design-to, certification/test, and verification should be retained.

Key Models, Data, and Tools Developed During ASIP Execution

Model based definition. 3D CAD model that defines the complete aircraft structure and major equipment and systems installations to include fasteners, interfaces, design notes, tolerances, etc.

Material and structural allowables test data. Since material and structural allowables serves as the foundation for determining structural integrity, the complete digital thread of these activities is needed which includes the following: test planning/matrix definition, formal test plans, raw material acceptance records, manufacturing records, inspection records, conformity and witnessing records, laboratory test data, data reduction, data analysis, data statistics, test report, and summarized material and design allowables for use in the structural analyses.

Aerodynamic database. The aerodynamic pressures are derived from wind tunnel testing and Computational Fluid Dynamics (CFD) analysis for the intended range of Mach numbers, altitudes, etc. The aerodynamic database is used to determine aircraft lift, drag, and other forces for aircraft ground and flight events from which aircraft performance (e.g., takeoff distance, time to climb, range/payload) and aircraft loads (e.g., wing bending and torsion and shear, fuselage bending and torsion and shear, landing gear vertical and drag and side) are determined.

6-degree of freedom (6-DOF) model. The 6-DOF model is used to develop the flight control laws (e.g., control surface positions throughout a maneuver) necessary to achieve aircraft handling qualities and stability and control requirements. The 6-DOF model calculates roll, pitch, and yaw rates and accelerations from which aircraft trajectories are determined for various maneuvers. These calculations combined with the aerodynamic database and criteria are used to determine aircraft loads. Multiple iterations of flight control laws are typically required throughout the design phase and into flight testing to balance aircraft performance, handling qualities, stability and control, and aircraft loads. While the focus is typically on design loads used in static strength analysis, this can have a very strong impact on the repeated loads (used for service life analyses) which takes longer and is more difficult to determine.

Flex-to-rigid ratio model. This model is used to adjust loads predictions based on rigid aircraft responses for elastic deformations that occur during flight.

External loads model. Model that integrates aerodynamics data, flight control laws models, and flex-to-rigid models to determine the aircraft external loads (e.g., bending, torque, and shear).

AV-FEM. AV-FEM to determine all member internal loads, load distributions, and displacements as well as structural responses such as frequencies and mode shapes. The AV-FEM provides the foundation for the following structural analyses: static strength, durability, damage tolerance, sonic fatigue, vibration, aeroelastic, aeroservoelastic, thermal, mass properties, and survivability. It is currently common practice to modify the AV-FEM to determine thermal loads (2nd AV-FEM) and to determine aircraft structure dynamic responses (3rd AV-FEM).

Analyses and assessment tools. There are too many to specifically list and many of them are contractor developed proprietary tools and commercially available tools. These tools cover all ASIP Task II “Design Analyses & Development Testing” analyses that includes loads, stress and strength, durability, damage tolerance, sonic fatigue, vibration, aeroelastic, aeroservoelastic, mass properties, survivability, structural risk, and economic service life. These tools also include those used for corrosion assessments such as corrosion modeling.

Structural development test data. This includes element, subcomponent, and component testing used to develop and validate empirical methods.

Full-scale testing data. Testing includes proof, functional, free-play, ground vibration, aeroservoelastic, static, durability, damage tolerance, and climatic testing ground testing and loads, flutter, aeroacoustic, and vibration flight testing. Data captured during testing includes strains, displacements, pressures, and temperatures.

Aircraft usage data. This includes data from other aircraft programs to establish the design spectrum used in the durability, damage tolerance, sonic fatigue, vibration, structural risk, and economic service life analyses for a new aircraft program. It also includes L/ESS data to determine baseline operational spectrum comprised of time-history aircraft recorded data such as vertical and lateral load factors, roll, pitch and yaw rates, roll, pitch, and yaw accelerations, altitude, velocity, control surface positions, selected strain measurements, ground loads, aerodynamic excitations, and thermal and chemical environments. It also includes IAT data, which is typically a subset of L/ESS data used to update durability and damage tolerance analysis so that inspection intervals are adjusted for each aircraft based on their actual usage.

Nondestructive Inspection (NDI) and Structural Health Monitoring (SHM) data. Data used to develop NDI Probability of Detection (PoD) distributions and digital records of NDI and SHM results [5].

Force management data. Digital record of all damage findings, repairs, modifications, replacements, component serial number tracking, etc.

USE CASE AND BENEFIT EXAMPLES

The aircraft design development process is increasingly more difficult as the number and complexity of the requirements have evolved. A typical aircraft design development process can take 10 to 20 years to complete. A DE capability that can translate requirements into an accurate prediction of aircraft development cost and schedule so that the initial requirements can achieve a better balance between performance, cost, and schedule is clearly needed. Furthermore, a DE capability is needed that can significantly reduce the time for each aircraft design and analysis iteration that occurs to achieve all performance requirements recognizing that each iteration currently takes about one to two years to complete. These design iterations include establishing structural arrangement, sizing each structural part considering static strength, rigidity, durability, and damage tolerance requirements, redesigns to achieve weight and cost objectives, and redesigns to correct deficiencies discovered during full-scale ground and flight testing. A DE environment is expected to eliminate years and the associated cost during the aircraft design development cycle by reducing the number of design iterations required and reducing the span during each.

Airworthiness certification is required to operate all USAF aircraft. The goal of airworthiness in a DE environment should be such that whatever models, data, calculations, documentation, etc. the industry partner needed to assert airworthiness is the same for the airworthiness authority to find airworthiness; the assertions and findings occur at the same time; and that Military Flight Release (MFR) or Military Type Certificate (MTC) is issue immediately upon completion of all AW sections. In other words, the industry team does not need to repackage data or generate a document just for USAF use and a DE environment can enable this goal. There are two primary airworthiness efforts to consider in the DE environment and they are very different: (1) activities leading to the initial flight clearance to initiate the flight test program and (2) activities leading to an MTC. For the initial flight clearance, a DE environment is needed to enable efficient and simultaneous airworthiness assessments by all stakeholders for testing activities that occur just prior to flight clearance authorization. In addition, a DE environment is needed that relates all aircraft limitations, restrictions, and maintenance actions driven by design requirements as well as airworthiness non-compliances to their sources and identifies and tracks efforts to modify them. For flight testing execution, a DE environment is needed to enable efficient execution of envelope expansion to include management of flight continuation, knock-if-off, and return-to-base criteria evaluations. In other words, the DE environment for airworthiness assessments should have the test data, AV-FEM, analyses, and requirements all tied through a digital thread to show and maintain airworthiness compliance in a model/tool.

Mechanical property test data generated during aircraft development and production may be needed to characterize material property distributions for use in structural risk analyses decades of years later. This specifically includes fracture toughness tests from each lot of material used to manufacture fracture-critical parts during production. Records that only show the material lot met the specification minimums provides no useful engineering data. All crack propagation, strain-life, strength, etc. test data that is generated over the life of the program should also be captured. Lack of the actual test results leads to uncertainty in the risk calculations that should be prevented.

Many aircraft programs have historically performed AV-FEM updates as model and computing capabilities increase during the aircraft sustainment phase to improve analysis fidelity, evaluate capability improvements, evaluate service life extension options, and other reasons. Retaining full-scale static test (FSST) data for AV-FEM correlation/correction/validation has saved significant testing cost but the labor to resurrect the test results was higher than it should be in some recent programs. A 3D CAD model that represents the full-scale static test (FSST) article configuration and depicts exact load application arrangement (pads, whiffle trees, straps, actuator locations), depicts exact instrumentation locations (with tagged photos that show actual installation), documents load cell feedback from each actuator at each test condition, documents instrumentation measurements for each location for each load condition, and is directly connected to the AV-FEM to compare AV-FEM predictions and test measurements for each load case would result in a significant reduction in the cost and time necessary to validate a new AV-FEM.

Evaluating the potential for an aircraft service life increase is a complicated problem that involves understanding all previous analyses (durability, damage tolerance, aeroacoustic, vibration, etc.), testing (building block, structural development, full-scale), and in-service damage findings (cracks, corrosion, wear, etc.) related to aircraft service life. Since there is significant variation in time to damage initiation, growth rates, and residual strength capability, probabilistic methods are employed which demands data to characterize the primary distributions. In many cases, reinterpreting previous full-scale durability test (FSDT) results is necessary due to differences between expected and actual crack findings. However, the cost and span for completing this task has been extensive. All FSDT programs should have a 3D CAD model that represents the FSDT article configuration and depicts exact load application arrangement (pads, whiffle trees, straps, actuator locations), depicts exact instrumentation locations (with tagged photos that show actual installation), documents load cell feedback from each actuator at each spectrum end point, documents instrumentation measurements for each location for each load condition and/or spectrum end point, documents each crack location and dimension to include NDI digital records and fractography result, and considers lessons learned from past FSDT programs for analysis and test correlation efforts to include test spectrum development and verification [6].

Quantifying structural maintenance impacts on cost and aircraft availability and quantitative structural risk analyses for fatigue cracking issues involves characterizing the probability distributions of damage types and locations, damage sizes, maximum stress per flight, material fracture toughness, and many other considerations for the application [7,8]. The typical process to obtain the data to generate these probability distributions takes weeks or months of effort and typically involves manual data extraction and manipulation from data retained in multiple unconnected sources. The architecture for storing and retrieving data generated during aircraft testing, operations, and maintenance, and the digital thread to connect them should consider future needs for quantitative analyses to include determining aircraft service life remaining for various scenarios.

PATH FORWARD

The use of models and data for design, analysis, structural certification, and sustainment for ASIP execution has continually evolved and improved as technology and capabilities have increased. The government and industry team must work together to determine roles and responsibilities, provide access to models & tools as needed, provide access to authoritative source of truth data as needed, protect proprietary models & tools, determine what data is delivered and via what method, and determine what data, models, and tools are maintained for the life of the program. One of the goals of a DE environment for ASIP execution is to replace relatively static documentation to include plans, ASIP Reviews, and other manual efforts with digital versions to the maximum extent practical. For example, MIL-STD-1530 [1] states the ASIP Master Plan "shall be integrated into the Integrated Master Plan (IMP) and Integrated Master Schedule (IMS)" and "shall depict the time-phased scheduling and integration of all required ASIP tasks for design, development, production, structural certification, and force management of the aircraft structure". The DE environment should accomplish these requirements in a digital manner.

Competencies and Personnel Required

An aircraft structures engineering workforce typically covers the competencies of loads, loads spectrum development, 3D CAD modeling, AV-FEM analysis, dynamics, strength, durability and damage tolerance, corrosion, materials and processes, mass properties, and structures sustainment. However, there are additional competencies required to execute DE for improved ASIP execution to include PLM workflow and configuration management, and digital force management consisting of usage and maintenance data collection and evaluation as a minimum. These new competencies require appropriately trained technicians and computer specialists familiar with aircraft structures. Furthermore, additional engineers are typically required for many of the existing structures competencies to fully achieve the DE environment vision. The total number of personnel required and the mixture of government and contractor personnel in each program office is dependent on the program phase (development, production, sustainment), number of aircraft in the fleet, program complexity, and many other considerations.

Priorities for Aircraft in Development

The following models and tools should be developed, verified, and validated, connected with a digital thread, used to develop an optimized structural design, used to achieve efficient structural certification, and maintained as appropriate to provide a digital twin of each aircraft for use during the aircraft life cycle.

Initial 3D CAD model (see Figure 2) that defines the design space such as outer mold line, aircraft volume, aircraft stay out volumes (e.g., crew station, engine bay, landing gear bays, major subsystems), control surfaces, and other key design features.

External loads (see Figure 2) calculation tool that uses appropriate structural design criteria (e.g., vertical load factors, gust velocities, hammershock pressures, taxi speeds, sink speed at landing), aerodynamic database derived from wind tunnel testing and CFD analyses, dynamic gear model, flight control laws, aircraft weight, and others as needed.

Design optimization tool connected to the 3D CAD model described above to automatically evaluate primary structural arrangement (e.g., number of wing spars, spar spacing, spar caps and webs thicknesses), component arrangements (e.g., skin stiffener type, spacing, and sizing), discrete part sizing (e.g., pocket-by-pocket and stiffener-by-stiffener sizing), and detailed part sizing (e.g., joints, fittings, cutouts) via a direct connection to the AV-FEM. Each major design iteration and design iterations within each major design iteration (see Figure 2), should be optimized for key performance parameters (e.g., minimum structural weight) considering as many structural failure modes as practical (e.g., static strength, local stability, global stability, durability, damage tolerance) to resolve locations with issues such as negative or high margins (see Figure 2).

AV-FEM that determines internal loads (see Figure 2) for each major design iteration and directly provides the results to the design optimization tool for design analysis. The AV-FEM should also enable structural dynamics analyses and thermal loads analysis with minimal changes to the AV-FEM to the extent practical. The AV-FEM should be modified to support the full-scale ground test programs and enable automated goodness-of-test and accuracy of analyses evaluations. The AV-FEM should be periodically updated to increase resolution and accuracy as technology allows and improvements are needed.

Structural analyses tools used for detailed analyses of each design iteration directly connected to the AV-FEM to the maximum extent practical (see Figure 2), directly connected to the verification data collected during ground testing (e.g., FSST, FSDT), flight testing (e.g., flutter, loads, noise & vibration), and directly supporting AW certification.

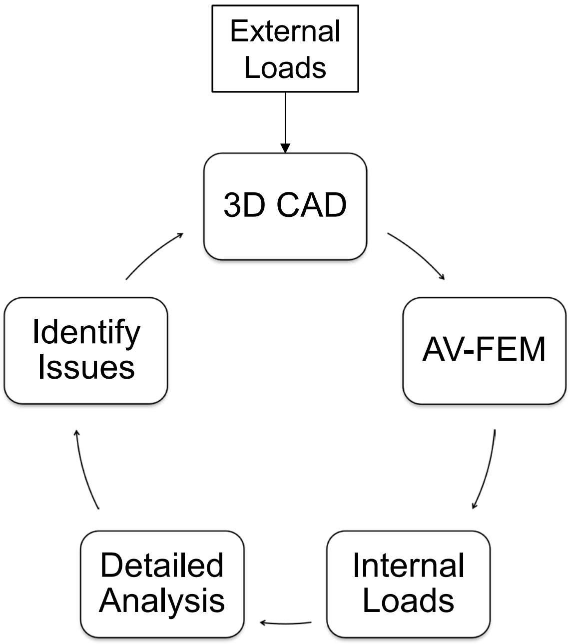

Figure 2: Aircraft Structure Design Iteration Process.

3D CAD model for each full-scale ground test article, flight test aircraft, and major design iteration that defines aircraft structure, major equipment and systems installations, and Bill-of-Materials (BOM). For the test articles and aircraft, the 3D CAD model should provide the capabilities described in the Use Case and Benefit Examples section above. For production, the 3D CAD model should enable efficient manufacturing planning and execution to include discrepancy resolution.

PLM tool to enable the authoritative source of truth for all data, and data exchanges between the models and tools described in this section.

Digital Force Management tool(s) to maintain the digital twin of each aircraft to include each flight test aircraft [9].

Priorities for Aircraft in Sustainment

The following models and tools should be developed, verified, and validated, integrated into PLM, connected with a digital thread, and maintained as appropriate to provide a digital twin of each aircraft for use during the aircraft life cycle. If a sustainment effort involves a major modification or redesign activity, the models and tools described above may also apply. The prioritization considers the immediate need and potential pay-off coupled with the complexity involved in achieving the capability.

3D CAD model that defines aircraft structure, major equipment and systems installations, and BOM for each major configuration. The near-term emphasis should be conversion of 2D drawings to 3D CAD models suitable for direct manufacturing of parts commonly needed to support maintenance requirements (i.e., accelerate parts procurement).

PLM tool such to enable the authoritative source of truth for all data, data exchanges between the models and tools described in this section, and efficient tracking of all aircraft configuration changes and modification programs in work.

Maintenance data capture tool to maintain the digital twin [9]. Examples of maintenance data include inspections performed (exact locations, aircraft actual flight hours, aircraft equivalent flight hours), damage non-findings and findings (type, locations, dimensions), non-destructive inspection records, structural health monitoring records, corrosion prevention actions, repair design and supporting analyses, modifications, component replacements, serialized part changes, aircraft basing history, weight and balance records, spatial positioning to know exact hole locations that were cold-worked, and puller force time-history during each cold work operation.

Digital IAT tool that integrates & automates all IAT tasks to include data collection (e.g., flight data recorder files, “bubble” sheets), data transmission, IAT calculations to include equivalent flight hours, technical data updates for technical orders, maintenance work specifications used to implement IAT-based inspection requirements, and inspection tracking & reporting. The digital IAT should also automate force structure projections based on IAT calculations and future projected usage for the most life-limiting structural component to determine the implications of usage severity and variability [10].

Digital Force Management execution tool that integrates & automates items listed above and the generated technical order updates, maintenance scheduling & tracking, maintenance analytics such as cost & availability impacts associated with different damage types (e.g., fatigue cracking, corrosion), and maintenance forecasting to include cost & availability impacts. This capability is expected to eliminate the need for separate Force Structural Maintenance Plan (FSMP) updates. The USAF has many examples of tools developed and implemented to achieve this capability but there is room for considerable improvement.

Risk analysis and economic service life analysis tools that automate these analyses to the maximum extent practical.

Digital Force Management update process tool that integrates & automates: L/ESS execution, Baseline Operational Spectrum (BOS) creation using L/ESS data, durability and damage tolerance analysis update using current BOS, IAT program algorithm revision as needed using updated durability and damage tolerance analysis, and IAT calculation updates for algorithm changes (run the entire database for all aircraft, a non-trivial task).

Probabilistic force management capability that accurately determines probability of failure and remaining useful life for each aircraft, accounting for all significant sources of variability and uncertainty, and accounting for user selected future aircraft usage, maintenance, etc. options. This requires more comprehensive data integration and modeling of materials, designs, manufacturing, maintenance, usage, environments, sensing, etc. relative to all residual strength degradation mechanisms that can jeopardize structural integrity.

Many aspects of ASIP force management activities during aircraft sustainment are iterative in nature and repeat at semi-regular intervals. Therefore, increased emphasis should be placed at developing DE capabilities that automate this process to the maximum extent possible. Figure 3 depicts the interrelationships between the major activities described above to illustrate the framework from which to continue the journey toward DE for improved ASIP execution.

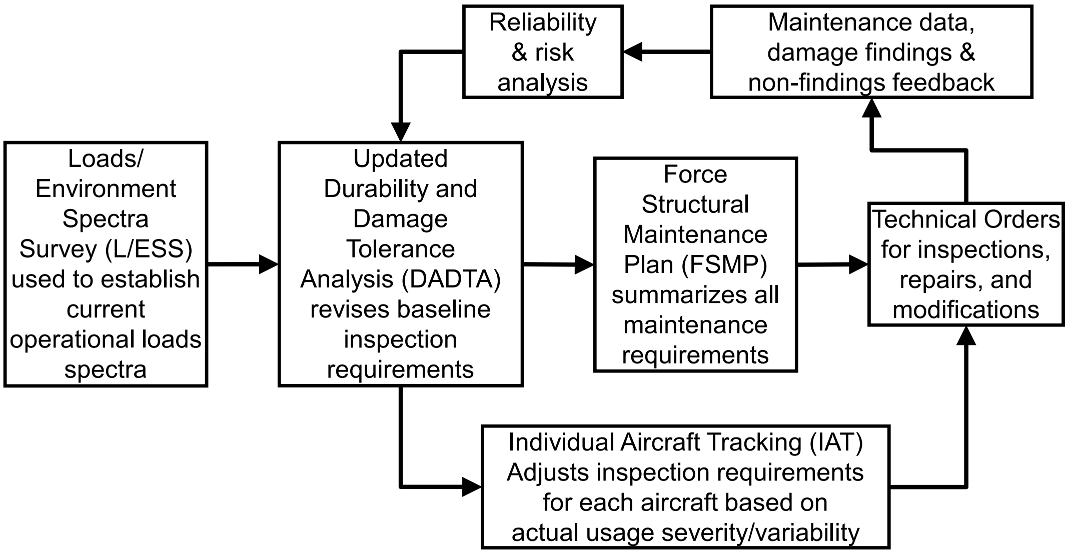

Figure 3: ASIP Force Management Iterative Process.

REFERENCES

[1] Babish, C. (2008), *USAF ASIP: Protecting Safety for 50 Years.*, Proceedings of the 2008 ASIP Conference.

[2] Tiffany, C. and Gallagher, J. (2010), *ASC-TR-2010-5002, Threats to Aircraft Structural Safety, Including a Compendium of Selected Structural Accidents/Incidents.*

[3] Lincoln, J. (1985), *Damage Tolerance – USAF Experience*, Proceedings of the 13th Symposium of the International Committee on Aeronautical Fatigue.

[4] MIL-STD-1530D (2016), *Department of Defense Standard Practice, Aircraft Structural Integrity Program (ASIP).*

[5] Lindgren, E. and Babish, C. (2015), *Recent and Future Enhancements in NDI for Aircraft Structures,* Proceedings of the 7th International Symposium on NDT in Aerospace.

[6] Babish, C. and Liu, K. (1997), *Lessons Learned from the C-17A Full Scale Airframe Durability Qualification Program,* Proceedings of the 19th Symposium of the International Committee on Aeronautical Fatigue.

[7] Berens, A. and Babish, C. (2005), *US Air Force Risk Analysis Approach for Aging Aircraft,* Proceedings of the 23rd Symposium of the International Committee on Aeronautical Fatigue.

[8] Gallagher, J. and Babish, C. (2005), *Damage Tolerant Risk Analysis Techniques for Evaluating the Structural Integrity of Aircraft Structures,* Proceedings of the Structural Integrity in Transportation Systems Symposium, International Conference on Fracture.

[9] Tuegel, E. and Babish, C. (2014), *Continuing Airworthiness and the Airframe Digital Twin,* Proceedings of the NATO AVT-222 Workshop on Continuing Airworthiness of Ageing Aircraft Systems.

[10] Babish, C. (2007), *Implications of Usage Severity and Variability Based on an F-16 Case Study,* Proceedings of the 24th Symposium of the International Committee on Aeronautical Fatigue.