CHARACTERIZING THE PHYSICS OF TAPER-LOK FASTENER HOLES TO SUPPORT B-1 SUSTAINMENT

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Abstract

Taper-Lok fasteners provide great benefit to fatigue performance but create a complex scenario for analysis to fully account for its effects. The interference due to the oversized tapered fastener introduces tensile hoop stress around the hole and compressive radial stress that combine with applied loading to effectively reduce stress amplitude and improve fatigue performance. The combination of the stress due to interference, applied stress, and the likelihood of plastic deformation near the hole results in a complicated scenario for damage tolerance analysis. The objective of this work was to develop an analytical approach to support explicit incorporation of the physics of a Taper-Lok fastener installation for B-1 critical locations. The work included experimental measurements and finite element predictions of residual stress utilizing manufactured coupons and aircraft excised structure. A comprehensive fatigue crack growth test program was conducted to obtain validation data using coupons representative of wing rear spar and wing carry-through lower cover control points. The analytical approach and validation data developed in this work are discussed in detail.

1. Introduction

With recent updates to USAF Structures Bulletin "Requirements to Establish the Beneficial Effects of Cold Expanded Holes in Development of Damage Tolerance Initial and Recurring Inspection Intervals", there is an opportunity for explicit modeling and additional damage tolerance life credit for enhancement processes such as Cold Expansion and Taper-Lok fastening systems. This newly proposed approach includes requirements for verified damage tolerance analyses (DTAs), inspection methods, and residual stresses prior to taking "full credit" and incentivizes the development of explicit physics-based modeling approaches.

Taper-Lok is an advanced legacy fastening system used in many airframes that not only fulfills the traditional purpose of mechanically fastening structures, but also adds great benefit to the fatigue life of the structure. The system is comprised of a tapered, conical-shank fastener, a precision tapered hole, and uniformly controlled interference preloading. The static preload, radial compression, and peripheral tension, induced by the interference fit, effectively reduces cyclic stress amplitude to proportionately enhance fatigue life. Although this system is greatly beneficial to the fatigue life of the hole, it poses a complex scenario to evaluate and fully quantify when it comes to the task of performing DTAs and setting inspection intervals.

Historically, DTAs of these Taper-Lok systems have been based on reduced initial flaw sizes or constant Life Improvement Factors (LIF) that do not physically account for the interference fit benefit the system provides. Although these simpler methods have been shown to be conservative via coupon testing, they leave a lot on the table relative to actual fatigue life benefits and likely force earlier inspections than necessary that can increase sustainment cost and reduce aircraft availability.

A physics based analytical methodology did not previously exist to fully quantify the fatigue life benefit of Taper-Lok installations. Under the USAF B-1 System Program Office (SPO) direction, the Boeing B-1 program with partnership from Hill Engineering and Southwest Research Institute completed a program to better understand the complex stress state from the Taper-Lok system. Following a systematic process, a methodology was developed that accounts for fastener interference (initial and retained), residual stresses, and the unique relationship of stress intensity factors and remote loading.

In this paper, we will discuss the journey on the B-1 Taper-Lok program, reviewing the analytical approach, supporting data, and validation testing developed over the course of the program. Developed data, including predicted and measured residual stresses and retained interference levels, will be reviewed. Comparisons between blind damage tolerance predictions as well as post-dictions will be presented relative to validation coupon test results representative of wing rear spar and wing carry-through lower cover control points. Comparisons between coupons and excised components from B-1 wing carry-through structure will also be shared. Ultimately, a detailed DTA approach and validated correlation analysis results will be discussed as the gateway toward the "full credit" approach.

2. Results

The overarching scope of the program included the development of a physics based analytical methodology (Figure 1) supported by experimental data and validation testing utilizing the methods and input data as described below:

a. Multi-point crack growth analysis was utilized to capture specific geometry and stress state. This proved critical to allow the crack front to naturally evolve capturing the unique crack progression and damage tolerant life.
b. Input data was derived from geometric and residual stress measurements of representative coupons. The results indicated significant amounts of plasticity induced during Taper-Lok installation in all but one tested condition. Subsequent remote loading created additional plasticity in all coupons and effectively stabilized the stress state at the Taper-Lok fastener hole.
c. Explicit modeling of retained interference and residual stress was incorporated into the multi-point analyses utilizing the developed geometric and residual stress input data. Retained interference was modeled utilizing full contact between the fastener and the hole. Residual stress was modeled utilizing crack face traction. The combination of these inputs captured the unique non-linear relationship between remotely applied stress and the resulting stress intensities along the crack front.

Utilizing this established analytical methodology and input data, blind DTA predictions were completed for each of the test conditions, including baseline open hole tests as well as Taper-Lok installations. Validation testing included coupon level representative tests. After validation testing was complete, comparisons between blind predictions and test results were accomplished resulting in refinements to the analytical approach.

To ensure coupon level results were representative of actual B-1 structure, test components were excised from a previously in-service B-1 wing carry through structure. Geometric and residual stress measurements were completed and compared to coupon level results, which indicated very similar retained expansion and residual stresses. These resulted confirmed the validity of the coupon results and demonstrated the stress state stability of Taper-Lok fastener holes for the evaluated locations. In other words, the beneficial Damage Tolerance impacts of the Taper-Lok did not degrade under normal B-1 operational usage. Two sets of fatigue tests were also accomplished from excised wing carry through structure (unnotched and notch fastener holes). Both of these tests demonstrated significant fatigue life benefit relative to baseline life predictions and were utilized for additional validation of the established analytical methodology.

The resulting analytical predictions, validated with testing, demonstrated Taper-Lok damage tolerant life improvements ranging from 4-7x relative to a baseline open hole.

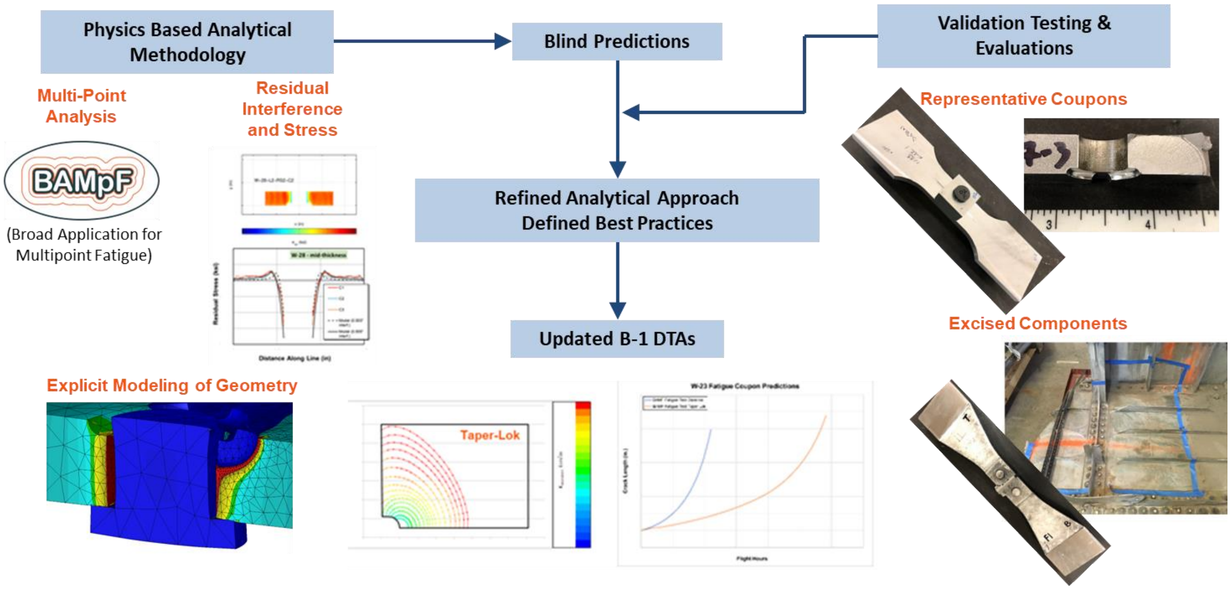

Fig.1 – B-1 Taper-Lok program approach.

3. Conclusions

A robust analytical process was established to characterize the behavior at Taper-Lok fastener holes. Key data was developed, including residual stress and interference measurements of replicate coupons and excised B-1 structural components. This analytical process was validated with a robust test program establishing baseline and Taper-Lok fatigue performance for a number of B-1 critical locations. Ultimately, this program established the analytical approach and validation data to support explicit incorporation of the physics of a Taper-Lok fastener installation for B-1 critical locations.

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