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A PRACTICAL APPLICATION OF THE RECENT FAR 25.571 REQUIREMENTS AND GUIDANCE FOR THE PRECLUSION OF WIDESPREAD FATIGUE IN A TRANSPORT AIRCRAFT

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Abstract. *The planned updates to FAA FAR 25.571 requirements for widespread fatigue damage in transport aircraft structures requires operators and manufacturers to establish on-going airworthiness maintenance programs that include inspections and component modification or replacement actions that preclude the on-set of such damage. The recent full scale fatigue test of the wings and fuselage of the P-3C Orion maritime patrol aircraft provided evidence of widespread cracking scenarios and offered an opportunity to trial the FAA proposed procedures as part of the test interpretation process. Examples are provided of both multi-site and multi-element damage scenarios and comment is made about the ease of using the FAA process and of the implications for future full scale testing.*

1 INTRODUCTION

US Federal Aviation Regulations (FAR) Part 25.571 for transport aircraft require a damage tolerance and fatigue evaluation to be carried out on the aircraft's structure. In 1998 amendment 25-96 introduced the requirement for test based clearance against Widespread Fatigue Damage (WFD) and stated that no airplane may be operated beyond half the equivalent number of cycles accumulated on the fatigue test article. More recently, the regulation and its accompanying Advisory Circular AC25.571 has been updated to provide more specific instructions regarding the preclusion of WFD in aircraft structures, including the establishment of an Initial Operating Limit (IOL).

From 1999 to 2006 the Defence Science and Technology Organisation (DSTO), a part of the Australian Department of Defence, participated in what was known as the P-3 Service Life Assessment Program, or P-3 SLAP. This was an international program led by the US Navy to conduct full scale fatigue testing and analysis of the Lockheed-Martin P-3 Orion anti-submarine warfare aircraft. As well as conducting one of the full scale fatigue tests in the program, a test of the empennage, DSTO carried out test interpretation activities for the complete structure using the results of all the full scale tests on behalf of its customer the Royal Australian Air Force (RAAF). The desire of the RAAF to extend the service life of their fleet of P-3 aircraft considerably beyond the original Safe Life limit set by the US Navy in their original testing program of the early 1960's meant the adoption of a safety-by-inspection program developed in accordance with FAR 25.571 airworthiness standard.

Within the P-3 SLAP the full scale test of the fuselage and wing structure was conducted by Lockheed-Martin, Marietta, Georgia and the test setup is shown in Figure 1. The structure was subjected to a relatively severe load spectrum for almost two and half lifetimes of 15,000 flight hours. The wing box structure proved to be the item that suffered the majority of the fatigue damage. A large amount of general cracking was observed during test cycling and upon teardown it was discovered that a number of structural items had also suffered from various manifestations of WFD. The extent of the fatigue cracking on the lower surface of the outer wing by the end of the test is shown in Figure 2. The subsequent WFD analysis for a selection of these wing locations will be presented in this paper.

2 CLASSICAL FULL SCALE FATIGUE TEST INTERPRETATION

The P-3 Orion maritime patrol aircraft evolved from the Lockheed Electra L-188 civilian turbo-prop passenger aircraft in the late 1950's and was thus designed against the US Civil Air Regulations CAR 4b. A test to demonstrate the fail-safe characteristics of both the pressurized fuselage and the wing box were conducted at the time. As part of the acceptance of the military P-3 version, the USN asked for full scale fatigue testing to be conducted on the P-3 wing using a USN usage based test spectra, subsequently adopting an aircraft durability limit based on the safe life approach and the results of the fatigue test. Whilst this approach has been satisfactory for the past 40 or so years, the desire for life extension coupled with the knowledge that aircraft usage patterns and structural configuration had changed led to the realisation that the structural airworthiness basis of the aircraft needed to be updated and so the P-3 SLAP program of full scale fatigue tests was conceived.

The RAAF chose FAR 25.571, the successor to CAR 4b, as the airworthiness standard against which to interpret the SLAP test results and conduct the durability and damage tolerance evaluation of the structure from which a program containing the necessary structural inspection and modifications and/or replacements could be determined. Guidance on conducting the fatigue and damage tolerance analysis (DTA) was taken from the applicable advisory circular, FAR 25.571-1C[1]. This advisory circular provides options for the determination of inspection threshold (either by crack growth from a small initial size or the application of a factor, generally of about three, on demonstrated test life) as well as requirements for the treatment of fail-safe and non fail-safe structure. The method chosen for the analysis used the factored test demonstrated life approach and combined both fatigue life modelling (strain-life based crack 'initiation' to a nominal crack size of 0.050 inches (1.27mm)) and crack growth analysis (classical linear elastic fracture mechanics) in a 'total life' analysis method. Estimation of inspection intervals used the calculated crack growth period from detectable size to the maximum permissible size under residual strength criteria divided by a suitable factor. The factor is not specified in[1] but a value of two was chosen in order to be consistent with equivalent US military standards. The method of conducting the durability and damage tolerance analysis and interpreting the test results is shown in Figure 3.

All in all some sixty locations where fatigue cracking had occurred on the various P-3 SLAP tests were examined using the above process, with the majority of the failure locations on the lower surface of the wing. For several of those locations it was apparent that rather than fatigue failures occurring at discrete local features, the failure mechanism was of generalised cracking in either the one part or adjacent parts and so assessments against WFD had to be conducted. Interacting cracks in one structural part is defined as Multisite Damage (MSD) whilst cracking in adjacent parts that may also lead to loss of residual strength is termed Multi-element Damage (MED). Examples are provided in the references.

3 WFD ANALYSIS

The WFD component of the test interpretation proceeded initially under the requirement in 25.571 for a clearance from WFD of a factor of two. For a location where the cracking was identified as MSD, the interacting nature of the cracking was modelled in the test interpretation analysis through adjustments to the beta factor solution and the critical crack size. During the DSTO work, however, the results of an FAA Airworthiness Advisory Working Group (AAWG) investigation into the prevention of WFD became available in the form of the AAWG reports and accompanying presentations[2,3,4] and these references were used to guide the WFD analysis Subsequently, the processes and requirements described in the AAWG reports and presentations have been incorporated with only limited changes into an advisory circular on Widespread Fatigue Damage, AC 120-YY[5]. A section has been added to AC 25-571, which is now at -1X (draft) status, to specifically address Widespread Fatigue Damage Evaluation and the regulations 25.571 (Damage tolerance and fatigue evaluation of structure) and Part 25 Subpart I – Continued Airworthiness 25.1807 have proposed amendments that will add the concept of an Initial Operating Limit (IOL).

3.1 The Concept of Limit of Validity (LOV) and Initial Operating Limit (IOL)

The original AAWG reports described the concept of a LOV, where an LOV designates the extent to which the maintenance program for supporting on-going airworthiness has been duly substantiated by testing, design and in-service data. The substantiating data could thus be a combination of in-service, analytical and test evidence. However, as described in the AAWG reports, whilst an LOV is the end of an existing substantiation path ‘it is not a brick wall but a gate that can be unlocked with a WFD program’ and the gathering of further data can lead to re-setting the LOV. The term LOV has not been carried forward into the draft advisory circulars, however the term IOL is used instead to describe the limit beyond which it has not been established that existing inspection, modification or replacement actions will preclude WFD from occurring. An aircraft thus may not operate beyond this limit. The IOL is required to be established via a WFD evaluation that uses the same range of data that was required to support the LOV concept. An Extended Operational Limit (EOL) is also defined, allowing persons to extend the IOL so long as the applicant can demonstrate that WFD will not occur based on the gathering of additional substantiating evidence.

3.2 WFD Evaluation

Under the proposed methodology WFD is precluded by establishing firstly a Structural Modification Point (SMP) beyond which an aircraft cannot be operated unless the relevant structural feature is modified or replaced. Secondly, precautionary inspections, where viable, are introduced at an Inspection Start Point (ISP). The SMP and ISP and their relationship to the point in time defined as the 'WFD average behaviour" point is shown in Figure 4. The SMP is established as a point reduced from the "WFD average behaviour" point by dividing by a factor of two if there are viable preceding inspections, or by a factor of three if inspections are not viable. This second option ensures that WFD in non-inspectable structure is treated in a similar fashion to the determination of a safe life for discrete cracking where AC 25-571-1C uses three as its underlying scatter factor. The "WFD average behaviour" point is the point in time when the average (50th percentile) WFD initiated crack reaches critical crack length in the WFD scenario which may include the effect of interacting cracks, $a_{crit\ WFD}$.

The ISP is to be determined via either statistical analysis of crack initiation data from test or in-service, or through the use of appropriate factors on average cracking behaviour. The AAWG documentation specifically noted that the inspections set up to detect emerging WFD are in addition to the normal inspection programs that may have been set up under a DTA program to detect discrete cracking. The WFD based inspections may well be at a different frequency if crack interaction results in adjustments to critical crack lengths or geometry (beta) factors. More typically, however, the existing DTA based inspections will have already been adjusted for such issues and therefore the inspection intervals from both programs will be the same.

The above requirements as they have been described were applied to the P-3 SLAP full scale fatigue test findings at those wing locations that were identified as exhibiting WFD. One MSD example and one MED example are described in the next two sections.

4 P-3 MSD EXAMPLE

One feature that failed consistently and relatively early in the test program were the chordwise rows of dome nut holes either side of each engine nacelle. These holes are essentially open holes in the wing planks, flanked by rivets supporting the underlying nut plate and through which screws fasten the nacelle fairings to the wing surface. Cracking occurred in nearly all the dome nut holes, the linking up of which in a classical MSD scenario would result in failure of one or more wing planks and the inability of the wing to support the required residual strength load.

The dome nut hole cracking that existed at about the midway point in the test is shown in Figure 5. The average size of the cracks at wing station (WS) 158 in the region identified as Fatigue Critical Area (FCA) 352, the row inboard of the inner nacelle and the location chosen for the analysis, was 0.56 inches (14.2 mm) at a total of 16,785 test hours plus 10,988 pre-test hours of equivalent service usage. Critical crack length ($a_{crit\ WFD}$) was calculated to be 0.45 inches (11.4 mm) and the combined hours to reach this point (27,200 hours - Figure 6), calculated by tracking back down the analytically determined crack growth curve from the 0.56 inch test determined point. The tight grouping of hours to failure of the individual dome nut hole cracks on the test, meant there was almost no uncertainty in the point of "WFD average behaviour". Using the factor of two required by the WFD methodology resulted in an SMP for the WS 158 dome nut hole feature of 13,600 test hours (see Figure 6).

In the US Navy P-3 fleet a large number of aircraft had already passed this calculated structural modification point by the time the P-3 SLAP test interpretation work had been completed, and so a fleet wide inspection program was immediately undertaken. A large number of cracked holes were found which then afforded a statistical approach to determine the probability density function of hours to crack initiation. Assuming a log-normal distribution for the cracking population means that when the time to crack initiation data is plotted on a probability versus log normal hours graph, the slope of the data represents the standard deviation and the 0.5 probability point the mean life. The US Navy results were plotted in this manner and are shown in Figure 7. Fifty percent probability of cracking is defined as the WFD average behaviour point and this occurs at 23,470 hours for the US Navy fleet, giving an SMP of 11,735 hours. In terms of full scale test hours, the US Navy results were adjusted for the difference between test and fleet usage severities, resulting in a WFD average behaviour point of 21,750 test hours and an SMP of 10,875 test hours. However, this result does not include the full crack growth to $a_{crit\ WFD}$ as the cracks found in the US Navy fleet were generally small. Consequently, the test derived SMP was regarded as validated by the service experience and its use would result in around 2% of the fleet experiencing one or more cracks in the dome nut holes at the SMP point.

5 P-3 MED EXAMPLE

At the conclusion of the full scale fatigue test it was observed that a large amount of cracking had occurred in the lower front spar cap and in the adjacent components at their common holes, ie in the front spar web and the first wing panel, see Figure 8. This cracking occurred along the length of the lower front spar cap of the outer wing but was most prevalent in the region of the inner engine nacelles covered by FCAs 351 and 361. Consequently, the region was selected for subsequent WFD analysis. Analysis calculated that if the front spar cap failed from a crack of critical length at the residual strength requirement of limit load, only very small cracks needed to be present in the adjacent structure before they in turn failed and complete wing residual strength was lost. The potential presence at the same wing station of a missed crack in the spar cap and un-detectable cracks in either the spar web or #1 plank thus represented a MED scenario that needed considering.

The crack findings in the cap, web and #1 plank at the completion of the test on the left hand wing are provided in Figure 9, demonstrably showing the possibility of cracks lining up in chordwise fashion. The cracking present in the spar cap at the conclusion of the test was initially taken to represent average cracking and by adjusting from the average crack size at the end of the test of 0.242 inches (6.1 mm) to the spar cap critical crack length of 1.17 inch (29.7 mm), a value for the SMP was determined as 20,300 test hours. However, whilst the end of the test point was judged to represent the point of WFD average behaviour, less than 50% of spar cap holes were cracked. How soon the frequency of cracking reached 50% was not initially calculated so the value of 20,300 test equivalent hours represents a conservative value. Calculating a combined probability of a critical crack in the spar cap with a crack in either the web or panel at the same fastener hole could also have been carried out, however the guidance from the AAWG reports and the draft AC-120YY is that the MED failures should be assumed to be adjacent and no benefit should be taken based on the probability of such an event. Subsequent work plotting the fraction of spar cap holes with critical cracks versus test hours in an effort to apply a more statistical approach in the same fashion as for the dome nut holes, see Figure 10, produces a WFD average behaviour point of 53,300 test hours and a related SMP value of 26,650 test hours. Note however, that the limited amount of data makes extrapolation to the 50% cracked point more uncertain as the standard deviation of the cracking population becomes difficult to know with confidence.

CONCLUSIONS

The availability of recently gathered full scale fatigue test cracking data as part of the P-3 SLAP test offered an opportunity to apply in a practical sense the proposed FAA WFD methodology as part of the test interpretation and life extension effort for the P-3 Orion. The methodology proved to be reasonably straightforward to apply in the context of the availability of extensive fatigue test data.

The most problematic step in the process was the definition of the "WFD Average Behaviour" point. In the current example this was facilitated by the availability of extensive test data from a test that was run longer than the sometimes suggested minimum of two lifetimes. Where WFD crack population data is limited or not existent, either from in-service or from tests that have been terminated prematurely, the definition of the WFD Average behaviour point will be uncertain and necessarily conservative. This suggests yet another reason for fatigue tests to be run for longer than two lifetimes as standard practice.

REFERENCES

[1] Federal Aviation Administration, *Advisory Circular – Damage Tolerance and Fatigue Evaluation of Structure*, Federal Air Regulations 25, AC No. 25.571-1C, 1998.

[2] Airworthiness Assurance Working group for the Aviation Rulemaking Advisory Committee's Transport Aircraft and Engine issues Group, *"Recommendations for Regulatory Action to Prevent Widespread Fatigue Damage in the Commercial Airplane Fleet"'* Final Report, Revision A June 29, 1999.

[3] Airworthiness Assurance Working Group for the Aviation Rulemaking Advisory Committee's Transport Aircraft and Engine issues Group, *"Widespread Fatigue Damage Bridging Task Mandatory modifications"*, Final Report July 2003.

[4] Airworthiness Assurance Working group for the Aviation Rulemaking Advisory Committee's Transport Aircraft and Engine issues Group, *"Widespread Fatigue Damage Bridging Task Multiple Element Damage"*, Final Report July 2003.

[5] Federal Aviation Administration, *Advisory Circular – Widespread Fatigue Damagee*, Federal Air Regulations 25, AC No. 120-YY (Draft).

Figure 1: P-3 SLAP Wing/Fuselage Fatigue Test Article and Rig at Lockheed-Martin, Marietta, GA

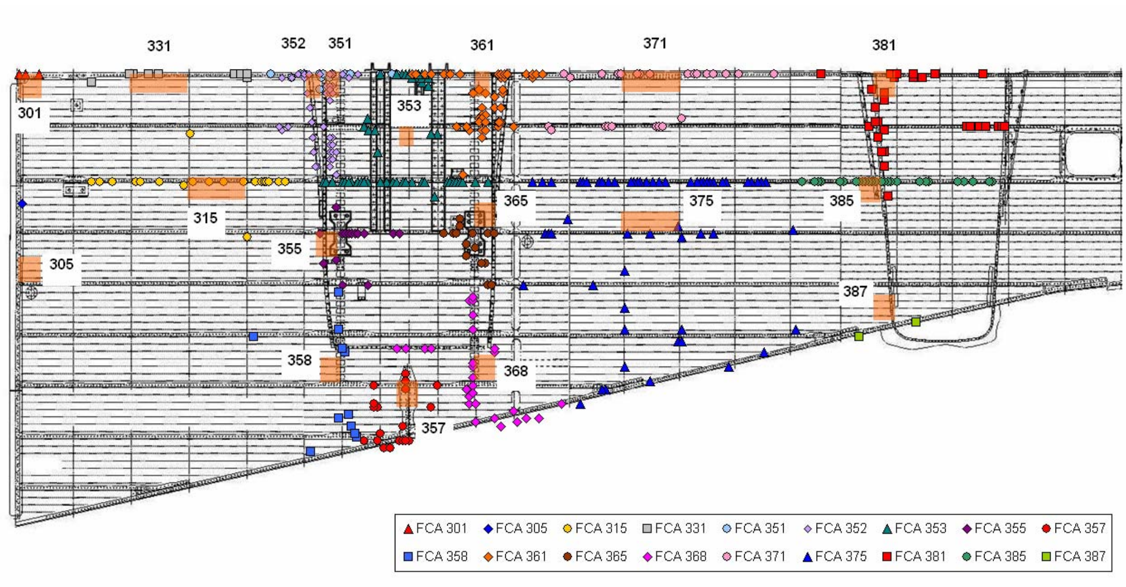

Figure 2: P-3 Lower Outer Wing Defect Locations identified and sorted by Fatigue Critical Area (FCA) during the test interpretation process

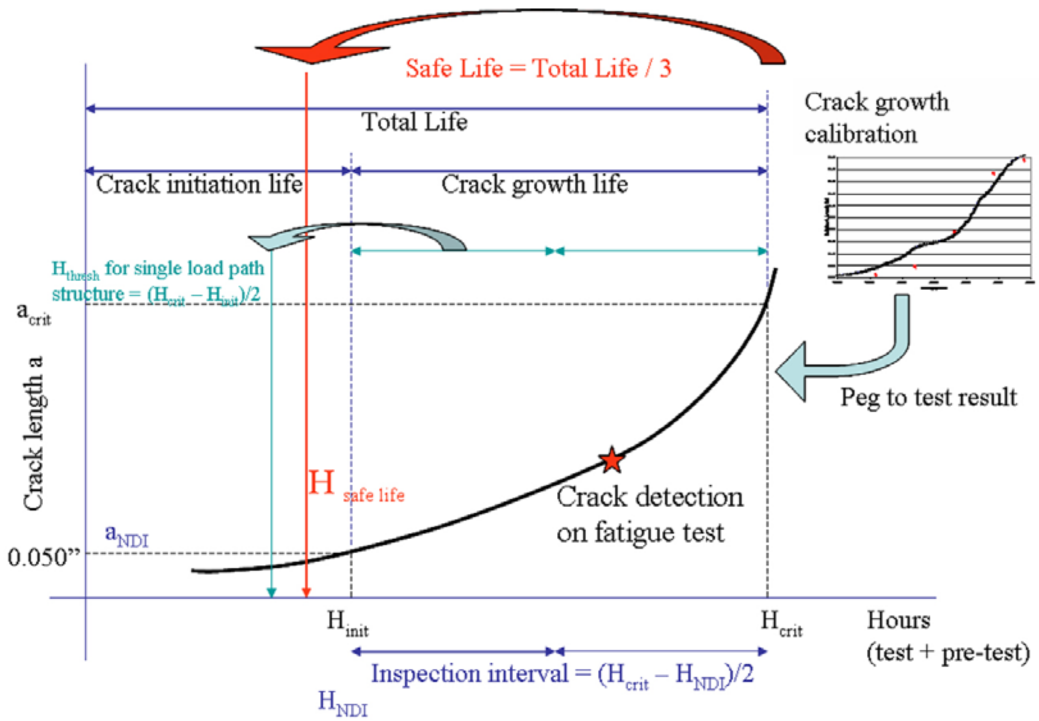

Figure 3: P-3 Test Interpretation Procedure used by DSTO

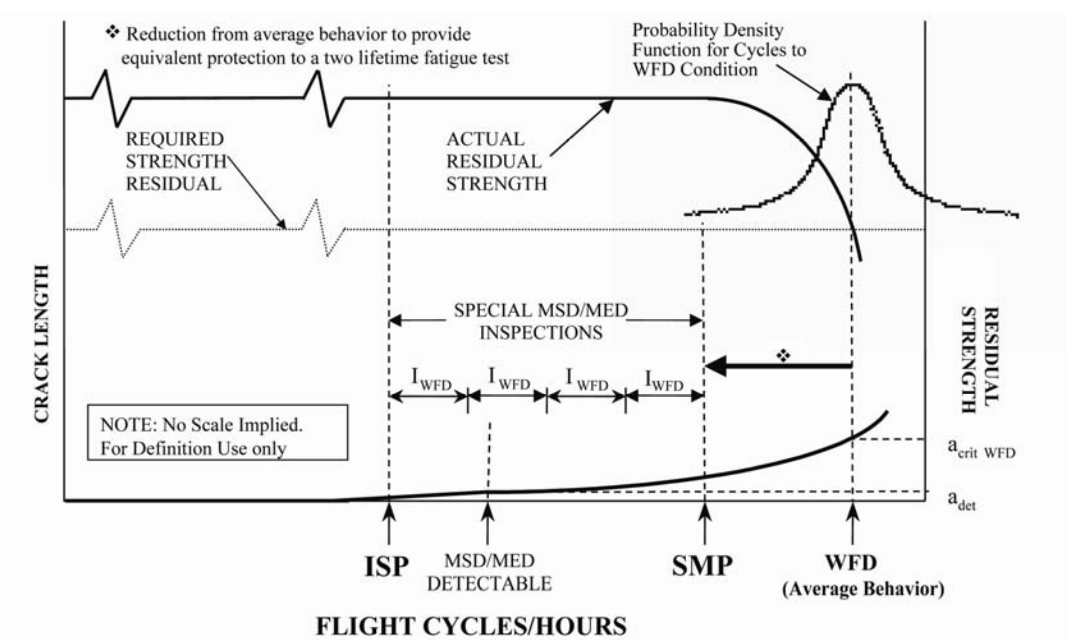

Figure 4: FAR 25 WFD Evaluation Process

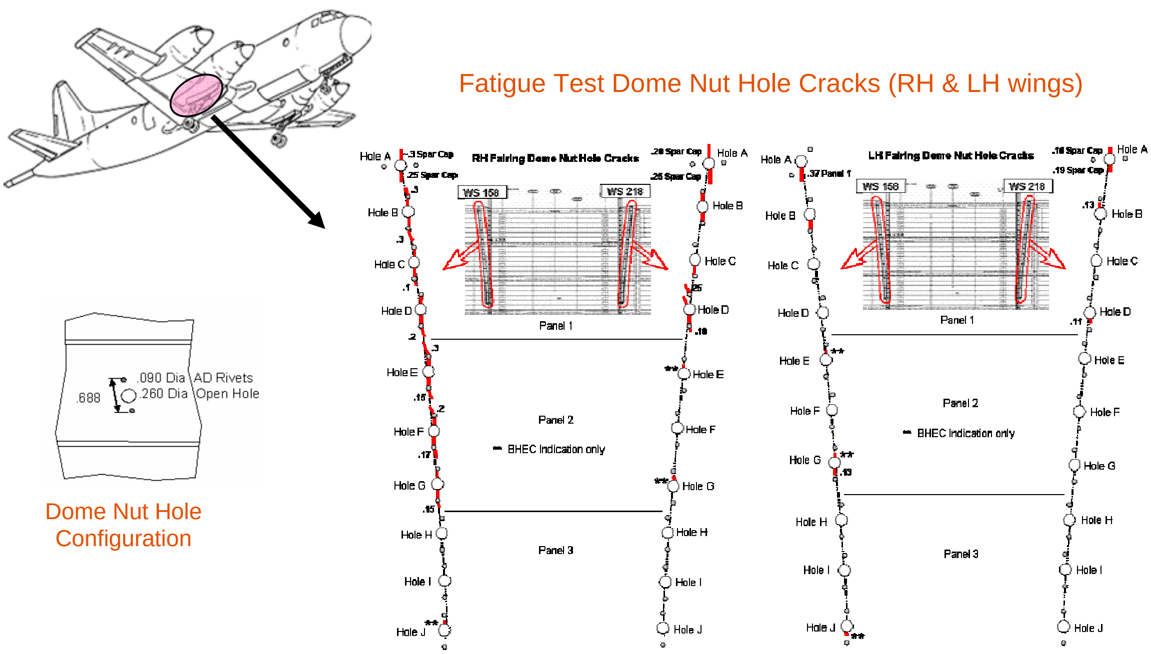

Figure 5: Inboard Nacelle Fairing Dome Nut Hole Cracks in Lower Wing Skin Planks

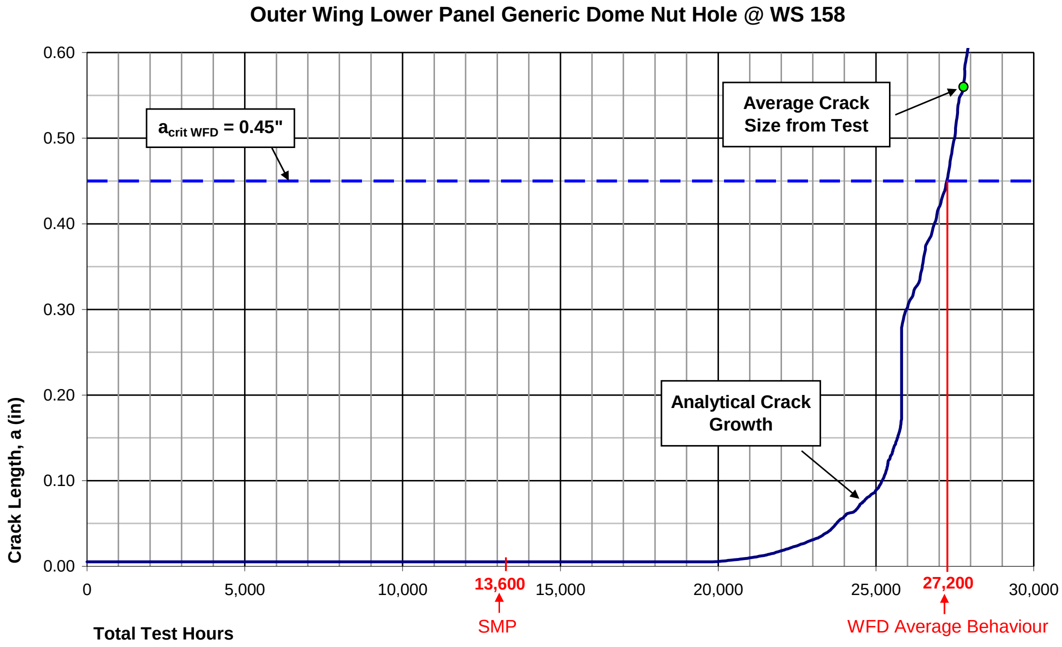

Figure 6: Dome Nut Hole WFD Analysis

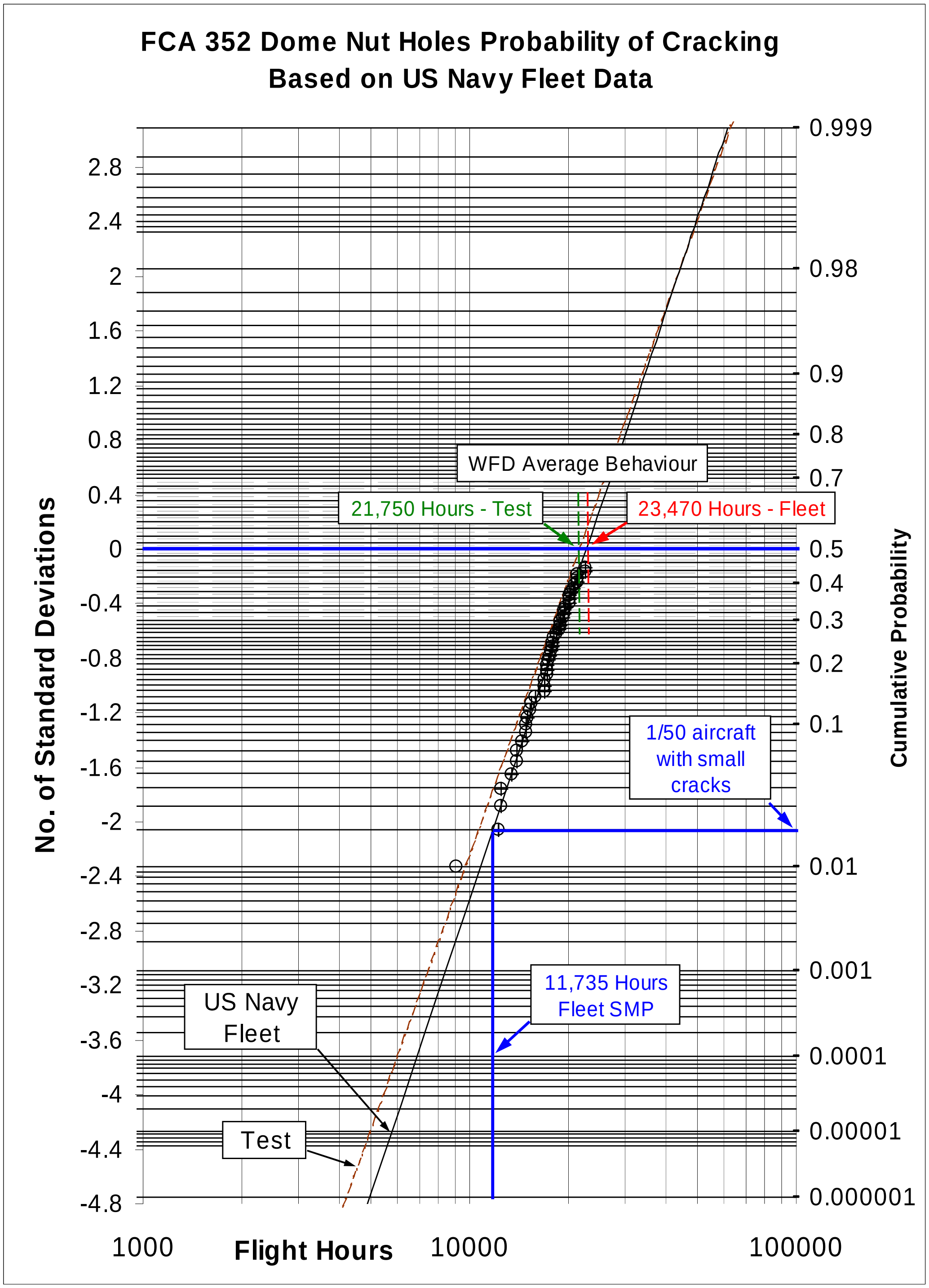

Figure 7: US Navy Fleet Probability Analysis at Dome Nut Holes

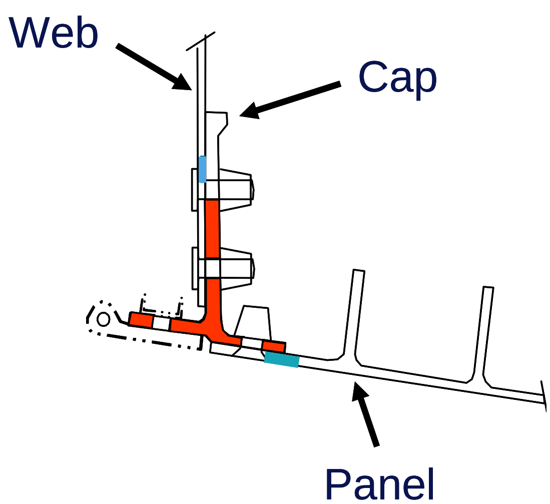

Figure 8: Lower Front Spar Cap, Web and Panel (Typical)

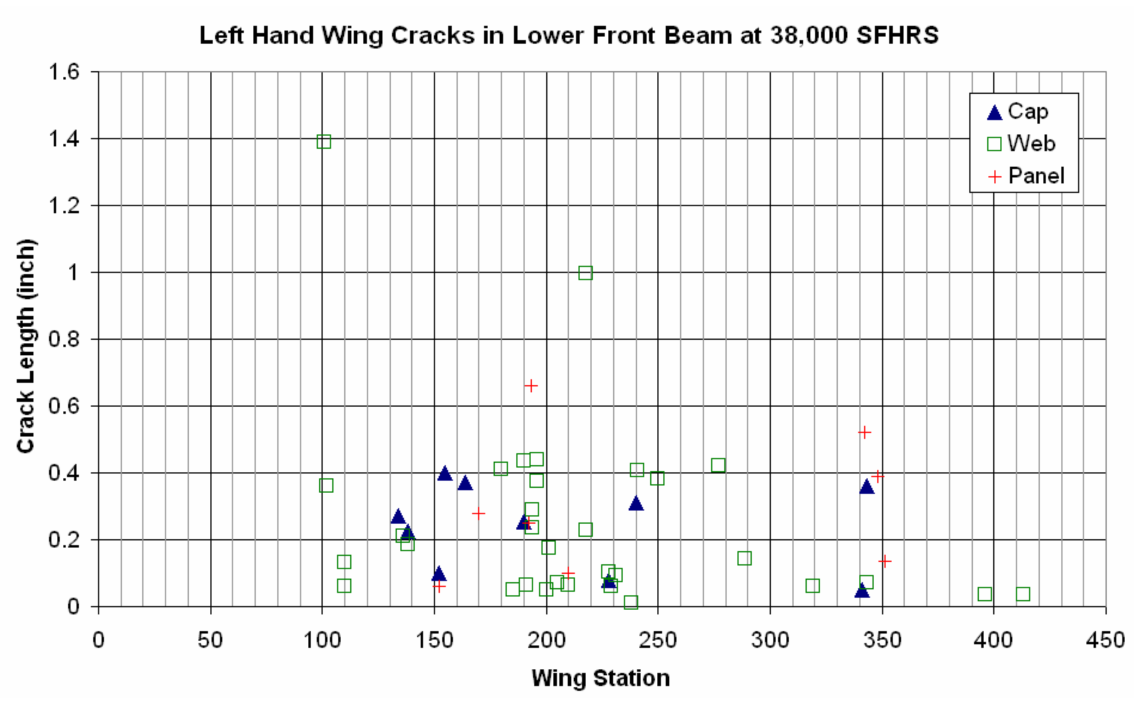

Figure 9: Cracks in Left Hand Lower Front Spar Cap, Web and Panel

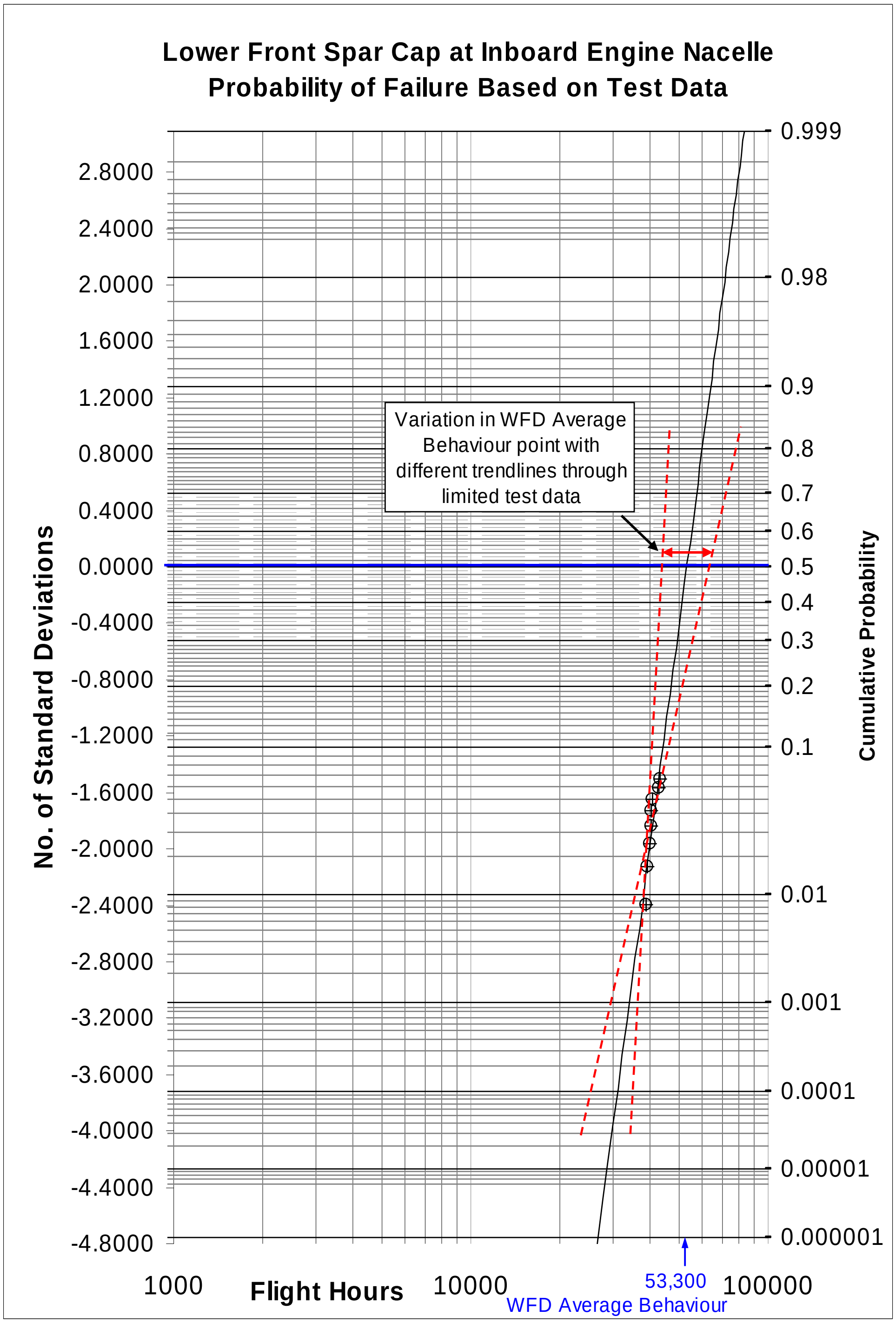

Figure 10: Test Probability Analysis at Lower Front Spar Cap