**Crack-like Effectiveness of Some Discontinuities in AA2024**

L. Molent1 and M.R. Fox2

1Molent Aerostructures, Melbourne, Australia

2National Transportation Safety Board, Washington, DC, USA

Correspondence: Molent Aerostructures, Melbourne Australia. Email: clanmolent@bigpond.com

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**Abstract**

Maintaining aircraft airworthiness to ensure the fleet’s safe operation and maintain its readiness is critically dependent on accurate modelling and reliable predictions of fatigue crack growth. In this process a knowledge of the representative initial discontinuity sizes that cause fatigue crack nucleation and early growth in aircraft is essential.

Here the effective pre-crack size of aluminium alloy 2024, from samples of aircraft production material and tested under aircraft spectra, are considered.

**Introduction**

For those maintaining aircraft airworthiness to ensure the fleet’s safe operation, conducting failure analyses of cracked components to ensure fleet readiness is critically dependent on accurate modelling and reliable predictions of fatigue crack growth (FCG).

Failures from metal fatigue and unexpected fatigue cracking that requires active management still occur in airframe components (e.g. [1,2]), despite over 170 years of research into the subject. Design tools and processes are generally adequate to ensure safety but are less satisfactory for cost effective sustainment (also referred to as ‘durability’), which may be impacted by unexpected fatigue cracking and non-critical failures.

Fatigue cracks of significance to fleet life management generally nucleate at high stress areas subjected to variable amplitude loads shortly after these loads are first introduced. These cracks nucleate from material or production induced discontinuities. Thus, one of the critical parameters required to conduct a FCG assessment is a measure of the crack-like effectiveness of the nucleating discontinuity.

Whilst several metrics have been proposed to characterize initial discontinuities or flaws (e.g. [3-10] including the Equivalent Initial Flaw Size (EIFS), this paper uses the Equivalent Pre-crack Size (EPS) concept [11-17] as described below.

Here the EPS distribution of aluminium alloy (AA) 2024, from limited available aircraft production material tested under aircraft spectra, are considered.

**2 Effectiveness of Initial Discontinuities**

Whilst many metrics have been proposed to estimate the crack-like effectiveness of initial discontinuities (e.g. depth, area, etc.), it is now known that despite these metrics, not all types of discontinuities (e.g. mechanical damage, inclusions, pits, pores, etc.) are similarly effective in nucleating FCG [12,14,15] (given the same material, loads spectrum, etc.). Early studies have shown the EPS concept is able to differentiate between the most effective discontinuity type (e.g. mechanical damage and etch pits) to least effective (e.g. porosity) [14,15].

Rudd [5,6], Pinckert [7], Manning and Yang [8,9] and Potter and Yee [10] were amongst the first to introduce the concept of an EIFS (or Equivalent Initial Quality Method (EIQM)). Manning et al. [8] then revealed that physically small crack growth in aircraft could be expressed in the form:

da/dt = Q ab (1)

where a is the crack length/depth, t is cycles, Q was both material and spectrum dependent and b was 0.97 (i.e. approximately 1). In the initial small crack region, it was subsequently recommended [9] that the value of b was taken as 1 so that the crack length could often be expressed in the form:

a = aoeλt (2)

where λ was a constant and ao was the EIFS. Both [8,9] recommended that the EIFS be determined via quantitative fractography (QF). QF of a fracture surface involves matching significant progression marks to known loading events in the spectrum or usage, environmental exposure etc, see [18].

Molent et al. [12,14], Molent [15], and Molent, Barter and Wanhill [11] recommended a similar QF-based lead crack approach where the EPS sizes for (mainly) AA7050 were shown to range from 0.0077 to 0.129 mm. Lead (or primary) cracks are those that result in failure. References [11-16] used the terminology EPS, rather than EIFS. This is because although the United States Air Force (USAF) recommended approach to calculating EIFS [5-10] has not been rescinded, the term EIFS (or more recently Effective Initial Discontinuity Size (EIDS)) is commonly used to refer to an “artificial” initial size that when used with FCG codes such as AFGROW, FASTRAN, NASGRO, etc., the resulting FCG analysis would give a reasonable estimate of the total fatigue life.

There are two different interpretations of the term EIFS results from statements contained in [5]:

1. “If the Equivalent Initial Quality Method is to be used to obtain the initial crack size to be used in economic life predictions, then it may be desirable to obtain good agreement between the analytical prediction and the fractographic test data for crack sizes up to 0.03 inch [sic 0.8 mm] allowing removal of cracks by reaming the fastener hole to the next nominal hole size.”

The EPS approach is consistent with this definition of the EIQM.

1. “Similarly, if the Equivalent Initial Quality Method is to be used to obtain the initial crack size to be used in establishing inspection intervals or fracture limits, then it may be desirable to obtain good agreement between the analytical prediction and the fractographic test data at failure (ae = ac). The initial crack size (crack size when the load history is first applied), ai, of the analytical crack growth curve which correlates best with the fractographic test data is defined as the equivalent initial quality.” This definition led to the development of the current EIFS concept. (Where ac is the critical crack size and ae is the crack size after Ne cycles).

However, it should be noted that whereas the use of an EIFS can give reasonable values for the total life, the shape of the resultant crack size versus cycles history is often erroneous. (Note: the method can be improved by using physical short FCG rate data).

Whilst the original EIFS method relied on the observation of exponential (or log-linear) FGC, there are some differences in the way an EPS is estimated. Importantly the EPS relies on early FCG (often in the physically short crack regime). This is primarily to avoid potential departures from exponential growth due to factors such as load shedding, changes in component geometry as the crack grows, etc. (see [14]). In the following analyses judicious choice was made of that early cracking period.

Molent, Barter and Wanhill [11] recommended an EPS of approximately 0.01 mm for 7000 series AA. A comprehensive list of the EPS values associated with 7000 series alloys was given in [12], where the EPS values are shown to range from approximately 0.002 mm to approximately 0.0774 mm. (Note in [12] the EPS values were evaluated based on surface finish of the items tested, whilst in [14,15] estimated EPS values were based on discontinuity type). The EPS value of 0.01 mm recommended in [14] represents the log average of a statistically significant sample size; see Figure 1 for AA7050 for example. This value was found to hold for both etched and machined specimens and was also shown to correspond to the value associated with numerous full-scale fatigue tests (FSFT).

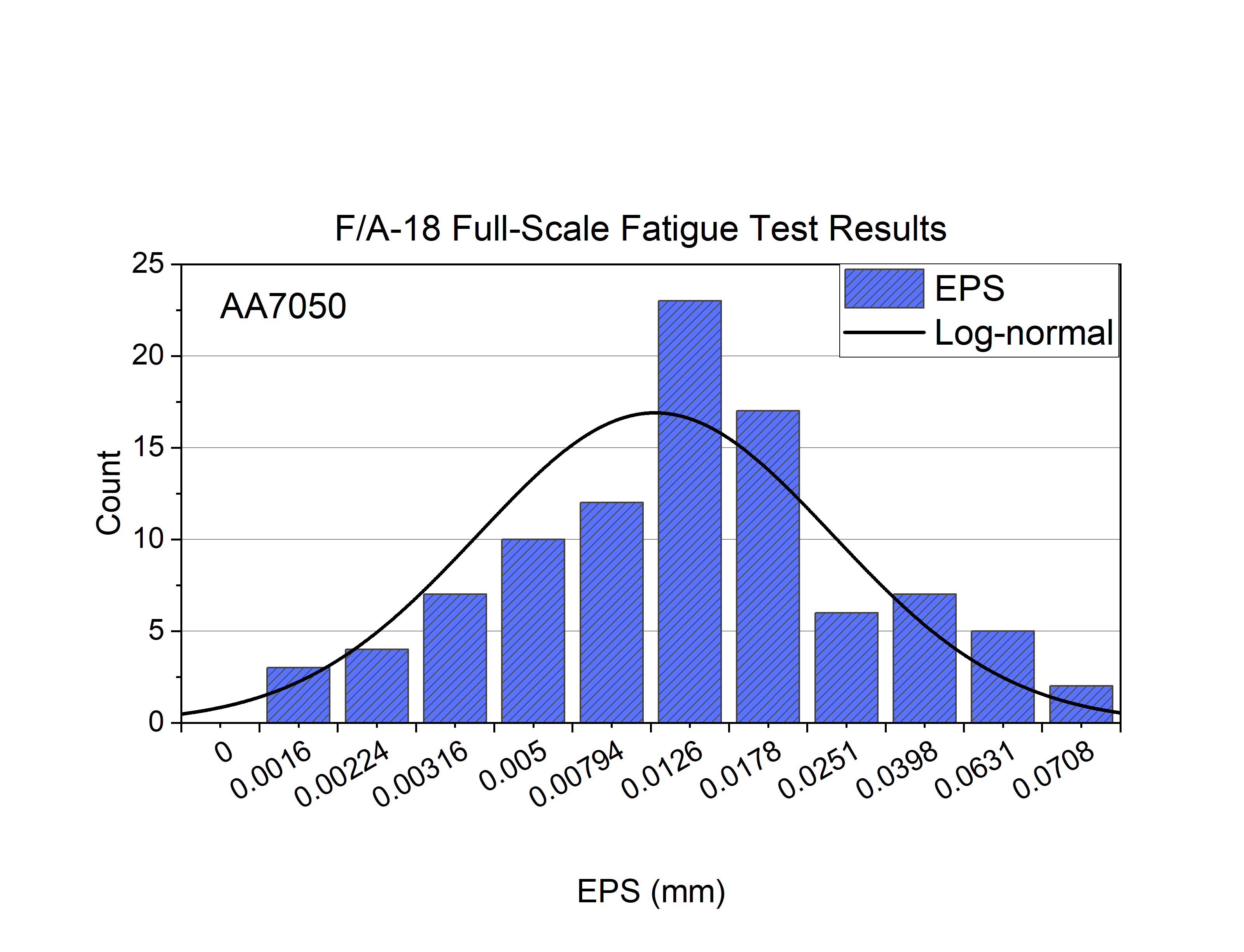


Figure 1: Log-Normal Distribution of EPS values from 97 full-scale fatigue test results, adapted from [14][[1]](#footnote-1)

**3. Data from aircraft representative AA2024**

It is important that the EPS represents the material and production finish of the subject in question. A review of the literature revealed a number of relevant data related either to FSFT or aircraft representative specimens with FCG data derived from QF [19-25][[2]](#footnote-2). EPS analyses of these data follow[[3]](#footnote-3).

1. Main spar from a Pilatus PC-9 turboprop training aircraft FSFT [19]

Material: AA2024-T3 alloy extrusion

Post analyses of the Pilatus PC-9 FSFT tested by the Australian Defence Science and Technology Group (DST) under service representative loading revealed cracking in several fastener holes about the root of the main spar. Each crack was likely to have experienced difference in stress given its location along the spar. The available data are shown in Figure 2 which also contains exponential trend lines which define the EPS (i.e. back-projection to zero hours). The derived EPS values are given in Table 1.

1. Representative USAF fighter and heavy bomber multi-hole, no-load-transfer specimens [20]

Material: AA2024-T851, thickness = 9.525 mm, no load transfer (note: the temper is not considered to effect resulting EPS).

These multi-hole, no-load-transfer specimens were tested by the USAF under both the General Dynamics F-16 fighter aircraft 400-hour spectrum and the Rockwell B-1 heavy bomber aircraft spectrum. Two different stress levels were tested. The fasteners were representative of those used on the aircraft. The available data are shown in Figure 3 through Figure 5. The derived EPS values are given in Table 1.

1. Main spar from a Pacific Aerospace Corporation CT-4 reciprocating single-engine flight trainer FSFT [21]

Material: AA2024-T3 extrusion

Measurement: QF (note: available data in [21] does not show individual data points (solid lines))

Results are from the FSFT conducted by the DST under representative service loads. The available data are shown in Figure 6 which also contains exponential trend lines which define the EPS. The derived EPS values are given in Table 1.

1. Representative multi-hole coupons for transport aircraft [22, 23]

Material: AA2024-T3

Multi-hole specimens tested by Wang under a transport aircraft lower wing spectrum. Two thicknesses were considered. The available data are shown in Figure 7 which also contains exponential trend lines which define the EPS. Note, as will be shown below an EIFS distribution was derived [22, 23] however the reference only provided data for two FCG curves. The derived EPS values are given in Table 1.

1. Wing structure from several General Dynamics F-111 fighter/bomber FSFTs and representative coupon testing [23,24]

Several General Dynamics F-111C aircraft wing FSFTs were conducted by the DST [see 24-25]. The material was AA2024-T851 and numerous cracks from the lower wing skin fastener holes (with Taper-lok fasteners) or specimens were analysed by QF.

In conjunction with the FSFT, significant coupon testing programs were conducted. The ‘dog-bone’ style coupons with a calculated stress concentration factor of 2.5 were cut from F-111 wing sections and designed to represent critical wing locations from the wing splice to Forward Auxiliary Spar Station (FASS) 281[[4]](#footnote-4). All coupons were manufactured from AA2024-T851 and were chemically pre-etched after machining.

The available data are shown in Figure 8 to Figure 10. The derived EPS values are given in Table 1.

3.1 Summary

The data considered for the EPS analyses represents aircraft-production AA2024 tested under various variable amplitude spectra. Different stress levels were considered as well as geometry variations including neat-fit countersink holes.

None of the references provided details of the type of nucleating discontinuity from which the cracks grew, therefore only the average EPS for ‘all’ discontinuities could be calculated.

From this limited analysis, a mean EPS for AA2024 of 0.0223 mm depth with a standard deviation of 0.0260 mm were derived.

4. **EPS probability distributions**

The distribution of the likely EPS population in a structure is an important consideration for the calculation of probability of failure from fatigue (e.g. [26]). In this section, a log-normal distribution approximation was used to conduct a preliminary assessment of the population of EPS. The log-normal distribution was chosen here as it had been used in previous investigations (see Ref. [12-16]). However additional analyses are required to determine the most appropriate distribution (preferably for each surface finish considered). Here the frequency distributions of the EPS were compared against a hypothesised log-normal distribution, Figure 11. The distribution appears to compare well to that derived for the AA7050-T7451 data (see Figure 1 and [12-16]).

**5. Other Studies**

A search of the literature revealed other studies for AA2024 that addressed nucleating defects [28-53], but few attempted to quantify the effectiveness of the initiating discontinuities.

Despite some shortcomings[[5]](#footnote-5) inherent in many of these tests, crack growth was, as stated in many, due to either crack nucleation at constituent particles, mechanical damage or near crystallographic pit colonies. As such, these nucleating defects were similar to those reported in [11] for other aerospace quality aluminium alloys.

An EIFS distribution for AA2024-T3 6.35 mm sheet was derived in [22,23]. “The procedure to generate the EIFS data generally consists of backward extrapolation of the crack growth curves to the zero cycles of loading. The experimental curves have been developed through regression analyses of fractographic test data.” Given that the FCG data conform to the lead crack concept, see Figure 7, then this definition is consistent with that of EPS. A log-normal distribution approximation was used to conduct a preliminary assessment of the population of EIFS/EPS, Figure 12. A mean EIFS value of 0.0193 mm with a standard deviation of 0.005588 mm was derived [23]. This compares favourably to the 0.026 mm mean and 0.0262 mm standard deviation calculated above.

For completeness, EIFS were also calculated for 1.6-mm-thick AA2024-T3 fuselage lap joint specimens in [41], with the FCG data reproduced in Figure 13. Unlike data presented above, the loading history was constant amplitude with some marker loads added to aid post-test QF, which was used to reconstruct the FCG curves. The AFGROW program was used to calculate the EIFS for the data shown and was limited to crack sizes less than 1.27 mm (chosen arbitrarily). The mean and standard deviation of the EIFS was 0.01833 and 0.003784 mm respectively. Due to the lack of data close to zero hours, no attempt at calculating the EPS distribution was made using this data.

**6. Conclusions**

The starting point for any fatigue failure calculation is the effective size of the nucleating discontinuity (in the absence of pre-test-cracked notches, etc.). A variety of nucleating discontinuities arise in production materials, including mechanical damage, pores, broken inter-metallics, etc. Several metrics have traditionally been proposed to characterise the effectiveness of the discontinuity in terms of its crack-likeness. As not all discontinuities are initially crack-like, the success of these metrics vary. Herein the Equivalent Pre-crack Size (EPS) of production quality aluminium alloy 2024, tested under multiple aircraft spectra, was considered using the lead crack concept. As the crack growth data considered did not identify the type of nucleating discontinuity, only a general discontinuity EPS was calculated. The mean and standard deviation of the derived EPS was approximately 0.0223 mm and 0.0260 mm, respectively. The data were also shown to adequately fit a log-normal distribution.

Future research should attempt to develop distributions for specific discontinuity types and address the efficacy of the log-normal distribution.

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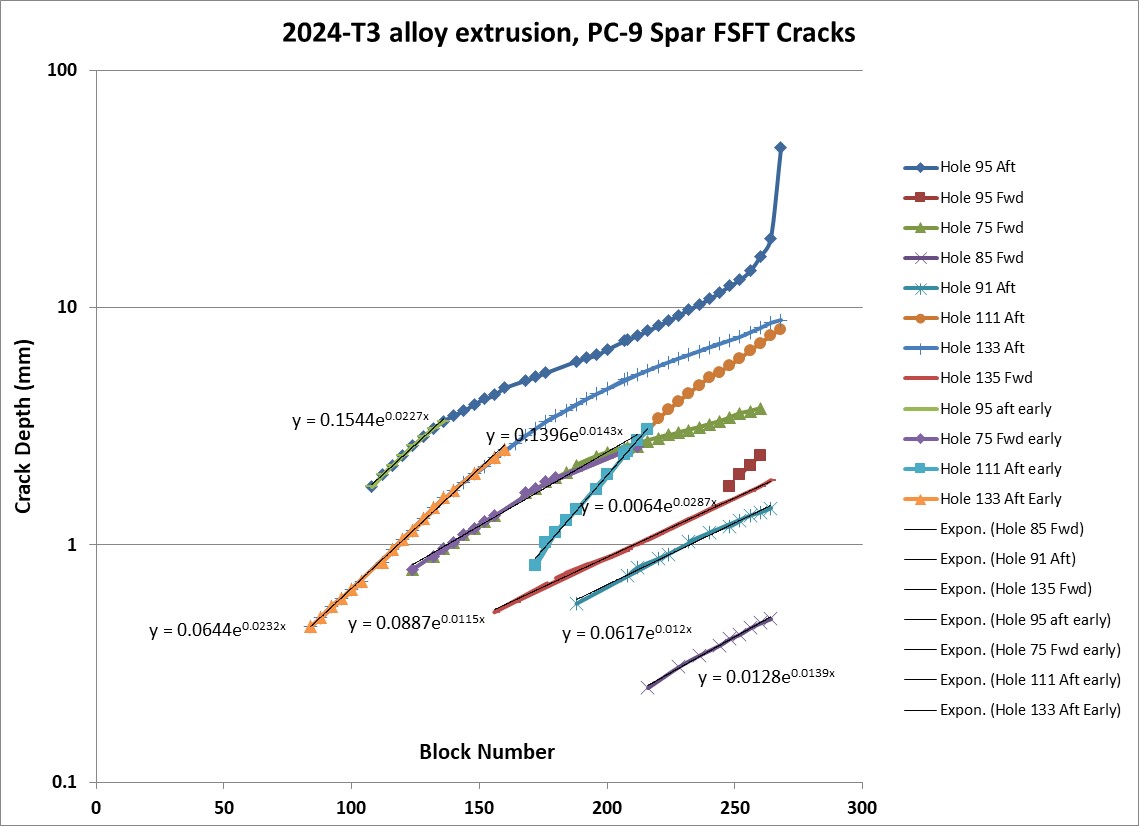


Figure 2: QF-derived FCG curves from the DST’s Pilatus PC-9 FSFT [18]. Shown are regression fits for the early or total exponential growth period.

Graphical user interface

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Figure 3: FCG in USAF TLFC and TFMC specimens with countersunk holes (NAS1580 fastener) tested using the 400-hour General Dynamics F-16 spectrum [20]. Regression lines shown.

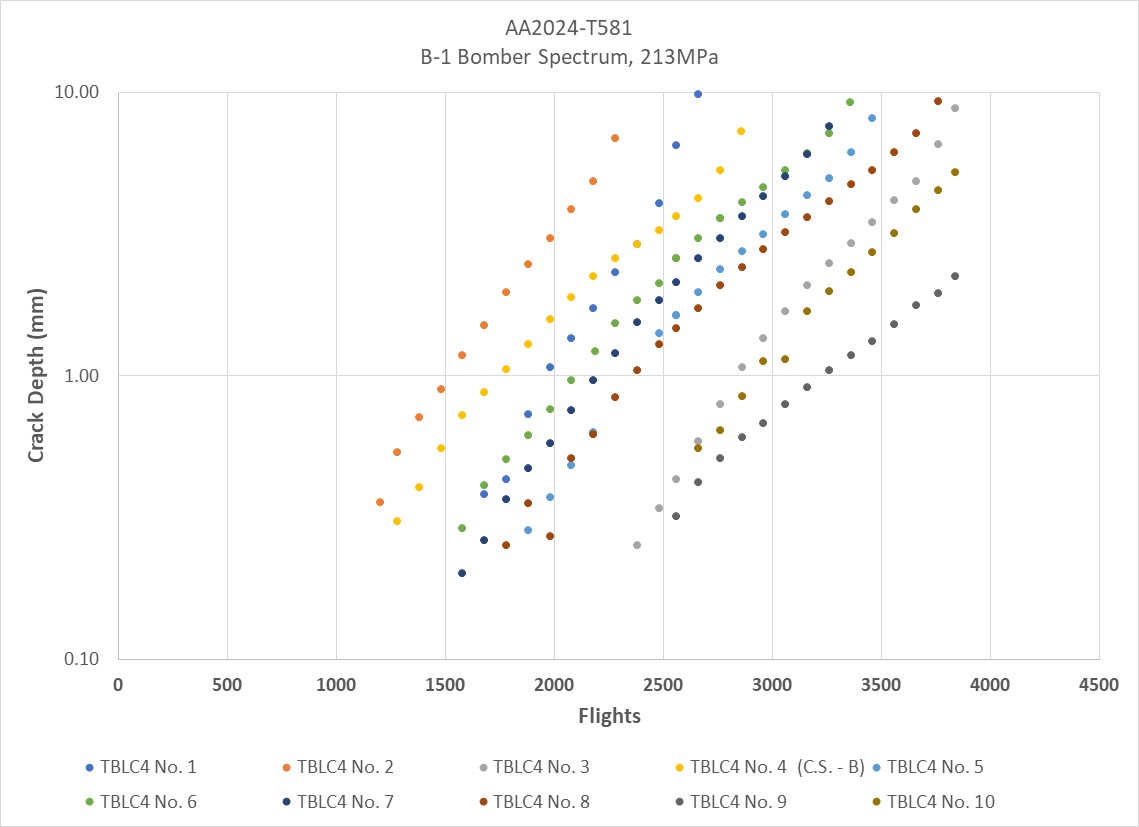


Figure 4: FCG in USAF TBLC4 specimens with countersunk holes (NAS1580 fastener) tested with the Rockwell B-1 heavy bomber spectrum [19]. Regression lines not shown for clarity.

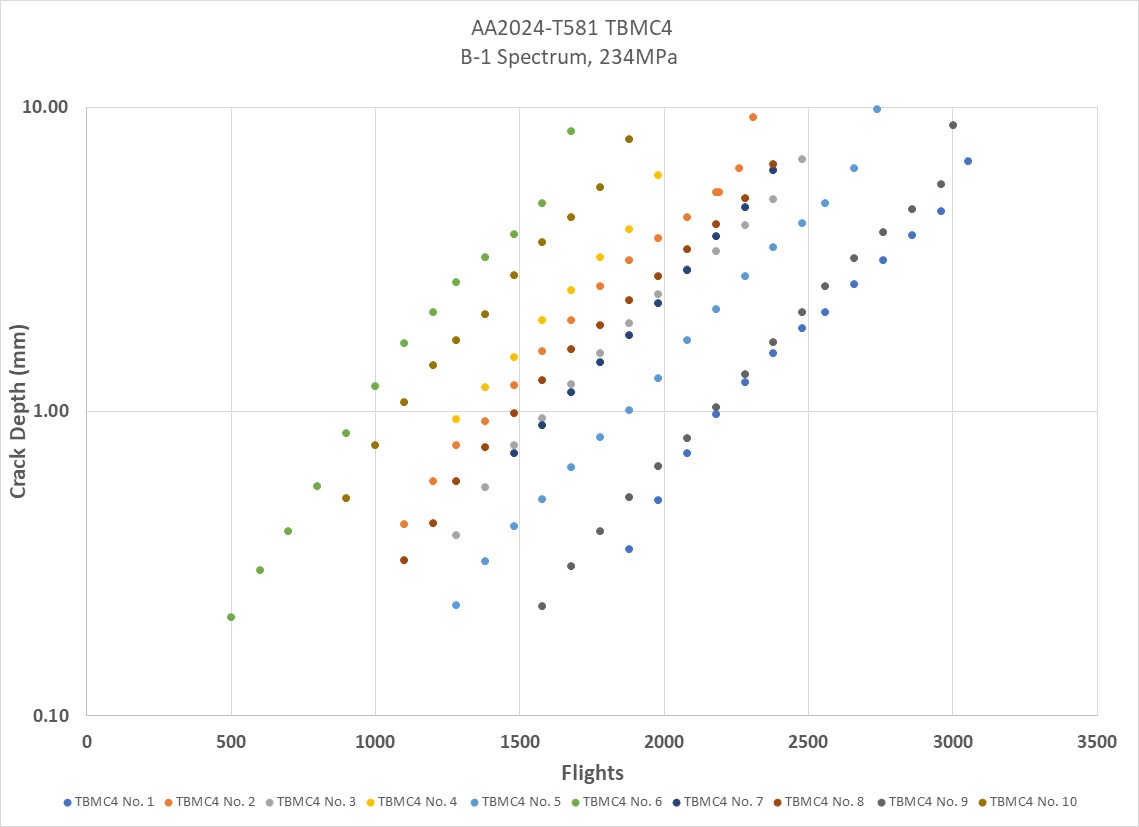


Figure 5: FCG in USAF TBMC4 specimens with countersunk holes (NAS1580 fastener) tested with the Rockwell B-1B heavy bomber spectrum [19]. Regression lines not shown for clarity.

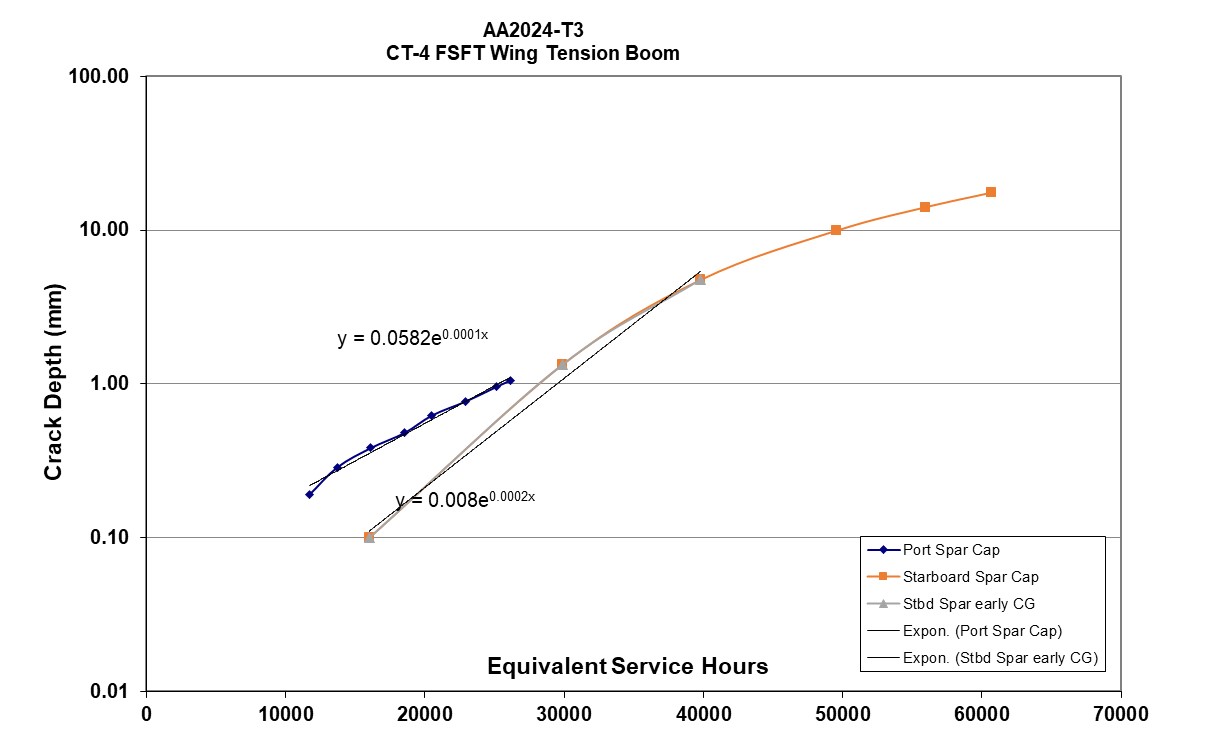


Figure 6: Main wing spar FCG in DST’s FSFT of a Pacific Aerospace Corporation CT-4, main wing spars cracking [20]. Shown are the regression fits.

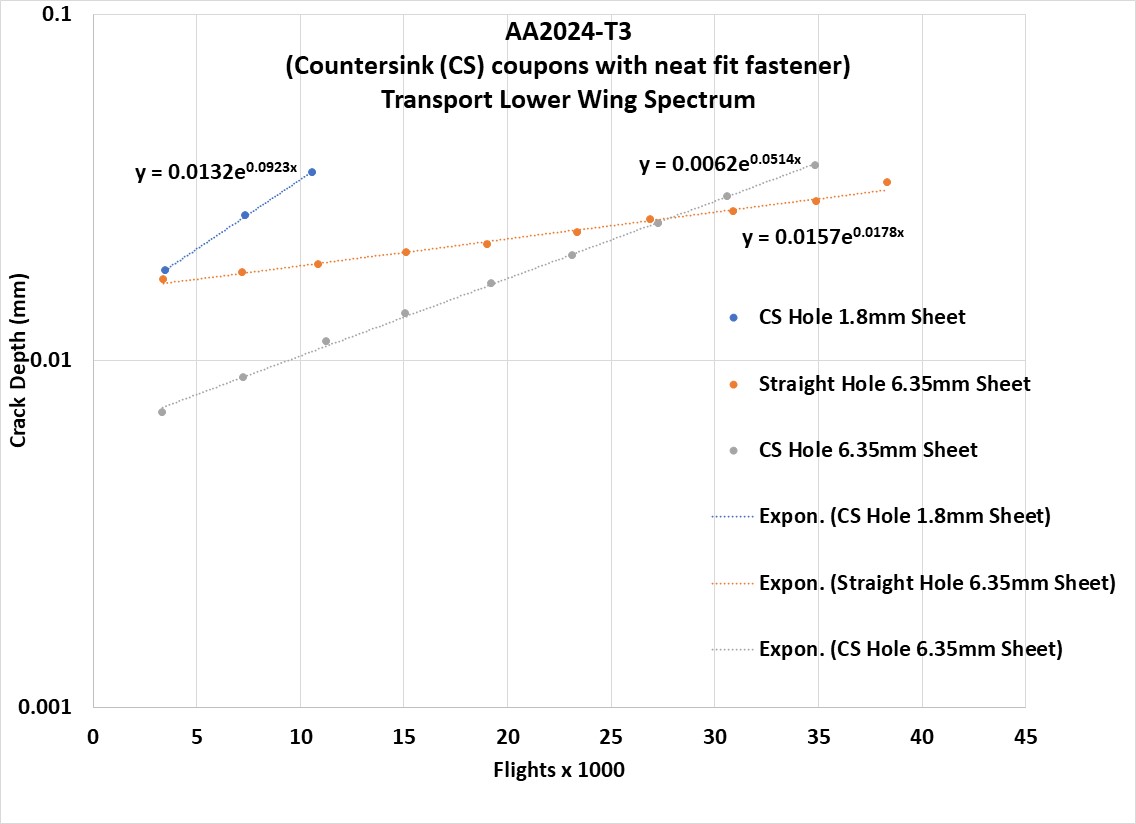


Figure 7: FCG in representative multi-hole coupons tested by Wang under transport aircraft lower wing spectrum loading with regression lines shown [22].

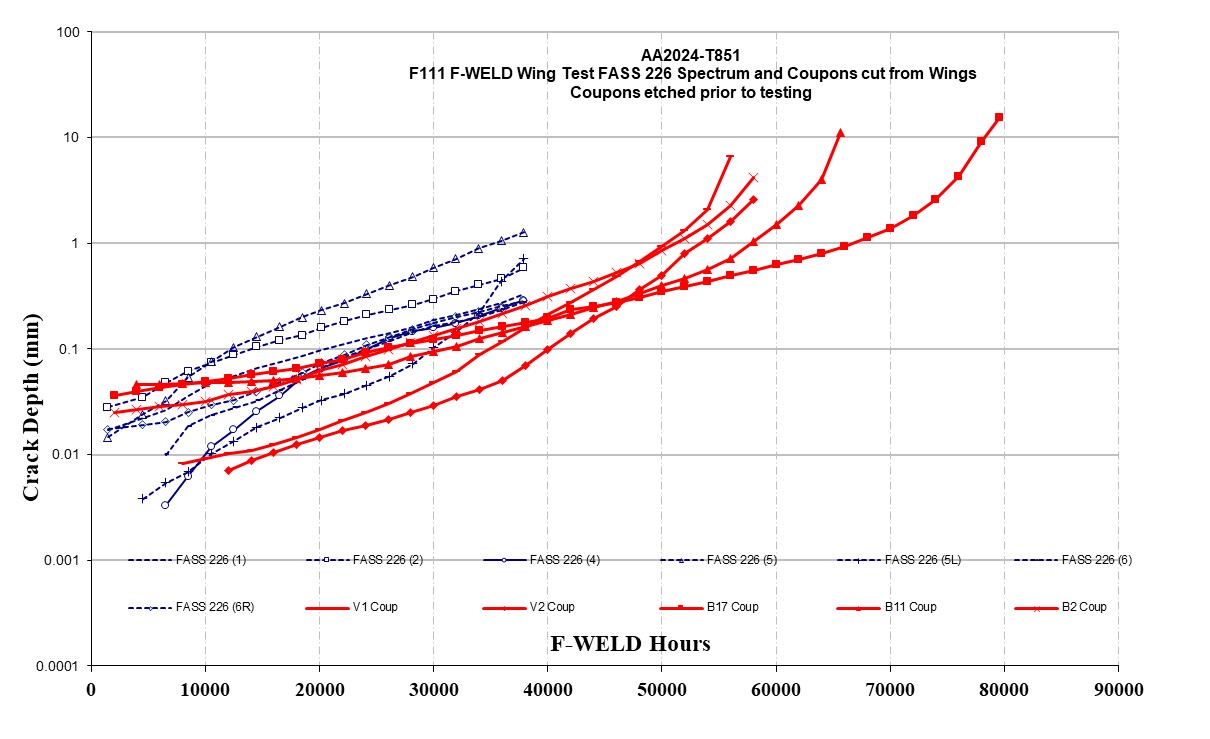


Figure 8: General Dynamics F-111 FSFTs by the DST showing FCG results for the FASS 226 location and for coupons (Coup) designed to replicate FSFT crack growth [24]. (F-WELD was the FSFT designation)



Figure 9: DST F111 coupon test results using the General Dynamics F-111 spectra designated FL1 and FL1A [24]

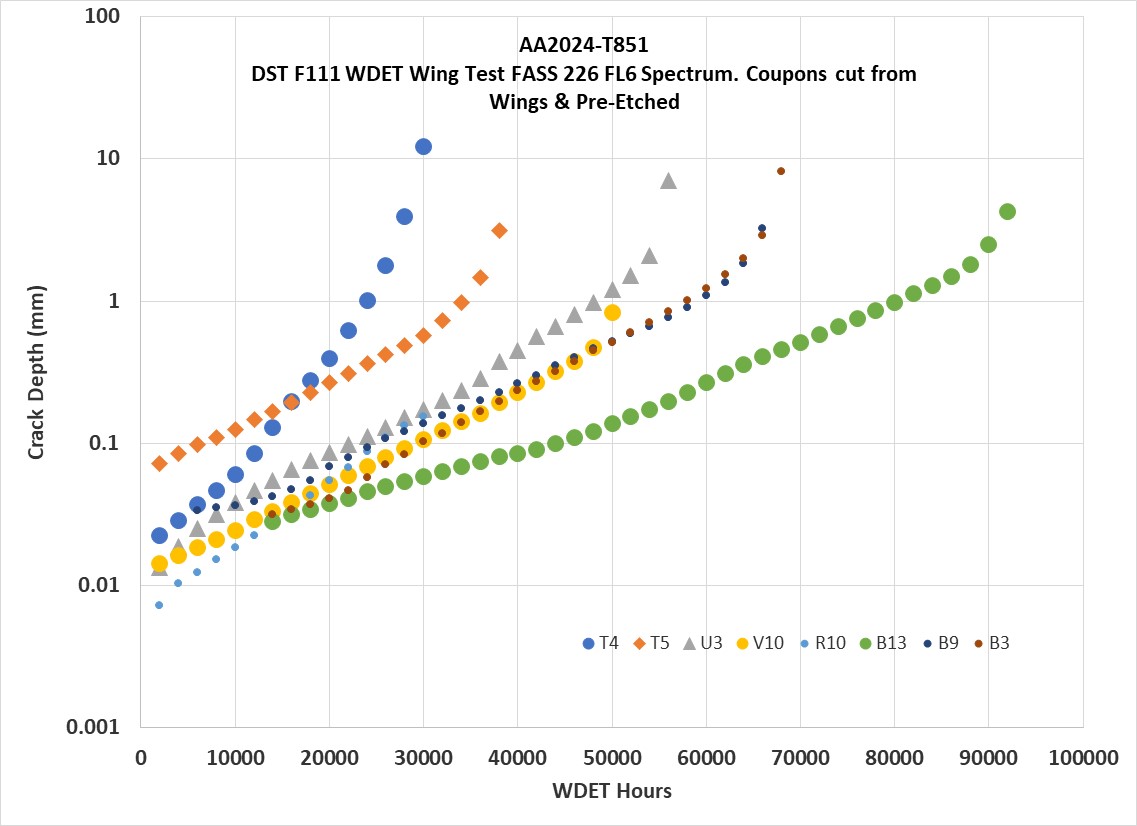


Figure 10: DST coupon test results using the General Dynamics F-111 spectrum designated FL6 [24]. WDET was the FSFT designation.

Table 1: Summary of EPS analyses for AA2024

|  |  |  |
| --- | --- | --- |
|  | | |
| **Reference** | **Specimen** | **Estimated EPS (mm)** |
| **Main spar from a Pilatus PC-9 FSFT** | | |
| [19] | Hole 95 Aft early growth | 0.1544# |
|  | Hole 95 Fwd\* |  |
|  | Hole 75 early growth | 0.0887 |
|  | Hole 85 Fwd early growth | 0.0128 |
|  | Hole 91 Aft early growth | 0.0617 |
|  | Hole 111 Aft early growth | 0.0064 |
|  | Hole 133 Aft early growth | 0.0644 |
|  | Hole 135 Aft | 0.0887 |
|  |  |  |
|  | Average | 0.068157 |
|  | \* Too few points # Potential outlier | |
|  |  |  |
| **Representative multi-hole coupons using a General Dynamics F-16 fighter 400-hour spectrum** | | |
| [20] | TFLC4#1 214MPa | 0.0013 |
|  | TFLC4#2 214 MPa | 0.0125 |
|  | TFLC4#3 214 MPa | 0.0168 |
|  | TFLC4#4 214 MPa | 0.0229 |
|  | TFLC4#5 214 MPa | 0.0231 |
|  |  |  |
|  | TFMC4#1 234 MPa | 0.0346 |
|  | TFMC4#2 234 MPa | 0.0706 |
|  | TFMC4#3 234 MPa | 0.0043 |
|  | TFMC4#4 234 MPa | 0.027 |
|  |  |  |
|  | Average | 0.02368 |
|  |  |  |
| **Representative multi-hole coupons using a Rockwell B-1 Bomber spectrum** | | |
| [20] | TBLC4#1 | 0.001632 |
|  | TBLC4#2 | 0.018153 |
|  | TBLC4#3 | 0.001341 |
|  | TBLC4#4 | 0.037231 |
|  | TBLC4#5 | 0.007528 |
|  | TBLC4#6 | 0.019535 |
|  | TBLC4#7 | 0.008924 |
|  | TBLC4#8 | 0.013482 |
|  | TBLC4#9 | 0.009657 |
|  | TBLC4#10 | 0.003637 |
|  |  |  |
|  | Average | 0.012112 |
|  |  |  |
|  | TBMC4#1 | 0.006038 |
|  | TBMC4#2 | 0.039497 |
|  | TBMC4#3 | 0.027084 |
|  | TBMC4#4 | 0.033452 |
|  | TBMC4#5 | 0.011306 |
|  | TBMC4#6 | 0.053173 |
|  | TBMC4#7 | 0.002718 |
|  | TBMC4#8 | 0.03268 |
|  | TBMC4#9 | 0.005113 |
|  | TBMC4#10 | 0.057005 |
|  |  |  |
|  | Average | 0.026807 |
| **Main spar from a Pacific Aerospace Corporation CT-4 FSFT** | | |
| [21] | Port | 0.0582 |
|  | Starboard | 0.008 |
|  |  |  |
|  | Average | 0.0331 |
|  |  |  |
| **Representative multi-hole specimens using a transport aircraft lower wing spectrum** | | |
| [22] | Countersink 1.8mm sheet | 0.0132 |
|  | Straight Hole 6.35mm sheet | 0.0157 |
|  | Countersink Hole 6.35mm sheet | 0.0062 |
|  |  |  |
|  | Average | 0.0117 |
|  |  |  |
| Wing structure from several General Dynamics F-111 fighter FSFTs | | |
| [24,25] |  |  |
| FWELD | FASS 226 1 | 0.0184 |
|  | FASS 226 2 | 0.0297 |
|  | FASS 226 4 | 0.0012 |
|  | FASS 226 5 | 0.0188 |
|  | FASS 226 5L | 0.0027 |
|  | FASS 226 6 | 0.0073 |
|  | FASS 226 6R | 0.0103 |
|  |  |  |
|  | Average | 0.012629 |
|  |  |  |
| Representative coupon testing using a spectrum designed to replicate the General Dynamics F-111 FSFT crack growth | | |
|  | V1 | 0.0011 |
|  | V2 | 0.0023 |
|  | B17 | 0.028 |
|  | B11 | 0.0126 |
|  | B2 | 0.0125 |
|  |  |  |
|  | Average | 0.0113 |
|  |  |  |
| Representative coupon testing using a General Dynamics F-111 spectrum designated FL1 | | |
|  | Q1 | 0.0002 |
|  | Q2 | 0.0175 |
|  | Q3 | 0.0333 |
|  | Q4 | 0.0101 |
|  | Q5 | 0.0129 |
|  | Average | 0.0148 |
|  |  |  |
| Representative coupon testing using a General Dynamics F-111 spectrum designated FL1A | | |
|  | R9 | 0.0088 |
|  | X3 | 0.0135 |
|  | V6 | 0.000688 |
|  | W8 | 0.0123 |
|  | B4 | 0.01604 |
|  |  |  |
|  | Average | 0.010266 |
|  |  |  |
| Representative coupon testing using a General Dynamics F-111 spectrum designated FL6 | | |
|  | T4 | 0.009 |
|  | T5 | 0.0602 |
|  | U3 | 0.014 |
|  | V10 | 0.0112 |
|  | R10 | 0.0064 |
|  | B13 | 0.0097 |
|  | B9 | 0.0169 |
|  | B3 | 0.0079 |
|  |  |  |
|  | Average | 0.016913 |
|  |  |  |
|  | **Total Average** | 0.02258 |
|  | **Total Standard Deviation** | 0.02618 |

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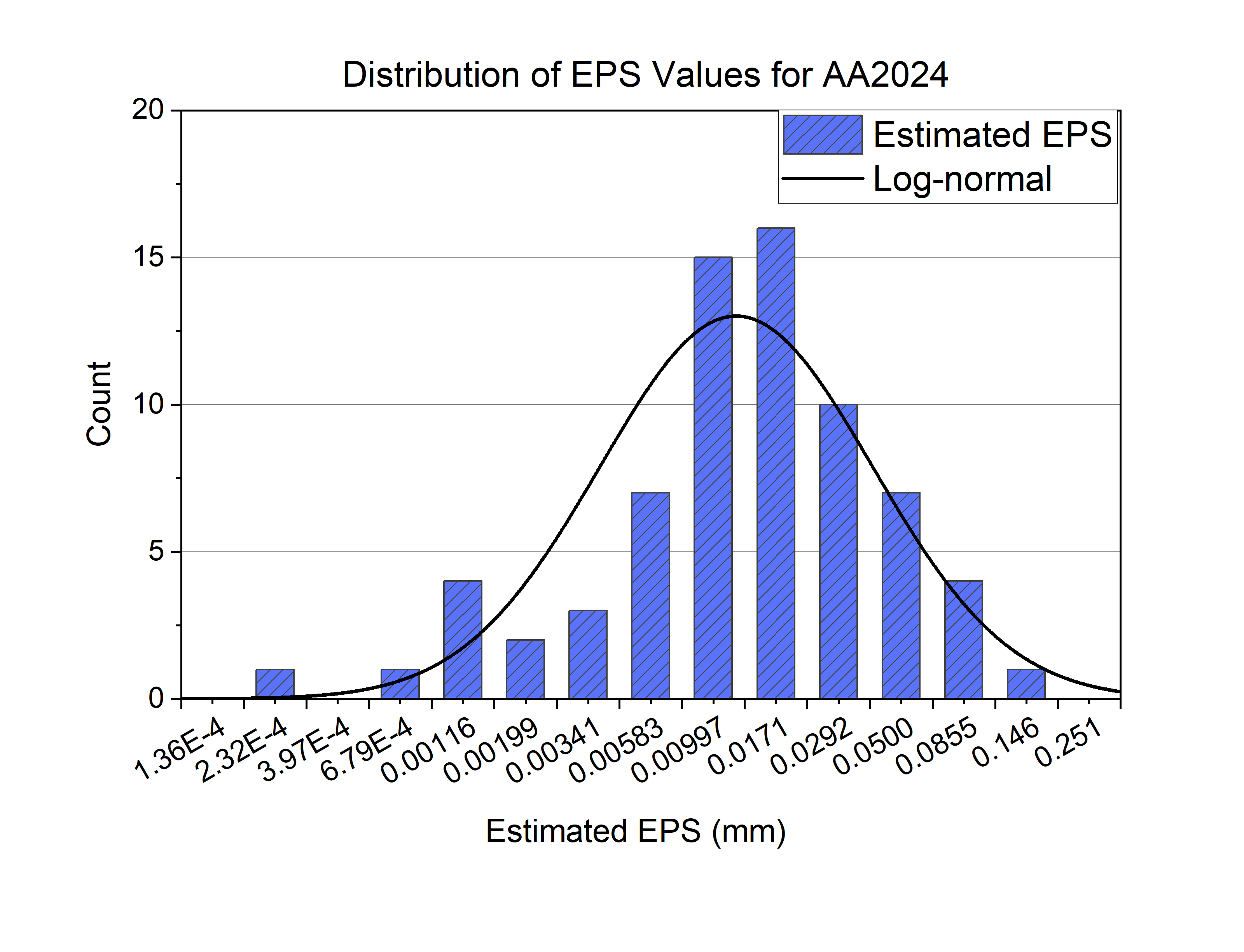


Figure 11: Log-normal distribution of the 71 AA2024 EPS values

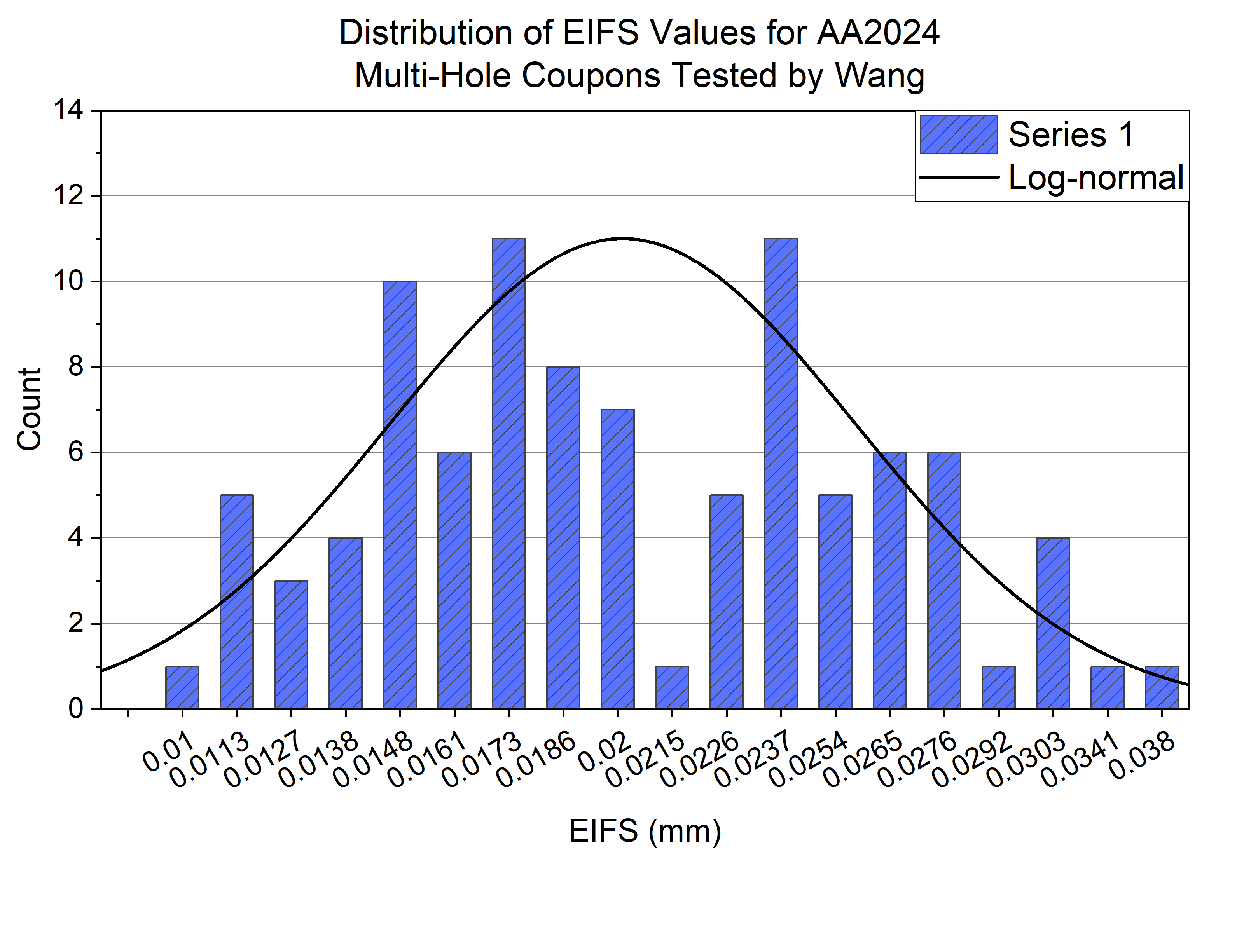


Figure 12: Log-normal distribution of the 96 AA2024 EIFS/EPS values. 6.35-mm-thick AA2024-T3 sheet with 4.76-mm open countersunk and reamed holes. Adapted from Fig 12 [23].

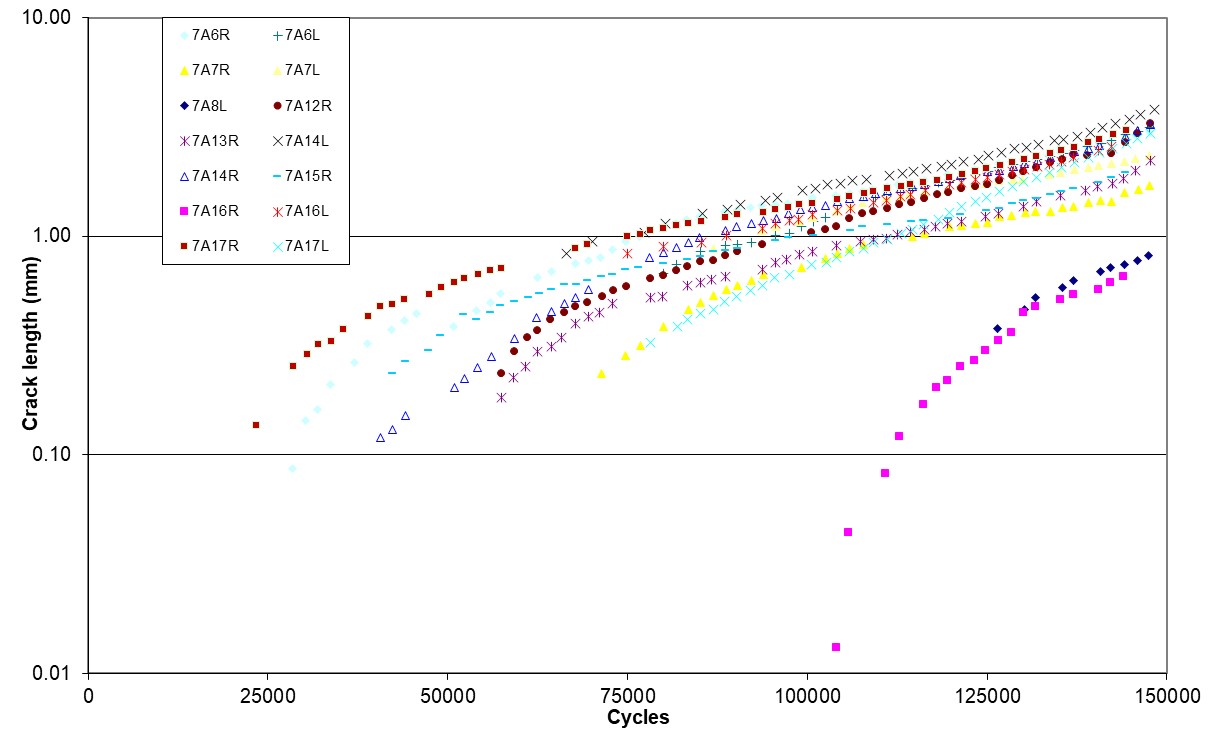


Figure 13: 1.6-mm-thick AA2024-T3 fuselage lap joint specimen data reconstructed from QF of faying surface cracks, adapted from [41].

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1. Note: distribution subject to number of bins chosen. [↑](#footnote-ref-1)
2. With the exception of [21,22] no analyses of EPS or EIFS were made. [↑](#footnote-ref-2)
3. Some data herein were digitised and is therefore subject to some error. [↑](#footnote-ref-3)
4. The FASS designation represents a length in inches from a reference point. [↑](#footnote-ref-4)
5. In addition to the lack of QF, some studies measured FCG using plastic replicate techniques which are known to influence FCG rate [26]. [↑](#footnote-ref-5)