Original article

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Short/small fatigue crack growth, thresholds and environmental effects: a tale of two engineering paradigms

<https://doi.org/10.1515/correv-2020-0096>

Received October 24, 2020; accepted February 1, 2021;

published online March 8, 2021

Abstract: This paper results from mutual discussions on the review ‘When do small fatigue cracks propagate and when are they arrested?’ in *Corrosion Reviews*, 2019; 37(5): 397–418. These discussions have arisen from the two engineering paradigms characterizing our fatigue research: (i) an aerospace research and technology remit for metallic airframes, and (ii) a materials science research programme supporting a methodology for steam turbine low pressure (LP) blade operations. In our opinion, this paper is of interest for other investigators of metal fatigue with respect to design requirements, life predictions and assessments. In more detail, the paper considers the fatigue design methodologies for airframes and steam turbine LP blades. This includes short/small fatigue cracks, fatigue crack growth thresholds, high-cycle fatigue (HCF) and very-high-cycle fatigue (VHCF), and the relevance of environmental effects (corrosion and corrosion fatigue).

Keywords: environmental effects; fatigue design; short/small cracks; thresholds.

1 Introduction

We have recently and independently published a review paper (Stanzl-Tschegg 2019) and a book (Wanhill et al. 2019) on fatigue crack growth (FCG) in metals and alloys, both concerning the short/small-to-long crack growth regime and the significance of FCG thresholds. The

research leading to these publications was done in the context of two engineering paradigms (PMs):

- (1) PMI: An aerospace (airframe structures) research and technology remit (Wanhill et al. 2019). The investigations included (a) the aluminium alloys 2024-T351, 2024-T851, 6061-T6, 7075-T6, 7075-T651, 7050-T7451 and 7050-T7452, the high-strength steels D6ac and AF1410, and duplex microstructure titanium alloy Ti–6Al–4V; (b) FCG analysis methods for service failures and full-scale fatigue tests (FSFTs); and (c) supplemental coupon tests simulating component as-manufactured surface conditions and in-service high-cycle fatigue (HCF) with variable amplitude (VA) flight load histories.
- (2) PMII: A broad-based materials science research programme with engineering implications, in the case of martensitic stainless steels, for steam turbine low pressure (LP) blades (Salzman et al. 2013; Schönbauer et al. 2015a,b; Stanzl-Tschegg 2019). The investigations concerned (a) two stainless steel types (403/410, 17-4PH), an aluminium alloy (7075-T651) (Arcari et al. 2012, 2015; Stanzl-Tschegg et al. 2016), and polycrystalline copper (Stanzl-Tschegg 2019); (b) environmental effects on FCG of 403/410 and fatigue lifetimes of 7075-T7651; and (c) HCF and very-high-cycle fatigue (VHCF) specimen tests, mainly under constant amplitude (CA) loading, but also VA mixed-cycle-frequency block loading for 7075-T7651 (Meischel et al. 2015; Stanzl-Tschegg et al. 2016).

In this paper, we shall discuss the similarities and differences in these paradigms with respect to airframe and steam turbine LP blade engineering fatigue design requirements, life predictions and assessments. The discussion includes the topics of short/small crack growth, FCG thresholds, fatigue load histories, and the relevance of environmental effects (corrosion and corrosion fatigue). This paper is in the spirit of August Thum (1881–1957), who collected, adapted and published a large amount of fatigue literature to the benefit of engineers and designers (Schütz 1996).

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Before proceeding to the main body of this paper, it is useful to briefly discuss the definitions of short and small cracks. Both terms appear in the literature, sometimes as synonyms. However, these terms have taken on different meanings, notably in the USA (McClung et al. 1996). A ‘short’ crack requires only one dimension that is small, while a ‘small’ crack’s dimensions are all small. This distinction is essentially between 2D and 3D cracks. In this paper, all of the short/small FCG data are from 3D cracks, and are designated as small crack growth.

2 Fatigue design methodologies

General schematics of the fatigue design methodologies for the two paradigms are given in Figure 1. These show broad similarities and also differences, as will be discussed with the aid of Table 1. Note that 12% Cr stainless steel is specifically mentioned as the steam turbine LP blade material. This is because the fatigue design methodology has been developed for this material (Salzman et al. 2013). However, the methodology is also potentially applicable to other candidate materials, in particular 17-4PH stainless steel. Another important point is that this methodology currently applies only to essentially constant-speed operation, although there is mention of considering the possible influence of off-line events on crack nucleation or growth at pits, see Table 1. The effect of two-shifting (flexible operation) is not considered. Its detrimental effects on fatigue life mainly concern low-cycle fatigue (LCF), which is outside the scope of this paper, but is important for steam turbine operations (Reid 2018). This could be a topic for further investigation and expansion of the Salzman et al. (2013) methodology.

2.1 Loads/stresses and critical components

For airframes the loads and static and cyclic stress analyses are the starting points. These analyses are conducted for the airframe as a whole, and also structural assemblies down to the component level. The analyses are supplemented and validated by Full Scale Fatigue Testing (FSFT) and component and specimen tests. For an overview see e.g. MIL-STD-1530D (2016).

For steam turbines the low pressure (LP) turbine blades are already known to be critical components. The steady and cyclic operational stresses are calculated using finite element (FE) analyses, including increases in cyclic stress owing to sustained operation at low power

Figure 1: General schematics of fatigue design methodologies: (A) damage tolerance (DT) analyses for metallic airframes; (B) safe-life (SL) analyses for 12% Cr steel steam turbine LP blades.

and/or high condenser back pressure (Salzman et al. 2013; Schönbauer et al. 2015a,b).

2.2 Fatigue analysis summaries

2.2.1 Damage tolerance (DT) analyses, airframe structures

These begin with assuming initial discontinuity sizes, preferably based on quantitative fractography (QF) data. The *depths* of these discontinuities are converted into equivalent precrack sizes (EPS). This approach has a broad compatibility for aircraft structures (Gallagher and Molent 2015). As shown in Table 1, the next steps are to determine the final (critical) crack sizes characteristic of the locations to be assessed, followed by FCG analyses.

There is a variety of FCG models available for aircraft structures. These may be classified into linear elastic fracture mechanics (LEFM) and exponential FCG models (Wanhill et al. 2019). The selection of a model, or a combination of models, should be based on ‘whatever works best’, whereby it is essential to calibrate and validate the models with *realistic data*, especially QF data obtained from tests employing VA load histories representative of in-service experience. N.B: The question of what constitutes a *realistic environment* with respect to the FCG data will be discussed in subsection 4.1.

Some models—but by no means all—recognize the importance of short/small fatigue cracks and their FCG behavior, including the FCG thresholds for short cracks.

Table 1: Summary of (i) damage tolerance (DT) fatigue analyses for metallic airframes; and (ii) safe-life (SL) + inspection fatigue analyses for 12% Cr stainless steel steam turbine LP blades.

Metallic airframe generic DT fatigue analyses	12% Cr stainless steel turbine blade SL fatigue
<ul style="list-style-type: none"> – Static and cyclic stress analyses and test results. – Specify EPS for (i) initial discontinuities and (ii) time-dependent discontinuities (corrosion pits, NDI-detected cracking, and incidental damage). – Determine the final (critical) crack sizes. – Select suitable model(s) to estimate the FCG lives to the critical crack sizes. – Consider effects of component geometry, load shedding, and residual stresses on crack growth. – Apply scatter factors (SF) to determine safe crack growth lives and/or NDI intervals. 	<ul style="list-style-type: none"> – NDI during outages and documentation of pitting corrosion. – Calculate blade steady and cyclic stresses. – Consider effects of sustained operation at low power and/or high condenser back pressure. – Define steady and cyclic stresses at locations of specific pits and plot a (K-T: R) diagram. – Consider the possible influence of off-line events on crack nucleation or growth at pits. – Specify a safety margin (SM) for pit widths, as documented during outages.

EPS, equivalent pre-crack sizes based on discontinuity depths; FCG, fatigue crack growth; K - T , Kitagawa–Takahashi (diagram); NDI, non-destructive inspection; R = stress ratio = $S_{\min}/S_{\max}$.

QF-obtained data are important, indeed essential, for determining the small crack growth rates and estimating the threshold values.

2.2.2 Safe-life (SL) analyses, steam turbine LP blades

The proposal begins with outage-coordinated NDI inspections of the LP turbine blades and documenting the sizes and locations of any corrosion pits on the blade and root surfaces (Salzman et al. 2013). The pit metrics are their *widths* normal to the principal steady stress. Also, the steady and cyclic stresses, and hence R values, at the locations of specific pits have to be derived from FE analyses (Schönbauer et al. 2012).

As shown in Table 1, the next step is to plot Kitagawa–Takahashi (K - T) diagrams (Kitagawa and Takahashi 1976) for various R values. These are the relevant stress ratios ($R = S_{\min}/S_{\max}$) for each specific pit (Salzman et al. 2013). By definition this approach means that the blade pit stress histories can be represented by constant amplitude (CA) cycling at various mean stress levels. As in the case of DT analyses for airframes, the question of what constitutes a *realistic environment* during fatigue cycling will be discussed in Section 4.

The (K - T : R) diagrams are intended to enable defining safe and unsafe combinations of pit widths and mean + cyclic stresses with respect to nucleation and growth of fatigue cracks from the pits. In principle, although fatigue cracks might nucleate at corrosion pits, they should become non-propagating, i.e. progressive FCG (which would lead to blade failure) is not allowed. This is what is meant by the safe-life (SL) designation. However,

there is a complication owing to off-line events, i.e. turbine start–stop cycles. These are relatively large cyclic excursions that could possibly nucleate fatigue cracks at pits.

2.3 Scatter factors (SF) and safety margins (SM)

As shown in Table 1, the airframe DT and turbine blade SL design methodologies rely on scatter factors (SF) or safety margins (SM) and NDI to ensure safety. A common SF value for airframe NDI is 2, signifying that the time for FCG from an initial or subsequently detected discontinuity to the critical crack size is twice the required NDI interval. Other SF values are possible, depending on the criticality of detailed designs and components, the materials used, and the NDI capabilities.

The turbine blade methodology (Salzman et al. 2013) is less explicit. But one possibility for continued operation after a (planned) outage is that NDI-detected and documented corrosion pit widths are no more than half the calculated critical pit widths (Salzman et al. 2013). In other words, blades should be withdrawn from continued operation when any corrosion pits reach half the calculated critical pit widths with respect to fatigue failure at the same locations. N.B: The NDI will have a detection limit for very small fatigue cracks, if there are any, nucleating from the corrosion pits. A judicious safety margin should ensure that any such non-detectable cracks become non-propagating. This condition is not stated in the proposal for a safety margin derived from the measured pit widths, but may be regarded as implicit from the following: “Once the

Kitagawa Diagram parameters were defined to be a function of R , these diagrams could then be applied to operating steam turbine blades to define a critical pit size (i.e. when the pit is at risk of forming a propagating fatigue crack)” (Salzman et al. 2013).

3 Short/small fatigue cracks and FCG thresholds

The behavior of short/small fatigue cracks and the existence (or non-existence) of FCG thresholds are inseparably related. This will be illustrated in the following subsections.

3.1 Airframe materials and structures

Since about 1990 it is known from QF of FCG in service failures and simulation tests that small fatigue cracks in airframe alloys can have FCG thresholds below those for long cracks (Barter et al. 1993; Blom 1990; Molent and Jones 2016; Tanaka et al. 1981; Wanhill 1991; Wanhill et al. 2019). An early test example for VA (flight simulation) loading is shown in Figure 2.

More extensive FCG investigations, validated by QF data from service cracking, FSFTs and component and specimen tests, have shown that the small crack FCG thresholds under both CA and VA load histories must be

Figure 2: Correlation of flight simulation small and long fatigue crack growth rates, da/dN , for AA2024-T3 sheet: data from Wanhill (1991). K_{mf} corresponds to the simulated mean stress in flight, S_{mf} .

much lower than the long crack thresholds, e.g. Jones et al. (2013), Jones (2014), Molent et al. (2011). An example of the use of this assumption for correlating small and long FCG under CA loading is given in Figure 3. The parameters A (the apparent fracture toughness under cyclic loading) and ΔK_{thr} (not the original ASTM Standard E647 parameter ΔK_{th} , see Jones et al. 2012) were chosen to collapse the small and long FCG data onto a single curve. To do this it was necessary to use a very low value of ΔK_{thr} for small cracks. N.B: A constant value of $\Delta K_{thr} = 0.1 \text{ MPa}\sqrt{\text{m}}$ could be used, owing to the small dependency of small crack FCG rates on R : see Jones et al. (2013) and the current version of ASTM Standard E647.

3.2 Steam turbine LP blades

As mentioned in Section 2, K - T diagrams are used in the LP turbine blade fatigue design methodology with the intention of defining safe and unsafe combinations of pit widths and mean + cyclic stresses with respect to nucleation of fatigue cracks from the pits. No fatigue crack nucleation and growth from corrosion pits is allowable.

The original K - T approach (Kitagawa and Takahashi 1976) envisaged that approximate regions of safe and unsafe combinations on K - T diagrams are given by boundaries representing the HCF *smooth specimen* endurance limit, ΔS_0 , and a slant line representing fatigue failure stress ranges, ΔS , calculated from combinations of the long crack FCG threshold, ΔK_{th} , and characteristic *crack sizes*. However, to capture small crack growth behavior below ΔK_{th} (already observed by Kitagawa and Takahashi), El Haddad et al. (1979) proposed an empirical expression for

Figure 3: Correlation of constant amplitude small and long fatigue crack growth rates, da/dN , for AA7050-T7451 using a variant of the Hartman-Schijve equation (Hartman and Schijve 1970) adapted by Jones et al. (2013): data provided by R. Jones.

ΔS , whereby an ‘effective crack size’ is added to the actual crack size. This empirical expression has been modified for corrosion pitting in 12% Cr steam turbine blades as follows:

$$\Delta S = \frac{\Delta K_{th}}{Y\sqrt{\pi(c+c_0)}} \quad (1)$$

and

$$c_0 = \left(\frac{\Delta K_{th}}{Y\Delta S_0} \right)^2 \cdot \frac{1}{\pi} \quad (2)$$

where c is the half-width of a corrosion pit; Y is a geometry factor (assumed to be 0.65); and $(c+c_0)$ is the effective half-width of the corrosion pit (Schönbauer et al. 2012). This modified approach means that corrosion pits are treated as if they are small cracks with approximate semi-elliptical shapes. This assumption is based on the fractography of corrosion pitting, e.g. Chen et al. (1996), Schönbauer et al. (2015), Stanzl-Tschegg (2019). Another significant point is that ΔS_0 is the fatigue limit at 10^9 cycles (not the more common value of 10^7 cycles), owing to the VHCF nature of fatigue in steam turbine blades.

Figure 4 gives examples of K - T diagrams using this modified approach, with ΔS_0 from smooth specimen tests and (failure/no failure) ΔS values from *pre-pitted* specimen tests. The tests were done with an ultrasonic resonance fatigue machine and hourglass-shaped specimens under strain control (Stanzl 1981). The specimen stresses were calculated assuming fully elastic behaviour. The

advantage of this type of testing at ultrasonic frequencies is the ability to achieve very long fatigue lives ($>10^9$ cycles) within reasonable testing times.

The diagrams in Figure 4 include (i) the effects of R on ΔS_0 , ΔK_{th} and the El Haddad et al. empirical expression, (ii) the effects of test environments (air and a dilute aqueous NaCl solution), and (iii) ranges of corrosion pit sizes for the pre-pitted specimens. The ΔK_{th} values were those for the test environments (Schönbauer et al. 2012). These diagrams show that the modified approach, represented by the El Haddad et al. dotted curves, provides reasonable (but not precise) lower bounds for the failure/no failure data. In other words, use of equations (1) and (2) provides reasonable *first estimates* of the maximum allowable ΔS values for a range of pit sizes and R values. N.B: Some follow-up research has shown that choosing $Y = 0.42$ for the pit *depth* and consequent changes in equation (1) (c and c_0 replaced by a and a_0 , the actual and effective pit depths) gives equally good results (Schönbauer et al. 2015a).

In view of the foregoing results, the El Haddad et al. estimates of the maximum allowable ΔS values appear suitable for use with a judicious safety margin (SM), see Section 2, as aids to assessing whether individual corrosion-pitted blades can continue in service until the next outage. However, it is advisable also to consider environmental effects on the long crack ΔK_{th} values used for the K - T diagrams: see subsection 4.2.

Figure 4: Kitagawa-Takahashi (K - T) diagrams for pre-pitted 12% Cr martensitic steel specimens tested in (A) air and (B) a dilute aqueous NaCl solution at 90 °C (Schönbauer et al. 2012): data provided by B. Schönbauer.

4 Environmental effects

Environmental effects on metal fatigue have a venerable history—probably the first published investigation was by Haigh (1917). Early work was concerned mainly with environmental (corrosion) effects on fatigue lives and strengths. Controlled studies of environmental FCG began in the 1960s, e.g. Hartman (1965) and Bradshaw and Wheeler (1966). Two early ‘corrosion fatigue’ publications covering both aspects for a range of materials were issued by the NACE (Devereux et al. 1972) and ASTM (Craig et al. 1978). Early publications with respect to the materials considered in this communication include the AGARD (1977) report on aircraft aluminium and titanium alloys and the AZT-EPRI 1981 workshop proceedings on steam turbine blades (Jaffee 1983).

There is now a vast literature on environmental (or corrosion) effects on fatigue and FCG. The general interest is high, owing to the complexity of the effects and the actual or potential significances for service problems in engineering structures, including aircraft and steam turbines.

4.1 Aircraft fatigue: role of the service environment

Corrosion in aircraft is a very important problem, e.g. Wanhill and Koolloos (2001), Shoales et al. (2009). These examples, investigating long-service aircraft, show that widespread corrosion can lead to numerous fatigue cracks late in the service life, whereby the cracks are usually of secondary consideration compared to the damage caused directly by corrosion.

In contrast, corrosion pitting may occur relatively early in the service life and in some cases provide primary fatigue nucleation sites (Barter and Molent 2013; Campbell and Lahey 1984; Molent 2014, 2015; Wanhill 2007; Wanhill et al. 1974). A survey by Campbell and Lacey (1984) covers 574 cases in both fixed wing and rotary wing aircraft, of which 62 (10.8%) were attributed to corrosion. The main causes of airframe fatigue are stress concentrations and high local stresses (Campbell and Lahey 1984; Wanhill et al. 2019). More specifically, there are many types of pre-existing discontinuities that provide potential (and actual) fatigue nucleation sites immediately, or very soon after, an aircraft enters service (Barter et al. 2012).

Corrosion-enhanced FCG (corrosion fatigue) has been observed in some military aircraft components (Barter et al. 1994; Byrnes et al. 2014), but this is unusual and not

to be generally expected (Barter and Molent 2013; Lang et al. 2001; Molent 2015; Molent et al. 2015; Trathan 2011). Also, there was some evidence of corrosion fatigue in extensively corroded pressure cabin lap joints in ageing civil transport aircraft (Wanhill and Koolloos 2001). However, QF of lap joints from the most famous (or infamous) ageing aircraft accident, the Aloha Airlines Boeing 737 pressure cabin failure in 1988, found fatigue striation spacings down to less than $0.1\ \mu\text{m}$ (Aircraft Accident Report, Aloha Airlines, Flight 243, 1989, Boeing 737-200, N73711, Near Maui, Hawaii, April 28, 1988). This would not have been possible if corrosion had played a significant role during the FCG process. N.B: A recent summary of more information on the accident-causing factors—which did include corrosion, but not of the lap joints—is given by Wanhill et al. (2016).

All the foregoing observations lead to the conclusion that, in general, the influences of corrosion and fatigue on aircraft service lives can be decoupled (Lang et al. 2001; Molent et al. 2015). In other words, although corrosion is a very important problem for airframe structures, it can—and should—be treated separately from fatigue design methodologies, and included only in later maintenance analyses; these may require revised estimates of FCG lives for corrosion-susceptible locations (Molent 2014; Molent et al. 2015).

4.2 Steam turbine LP blades

For steam turbine 12% Cr steel LP blades corrosion pitting and pit growth occur mainly during off-load conditions, when oxygen is present with chloride contaminants. During operation the condensate is oxygen-free and pitting is arrested. This means that the corrosion fatigue process is predominantly corrosion followed by high-frequency fatigue, rather than simultaneous corrosion + fatigue. It follows that corrosion-enhanced FCG should not be a design issue. On the other hand, the question arises whether the totality of the steam turbine internal environment could promote FCG from corrosion pits by lowering the long crack ΔK_{th} values used for K - T diagrams like those in Figure 4.

4.3 Environmental effects on the long crack ΔK_{th} values

FCG tests on 12% Cr martensitic steels at $90\ ^\circ\text{C}$ and over a wide range of R (–1 to 0.9) have shown that the long crack ΔK_{th} values tend to be slightly higher in dilute aqueous

Figure 5: SEM secondary electron (SE) near- ΔK_{th} fractographs of 12% Cr martensitic steel specimens tested at 90 °C in (A) air and (B) a dilute aqueous NaCl solution (Schönbauer et al. 2012). The fracture surface produced during fatigue crack growth in the aqueous NaCl solution is rougher and shows evidence of corrosion product (oxides) accumulated on the fracture surface, and also intergranular fracture (circled in Figure 5B): original fractographs provided by B. Schönbauer.

NaCl solutions than in air (Schönbauer et al. 2012). This was an unexpected result, and fractographic examination suggested that the reason is a combination of enhanced crack closure owing to increased fracture surface roughness and corrosion product (oxides) build-up on the fracture surfaces, for example Figure 5. There was also some evidence of intergranular fracture, circled in Figure 5B, which would also have increased the fracture surface roughness (Suresh and Ritchie 1984).

For 12% Cr martensitic steels the result of slightly higher long crack ΔK_{th} values in dilute aqueous solutions signifies that tests in air at 90 °C are sufficiently conservative for $K-T$ design diagrams. This can greatly facilitate testing, as may be inferred from Schönbauer et al. (2012). However, this fortuitous result does not necessarily apply to other turbine blade materials. An important example is 17-4PH martensitic stainless steel, for which the long crack ΔK_{th} values are significantly decreased by corrosive environments (Schönbauer et al. 2015b).

5 Concluding discussion: PMI and PMII

PMI is the result of decades of experience supporting aircraft operators with respect to aircraft safety and sustainability (Jones et al. 2018; Wanhill et al. 2016). PMII has a similarly decades-old background with respect to steam turbine blades, e.g. Jaffee (1983), and has contributed significantly to the fatigue design methodology proposed by Salzman et al. (2013) under the aegis of the Electric Power Research Institute (EPRI), an independent

USA-based organization aiding the power generation industry. In particular we refer to the PMII publications by Schönbauer et al. (2011, 2012, 2015a, b).

PMII also has a broader scope for example, a recent PMII analysis of how to treat surface defects as cracks in the $K-T$ safe-life design approach (Schönbauer and Mayer 2019) has implications for the helicopter Flaw Tolerance methodology. N.B: Although this methodology has been introduced by some manufacturers, it is controversial and disfavored by the Federal Aviation Administration and the Civil Aircraft Authority with respect to DT design (RTO 2000): the debate continues.

It might be thought that the two paradigms, PMI and PMII, would generally differ on the topics covered in this paper, namely engineering fatigue design methodologies and analyses that include the behaviour of short/small fatigue cracks; FCG thresholds; and environmental effects. However, there are both similarities and differences that merit further discussion.

As Figure 1 shows, the fatigue design methodologies for the two paradigms have broad similarities. In detail, however, these similarities break down into a mix of some similarities and numerous differences. A concise indication of this is given by Table 1, and a more extensive summary is given in this section.

5.1 Loads, stresses, critical components and materials (alloys)

PMI: The design loads and stresses have to be determined for the complete aircraft before selecting the fatigue-critical

components for further analysis. The service loads are usually VA-HCF, although pressure cabins, for example, experience predominantly CA low-cycle fatigue (LCF) pressurisation cycles with superpositions of fuselage bending loads. The main classes of alloys are aluminium, titanium and high-strength steels.

PMII: In this context the critical components are stainless steel LP steam turbine blades. The service cyclic loads and stresses are assumed to be basically CA-VHCF, but with a wide range of R in both the spanwise and chordwise directions. Both the static and cyclic stress distributions require detailed FE analyses.

For these topics there is hardly any commonality between the two paradigms. We note that stainless steels are used in aircraft, but mainly for fuel lines and hydraulic tubing, which are not considered fatigue-critical items. In fact, their main potential (and actual) problem is stress corrosion cracking (Wanhill and Byrnes 2017).

5.2 Fatigue design approaches: initial and time-dependent discontinuities

PMI: Aircraft fatigue design has seen a steady evolution from Safe-Life (*defect-free*) to DT since the mid-1950s. A broad-based consensus has recently been reached on the specification of effective pre-crack sizes (EPS) for initial discontinuities (Gallagher and Molent 2015). The EPS values, derived from QF of discontinuity *depths*, are much smaller than the 1.27 mm equivalent initial flaw size (EIFS) proposed by the United States Air Force in MIL-A-83444 (1974). Typical EPS values are below 0.1 mm, which is a convenient starting point for FCG safety and sustainability analyses and, as must be noted, well within the short/small crack regime.

Time-dependent discontinuities include corrosion pitting and fretting damage. These are NDI-detected, along with any associated fatigue cracking, during periodic maintenance that includes any refurbishments, repairs or replacements. A survey of managing corrosion and any associated fatigue cracking, including the estimation of EPS values when only corrosion is detected, is given by Molent (2014, 2015).

PMII: The steam turbine LP blade design approach considers corrosion pitting discontinuities that occur during service. As mentioned in subsection 2.2, the current proposed methodology begins with outage-coordinated NDI inspections of the LP turbine blade and root surfaces, and documenting the sizes and locations of corrosion pits (Salzman et al. 2013). The need to examine the blade roots means removing the blades for NDI, which

gives easier access and is consequently beneficial to the NDI.

Detailed light microscopy and fractography have shown that for 12% Cr martensitic stainless steels the pits have semi-elliptical shapes with depth-to-width ratios $a/2c \approx 0.95$; and also that fatigue cracks nucleate at the surface corners of the pits (Schönbauer et al. 2015a). Thus the preferred pit metrics are their widths normal to the principal steady stress, and not the pit depths—which are anyway not easily measurable by NDI. N.B: There is no need to convert pit widths to effective crack sizes, since progressive FCG is not allowed, and the pits behave in an analogous way to small cracks in K - T diagrams, e.g. Figure 4. Also, the NDI will have a detection limit for very small fatigue cracks nucleating from the corrosion pits. This can be accounted for by imposing a judicious safety margin, as is implicit in the proposed fatigue design methodology by Salzman et al. (2013).

Two further points should be noted:

- (1) The depth-to-width ratios of corrosion pits in 12% Cr martensitic steels do not necessarily apply to other materials. For 17-4PH martensitic steel the average value was found to be $a/2c \approx 0.61$ for pit sizes below 0.2 mm (Schönbauer et al. 2015b). This means that the pit shapes for 17-4PH steels were significantly shallower than those for 12%Cr steels.
- (2) The sizes of representative corrosion pits for both types of steels are less than 0.2 mm (see Figure 4 also). Hence, although they are not fatigue cracks, these pit sizes, like airframe EPS values, are well within the short/small crack regime.

5.3 Short/small fatigue cracks and FCG thresholds

Both PMI and PMII recognize that (i) the behavior of short/small fatigue cracks is related to FCG thresholds; (ii) the sizes of important design and in-service discontinuities, represented by airframe EPS values and steam turbine blade corrosion pits, are within the short/small crack regime; and (iii) long crack ΔK_{th} values do not directly apply with respect to preventing fatigue cracking from these discontinuities. But there the similarities end, since the fatigue analysis methods are very different. Most of the PMI FCG analyses are not based on approaches using long crack ΔK_{th} values (Wanhill et al. 2019). The PMII analyses use long crack ΔK_{th} values, since these are inherent to the K - T approach (Kitagawa and Takahashi 1976), but the limitations of this approach are explicitly demonstrated by small crack FCG data like those in Figure 4. However, this

diagram also shows that the El Haddad et al. (1979) empirical estimates of the maximum allowable ΔS values capture most of the short (small) crack data. Thus these empirical estimates appear suitable for use, albeit with a judicious safety margin (SM), as discussed in section 2.3.

5.4 Environmental effects

For both PMI and PMII the available evidence concerning service environments is that corrosion and fatigue can generally be decoupled, even though corrosion is an important problem for (ageing) aircraft and steam turbine martensitic steel LP blades, see section 4. In other words, corrosion-enhanced FCG need not be a design consideration.

However, environmental effects on the long crack ΔK_{th} values can be design considerations; see the discussion in subsection 4.2. It must be noted that although the long crack ΔK_{th} values do not necessarily represent short/small crack FCG thresholds, they are used together with the El Haddad et al. curves to help define the boundaries between safe and unsafe regions on the K - T diagrams. This demonstrates the usefulness of PMII-type testing in evaluating environmental effects relevant to the service operation of steam turbine LP blades.

Acknowledgements: We thank Bernd Schönbauer, Institute of Physics and Materials Science, University of Natural Resources and Life Sciences, Vienna, Austria, and Rhys Jones, Emeritus Professor at Monash University, Melbourne, Australia, for advice and permission to use their data in the preparation of Figures 3, 4, and 5; and Lorrie Molent, Defence Science and Technology Group, Melbourne, Australia, for advice. We are also grateful to Ron Latanision, Emeritus Professor at the Massachusetts Institute of Technology, Cambridge, MA, USA, for encouraging the preparation of this paper, and the reviewers.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: None declared.

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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