FIRST DIAMOND

‘Damage tolerance’ for the structural honeymoon

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Abstract: This paper offers a fresh and simple approach to setting the threshold for structural inspections. It shows how damage tolerance and the diamond work the same as for any other interval, and how they would work even better with risk management, human factors and less prescriptive regulation.

INTRODUCTION

*I sorrow that all fair things must decay*

— American poet, Fitz-Greene Halleck

Aircraft structure decays. So, it needs inspection.

A big issue is the threshold. When does the ‘honeymoon’ end so the structure needs its first inspection? This paper offers a fresh and simple approach.

The threshold is a big issue because it affects:

- safety for air travellers
- sales for aircraft manufacturers
- costs for airlines

1 The views in this paper are personal and not necessarily CASA policy

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Getting it right is hard:

- tension between economy and safety
- uncertainty and variability
- sensitivity to small changes
- prescriptive regulation

Disputes are common. Most are behind closed regulatory doors. But, some have emerged at ICAF and other fora.

What is the best and fairest way to set thresholds? For the answer, this paper looks:

- anew at damage tolerance
- afield at risk management and human factors

It continues the ‘diamond’, which, in 2007, won the Whittle Safety Award from the International Federation of Airworthiness.

Figure 1

The paper’s pragmatism comes from 25 years of putting threshold theory into practice for Australia’s 13,000 civil aircraft, acknowledged as one of the hardest-working fleets in the world. Its scope is metallic structure in civil aircraft, but some issues are universal.
DAMAGE TOLERANCE AND THE DIAMOND

First, what is, ‘damage tolerance’?

As Rough Diamond [1] explained at ICAF 2005, for civil rules it is not fracture mechanics or a design property, but aviation’s application of a universal method for maintaining anything prone to damage or decay.

In aviation, we use it to set the interval between structural inspections. Reliability-centred maintenance uses it to set the P-F interval for on-condition tasks for machines. [2] Health professionals use it to set the interval for check-ups, for our teeth to our bowels. It can even tell you how often to weed your lawn.

Figure 2: Damage tolerance is not just for aviation

Rough Diamond proposed a simple teaching tool and memory aid for the method, called the diamond:

![Diagram of the diamond model]

Figure 3

2 In the jargon (and in this paper), ‘damage’ includes the natural and gradual (like fatigue and corrosion), which we might also call ‘decay’, as well as the unnatural and sudden (like a scratch or a ding), its more normal sense.
Then, at ICAF 2007, a USAF paper [3] mentioned the importance of ‘human factors’ for inspection, including the detectable size. Some are:

- skill variation – ask about the worst inspector, not the best
- environment – ask about the worst conditions, not the best
- optimism – ask about the worst missable, not the best detectable
- pride – ask about the ability of others, not their own

So, human factors would prefer the diamond’s ‘detectable’ facet be ‘missable’.

At the same ICAF, *Rusty Diamond* [4], a paper that applied damage tolerance and the diamond to corrosion, reminded us the issue is not always safety. Often, it is repairability. So, flexibility would prefer the ‘dangerous’ facet be ‘permissible’, as Broek recommends in [5].

Third, memorability would prefer the ‘duration’ facet be ‘interval’ (to rhyme more with ‘missable’ and ‘permissible’).

So, the diamond evolves. For this paper, it is:

![Diagram](image)

**Figure 4**

If the diamond works for the interval, including for corrosion, will it also work for the threshold?
DOES THE DIAMOND WORK FOR THE THRESHOLD?

For each site and scenario, here is how the diamond works for the interval:

The interval must assure that damage missable by one inspection stays permissible until the next.

Isn’t the threshold the same, except the first inspection is in manufacture, not maintenance?

So, the diamond works for the threshold too. But, will it always work in the form we call the initial flaw method? We will soon see.
USING THE DIAMOND FOR THE THRESHOLD

Site
We should think more broadly than we often do. Sites are:

- not just stress peaks on a finite or boundary-element mesh, but also…

![Images of wet areas (corrosion), exposed areas (accidental damage), and assembled areas (fretting and pre-loading)]

- not just holes, but also…

![Images of near holes, free edges, and internal flaws]

- not just their corners, but also…

![Images of down their bores, like in this wing attach fitting (left) from a Strikemaster (right)]

For an old aircraft type, compare service bulletins with predictions. It is sobering how often we get the site wrong. [7] has several examples.
Scenario
We should think past fatigue to the other damage FAR 25.571 [8] lists:

- corrosion, such as…

- manufacturing defects, such as…

- accidental damage, such as…

Of course, some will interact with or transition to fatigue, as happened with some of the above. And, like the site, we often get the scenario wrong.
Missable
This is where we question the range of applicability of the initial flaw method.

For each scenario at each site, *missable* helps us size the damage for the start. In FAR 25.571, it is the ‘maximum probable size that could exist as a result of manufacturing’.³ So, isn’t it also the maximum size probably *missable* by manufacturing inspections?⁴ Either way, for the initial flaw method, it is the size that fracture mechanics analytically ‘grows’ to the threshold.

The other method in FAR 25.571, the *fatigue* method, does *not* need to know the missable size, but *does* need a random sample that has damage *typical* of what is missable for manufacture. It starts by testing it, and then statistics account for uncertainty and variability, by a probability density function, to get the threshold.⁵

Figure 7 shows the two methods graphically:

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³ ‘Probable’ is similar to ‘likely’ in MSG-3 [9]. Civil rules do not expect us to anticipate the ‘improbable’, ‘unlikely’ or ‘rogue’.
⁴ We refer to POD (probability of detection) more than its complement, POM (probability of missing). But, missable damage, which could keep growing, is more important than the detectable.
⁵ Common probability density functions for fatigue are log-normal and Weibull
Even for crack-like initial flaws, neither method is intrinsically better. They should both calculate the same threshold. But, it is often shorter for a so-called ‘rogue’ flaw, which is improbably big. We could shorten a fatigue threshold too, if we wanted, with an improbably big scatter factor.

Both methods influence design: they keep stresses low, and the initial flaw method favours tough materials. The initial flaw method is less likely to influence manufacturing quality, because the initial flaw is often prescribed.

Both methods have uncertainty. For the initial flaw method, it is in the fracture mechanics and the data it uses, especially for the short cracks common for thresholds. For the fatigue method, it is in the probability density function, if the structure tested is similar but not the same.

The FAA agree with Emmerson [10] when they accept both methods for:

- all old aircraft (FAA Advisory Circular 91-82) [12]
- some structure in new large aircraft

For the third, for new large aircraft, why do the FAA only accept the initial flaw method for:

Single load path structure and multiple load path ‘fail-safe’ structure and crack arrest ‘fail safe’ structure, where it cannot be demonstrated that load path failure, partial failure, or crack arrest will be detected and repaired during normal maintenance, inspection or operation of an airplane prior to failure of the remaining structure.\(^7\)

If such partiality is not necessary, is it even desirable? As Airbus reminded us at ICAF 2005 [13], a problem with exclusively requiring the initial flaw method is the tendency to neglect non-crack-like manufacturing damage, which is just as dangerous and likely, just because fracture mechanics cannot analyse it.

Others have aired similar concerns in the past. Fortunately, for large airliners, Maintenance Review Boards (MRB), working to MSG-3, look more broadly than does Certification, working to FAR 25.571.

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\(^6\) AC 23-13A has fatigue curves from World War 2 aircraft, which should be conservative for modern civil manufacturing quality

\(^7\) FAR 25.571 (a) (3) (i) and (ii). It is often problematic sorting this structure from the rest. Except for fracture mechanicists, who prefer the initial flaw method for all structure.
So, when using the diamond, remember that missable is not just for cracks and the initial flaw method. The concept holds for all damage scenarios and applications of damage tolerance and the diamond, whether by analysis or test.

Permissible
Residual strength should end the threshold, just like any other interval, because strength is what FAR 25.571 says our inspections must assure. But, for example, [2] and [14] suggest inspectability.

It would have two problems. First, inspectability is no measure of strength (sometimes damage is dangerous before detectable). Second, it would discourage improving inspectability (because improving it would shorten the threshold!).

Interval
This is the time from missable to permissible. The threshold is just a special interval – the first. That is exactly how MSG-3 defines it.8 So, like any other interval, we should factor it for uncertainty and variability from all sources, not just initial damage size and inspectability.

The simple factors of 2 or 3 by which we often divide the interval seem more arbitrary than the scatter factors we use for traditional life limits. See [11] for example. There is still uncertainty and variability. Is there still statistical rigour?

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8 From MSG-3’s Glossary: “Threshold: See ‘Interval – Initial’”
RISK MANAGEMENT

Risk management is part of any Safety Management System. From ICAO’s *Safety Management Manual* [15], the steps are simple and common sense:

Figure 9: Risk management process

Although for an organisation, could it not also be for structure, with the hazards being the *scenarios* at the sites? Could it not broaden the range of sites and scenarios we assess, for the ‘holism’ Hoeppner [16] and others advocate, by broadening the input, as we do for MRB [17]? With MRB, experienced operators team their wisdom with the regulator and the manufacturer. It helps when the manufacturer’s representatives are from the materials, production and product support departments, as well as from design.

Then, safety management systems require the process to continue. In this context, it means what we often call ‘continuing airworthiness’.
HUMAN FACTORS

We have already considered human factors for the diamond. There are also human factors for thresholds. For example, conservatism is good. But, not too much.

Too short a threshold can cause:

- disbelief
- disengagement
- delusion

Disbelief

The Fairchild Metro is a 19-passenger turboprop airliner. First, Fairchild did the thresholds by the fatigue method. Years later, the FAA paid Fairchild to redo them by the initial flaw method. [18] The latter are shorter – so short no one believes them. Not even the FAA. They do not think exceeding them is ‘unsafe’ (FAR 39) enough for an Airworthiness Directive. So, in the USA at least, they languish.

The story is similar for most of the initial flaw based inspection thresholds for Cessna’s propeller-driven twins.

Figure 10: Fairchild Metro (left) and Cessna 402C (right)

Disengagement

Too short a threshold means too many inspections finding too little. It fosters complacency and disengagement for future inspections, reducing their effectiveness.

Delusion

Too many inspections finding too little means too much chance of the delusion to extend the interval instead of the threshold. You will even see it in international maintenance publications, like [19]. See A Collective Approach To Aircraft Structural Maintenance Programs [20]. It includes an example of a turboprop airliner that threw a blade soon after take off.
SPECIAL ISSUES

Realism
The aim for a threshold is often the Design Service Goal (DSG), often 20 years.\textsuperscript{9} But, if the optimism survives certification, how long will it survive service?

![A380 flap track fairings](image)

Figure 11: A380 flap track fairings

Sometimes, not long. Flap track fairings on Airbus’ A380 cracked unexpectedly, so early, the threshold is now only 100 flights!\textsuperscript{22} This is not to criticise Airbus. It is just to remind us again about the difficulty of prediction.

Extension
Service experience \textit{can} extend a threshold. But, statisticians warn that it takes \textit{hundreds} of nil findings, not the \textit{handfuls} many think suffice. And, it takes confidence that findings, if any, have been reported. Often, by the time extension is justifiable, it may be too late if too few aircraft are still young enough to benefit.

Efficiency
Is a threshold always efficient? Sometimes it costs more to calculate and certify than the inspections it saves. It could if the fleet is small or the inspection is easy. But, beware too much conservatism.

Is a threshold always safe? MSG-3 warns it is not if accidental damage is likely.

Cold expansion\textsuperscript{10}
Can a threshold take credit for cold expansion? Has its quality risen faster than its quantity per aircraft, so that error is now no more ‘probable’ than for other manufacturing processes we trust? Sometimes, regulators allow cold expansion for fatigue tests, but not for analyses. The inconsistency comes from their wavering as they struggle to balance encouragement with caution.

\textsuperscript{9} For a definition of DSG, see FAA Advisory Circular 25.571-1C, page 2 [21]

\textsuperscript{10} Cold expansion is a fatigue-improvement process for holes and other structural features. A modern airliner has thousands of cold-expanded holes.
Safe life
Some civil rules, like FAR 23.573 [23], allow ‘safe life’ or ‘damage tolerance’. Imagine certifying a structure with a safe life. Then, imagine recertifying it later for damage tolerance. This is common for civil aircraft, for life extensions.

Why should the old safe life not become the new inspection threshold? Intuitively, why should it change the inspection-free period (the ‘structural honeymoon’) if all we change is the maintenance after it ends?

Also, why do regulators require ultimate strength at the safe life, but only limit strength at the threshold?

Grace
What do we do with a new threshold for an old fleet? Safety says inspect immediately; economy says inspect conveniently. How should we balance the two? A present problem – and a challenge for regulators – is that there are no rules.

Figure 12: Ansett Boeing 767
New thresholds, with no grace, grounded seven of Ansett’s Boeing 767s (some of the oldest in the world) until they could inspect them. [24]

Structural Health Monitoring (SHM)
SHM inspections are often free and frequent, if not continuous. So, they should not need a threshold. But, can we trust SHM alone?

The SHM method would have to prove it is adaptive and extensive, as well as reliable. So far, most methods are so fine-tuned to one scenario at one site they would be unforgiving if we got either of them wrong, as we often do.
CONCLUSIONS

Yes, damage tolerance works for the ‘structural honeymoon’, so the diamond can help us set the threshold, the time when inspections must start.\textsuperscript{11} This \textit{first} diamond is the same as the diamond for later intervals, except sizing the ‘missable’ damage depends on the inspections in manufacture, not maintenance.

But, a particular form of damage tolerance, the initial flaw method, does \textit{not} always work, because not all damage is crack-like and analysable by fracture mechanics. And, sometimes it is too conservative to be credible and enforceable. Its prescription, by policy if not by rule, hinders safety and economy.

RECOMMENDATIONS

We should:

- unify and simplify our regulation and management of thresholds and intervals
- specify principles and outcomes and not prescribe methods
- learn from the fields of risk management and human factors
- anticipate surprises in service by designing structure that does not need sensitive local NDI\textsuperscript{12}, and by having a robust continuing airworthiness system
- encourage Structural Health Monitoring that is adaptive and extensive, so a threshold is no longer necessary

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\textsuperscript{11} Purists will note that this paper uses ‘threshold’ as both a period and a point in time. Strictly, it is only the second. MSG-3 has the same ambiguity. Practically, since the reference is zero, it makes little difference. At times, the first sense is more helpful.

\textsuperscript{12} The structure needs ‘fail-safety’ or ‘large damage capability’
REFERENCES


[12] FAA (2008), *Fatigue Management Programs for Airplanes with Demonstrated Risk of Catastrophic Failure Due to Fatigue*, AC 91-82, page 17, USA


