March 17, 2023

Brandon Roberts
Executive Director, Office of Rulemaking, ARM-1
Federal Aviation Administration
800 Independence Avenue, SW
Washington, DC 20591

Re: Recommendation Report – Transport Airplane Metallic and Composite Structures Working Group – Crack Interaction

Dear Mr. Roberts,

On behalf of the Aviation Rulemaking Advisory Committee (ARAC), I am pleased to submit the enclosed Recommendation Report from the Transport Airplane Metallic and Composite Structures Working Group (TAMCSWG).

At the March 16, 2023, ARAC meeting at FAA's Washington, DC headquarters, Mr. Doug Jury presented an overview of the report, recommendations for rule and guidance changes, the rationale behind the proposed recommendations, dissenting views on recommendations (including alternate proposals), the rationale both in support and in opposition to various proposals considered, and the cost and benefit analyses associated with the recommendations for the topic of crack interaction when establishing inspection programs.

ARAC members who attended the meeting, in-person and virtually, accepted the report, as presented. With that, I would welcome the agency's timely review, acceptance, and implementation of the working group's recommendations.

I thank the members of TAMCSWG for their comprehensive work. I am hopeful that, once implemented, the working group's recommendations will result in marked improvements to both fatigue and damage tolerance – ultimately improving aviation safety.

Sincerely,

David Oord
ARAC Chair

Enclosure: Recommendation Report – Transport Airplane Metallic and Composite Structures Working Group – Crack Interaction

Transport Airplane Metallic and Composite Structures Working Group – Recommendation Report to FAA

Crack Interaction

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Transport Airplane Metallic and Composite Structures Working Group

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Executive Summary

On January 26, 2015, the Federal Aviation Administration (FAA) published a notice of a new task assignment for the Aviation Rulemaking Advisory Committee (ARAC). In short, the FAA assigned and ARAC accepted the task to provide recommendations regarding revision of the damage tolerance and fatigue requirements of Title 14, Code of Federal Regulations (14 CFR), part 25, including subparts C and E of 14 CFR part 26, and development of associated advisory material for metallic, composite, and hybrid structures (structure that includes a combination of composite and metallic parts and assemblies). Under the Transport Airplane and Engine (TAE) Subcommittee, the Transport Airplane Metallic and Composite Structures Working Group (TAMCSWG), also referred to in this report as Working Group (WG), was assigned to provide advice and recommendations on the tasking. The TAMCSWG developed an initial report providing various recommendations on broad variety of related topics to TAE and ARAC, which was released on June 27, 2018 and has been made available to the general public ((https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/TAMCSWG%20Recommendation%20Report.pdf) [1].

During the review and acceptance of this report by ARAC, three separate follow-on tasks were requested to be addressed in an extension of the original tasking. These three topics include:

- Develop requirements and guidance material for single load path (SLP) structure;
- Provide further clarification on how to address disbonds and weak bonds as a manufacturing defect; and
- Provide requirements and guidance on how to address crack interaction when establishing inspection programs for metallic principal structural elements (PSE).

Each of these three topics are addressed using the same approach applied in the original tasking effort, which includes:

- Evaluate current § 25.571, subparts C and E of Part 26, and associated guidance material;
- Determine if changes to the rule or associated guidance are required and, if so, to advise and make recommended changes;
- Estimate the costs and benefits associated with any changes; and
- Consider benefit of harmonization with other National Aviation Authorities (NAA) rules and guidance materials on the relevant subject material.

With concurrence from TAE and ARAC, the WG decided to address each of the three extension topics in standalone reports to supplement the original report released in 2018. Note, at the time of release of this report both the SLP (https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/TAMCSWG%20Extension%20Report%20SLP%20REV%20A.pdf) and structural bonding (https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/Bon ded%20Structure%20Task%20Extension-Final%20Report.pdf) reports have been released [2], [3].

This report provides the recommendations for rule and guidance changes, the rationale behind the proposed recommendations, dissenting views on recommendations (including alternate proposals), the rationale both in support and in opposition to various proposals considered, and the cost and benefit analyses associated with the recommendations for the topic of crack interaction when establishing inspection programs. The WG considered the overall safety objective of the fatigue and damage tolerance rule to develop maintenance tasks (i.e., inspections or other procedures) to ensure residual strength capability over the operational life of the airplane when deliberating on recommendations related to crack interaction approaches.

The TAMCSWG deliberated on the FAA's tasking on how crack interaction should be addressed when establishing inspection programs. The TAMCSWG's recommendations include new content the FAA should add to regulatory guidance (e.g., Advisory Circular (AC) 25.571-1X[1]) and actions the FAA should not pursue. TAMCSWG members reached general agreement to recommend the following:

1. Part 25 rule-level requirements should not be revised.

2. Guidance material, AC 25.571-1X should be revised as follows:

   a. Revise AC 25.571-1X, Paragraph 6.d (extent of damage) to add language similar to AC 91-82A stating "cracking scenarios can be complex, involve multiple sites, and at some point, include crack interaction."

   b. Revise AC 25.571-1X, Appendix 1 (References and Definitions), Paragraph 2 to introduce a new definition as follows:

      "Crack interaction - The effect on crack growth rate due to the simultaneous presence of more than one crack".

3. AC 25.571-1X should not be revised to include examples (lists or illustrations) of structural details showing scenarios where crack interaction should be considered.

4. AC 25.571-1X should not be revised to include example methods[2] of compliance to address crack interaction.

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[1] At the time this report was authored the AC was at revision level 25.571-1D. In this report when the AC is identified as 25.571-1D the WG is commenting on or referencing what the AC presently states. When the AC is identified as 25.571-1X it is to convey the revision level of the AC at the time the FAA acts upon WG recommendations if the FAA acts upon them.

[2] While the WG recognizes a distinction between terms "methods" and "means" of compliance exists relative to Part 23, Amendment 23-64, for this report this WG uses the terms "methods" and "means" of compliance interchangeably with no implied difference. FAA Order 1320.46D provides information on ACs.

5. The FAA should not sponsor a separate Standards Delegation Organization (SDO) to develop method of compliance to publish in other industry guidance materials.

While general consensus on this report was reached by the WG, dissenting positions of WG members were raised on each of the above separate recommendations. By and large, members with dissenting positions noted that these recommendations do not provide sufficient detail or clarification to fully address the FAA's and their own company-specific concerns. All options considered by the WG, including alternative proposals presented by dissenting members, along with the relevant supporting and opposing arguments are presented in this report. The summary of member votes on all considered proposals is also included in this report.

As a related subject to crack interaction, the WG considered whether additional guidance was needed to address damage tolerance-based recurring inspection intervals. The WG reviewed previous recommendations, the relationship between AC 25.571-1D [4] and AC 91-82A [5], and harmonization with the European Union Aviation Safety Agency (EASA) Acceptable Means of Compliance (AMC) 25.571 [6]. The WG members were split on whether there was a need to revise the guidance to clarify the considerations for developing repeat intervals. As a result, the WG does not recommend revision to AC 25.571-1D on this topic. This report includes the proposals and rationale for supporting or opposing considerations.

1 Introduction

This report documents the recommendations from the TAMCSWG to the FAA for the extended tasking focused on crack interaction considerations in the context of developing damage tolerance-based inspection programs. In addition to the recommendations, relevant background, technical discussions, this report also presents additional proposals the TAMCSWG considered but was unable to reach agreement to recommend to the FAA.

This introduction section includes the following:

- Basic report organization (Section 1.1);
- Background information for this tasking (Section 1.2);
- Discussion on what the TAMCSWG identified as being in-scope and out-of-scope for addressing the task (Section 1.3); and
- Technical background related to the relevant subjects addressed by the TAMCSWG (Section 1.4).

1.1 Report organization

Section 1.2 provides background of the tasking.

Section 1.3 describes the WG's approach to address the tasking. This section also explains why the WG considers certain structure to be out-of-scope for this tasking.

Section 1.4 provides a summary of WG technical discussions related to crack interaction. This material was discussed largely to ensure a common understanding among the WG members of the fundamental physics, concepts and definitions, and fracture mechanics-based effects of crack interaction.

Section 2 summarizes the tasking and the guidelines used by the WG for establishing recommendations and addressing dissenting positions.

Section 3 provides the WG recommendations and the supporting rationale for those recommendations related to the damage tolerance and fatigue requirements. This section also addresses two dissenting positions.

Section 4 provides the WG recommendations and rationale for those recommendations on changes to guidance materials. It also provides detailed discussions on the current FAA published guidance materials, previous guidance proposals, current EASA guidance materials, various practices employed by WG members to address crack interaction, and various proposals that were considered by WG members, including those that were not adopted as recommendations. This section also addresses several dissenting positions.

Section 5 summarizes the cost and benefit evaluation for the agreed upon recommendations.

Appendices to the report provide more extensive discussion on certain subjects. The appendices are referenced in the main report body where appropriate. The appendices are as follows:

- Appendix A: Reproduction of tasking
- Appendix B: Review of the FAA's questions posed to TAMCSWG on crack interaction
- Appendix C: Example of test and in-service findings demonstrating presence of multiple cracks, where crack interaction may have an impact on crack growth
- Appendix D: Summary of three analytical examples WG reviewed for evaluation of crack interaction effects
- Appendix E: Tabulated summary of WG member votes on proposals considered
- Appendix F: Summary of one OEM procedure for crack interaction consideration in a DTE
- Appendix G: Example scenarios for crack interaction, to accompany a considered proposal to revise AC 25.571-1D
- Appendix H: Example detailed considerations for a DTE to account for crack interaction for a proposal to revise AC 25.571-1D

1.2 Tasking background

This task is applicable to the damage tolerance evaluation (DTE) of metallic PSEs. The FAA provided examples of in-service damage findings of non-WFD susceptible structural details with multiple (i.e., concurrent) and/or extensive cracking. The FAA has expressed concern that the associated DTE accomplished by applicants may not be adequate if it does not consider the effect of multiple cracks as the current regulations do not explicitly prescribe this consideration. This may present a safety concern because the growth rate of the concurrent cracking may be greater than that envisioned in the DTE if only one crack was considered resulting in an unconservative inspection program. The FAA has also expressed concern related to product certification efficiency or potential need for standardization for the following reasons:

- the varying complexity of analytical solutions in use by applicants to model this effect, and

- potential alternative means to demonstrate that an applicant's maintenance program is suitable for probable cracking scenarios containing multiple interacting cracks.

AC 91-82A provides guidance for establishing a fatigue management plan (FMP) for both Part 23 and 25 certificated airplanes to address observed in-service fatigue damage to metallic structure. Applicants of type-certification programs may also use the guidance to supplement other ACs to develop damage-tolerance based inspection programs to look proactively for potential cracks. An FMP may include DT-based inspections to mitigate the demonstrated risk. This AC includes guidance on establishing an inspection threshold and repeat interval as elements of DT-based inspection program. Some elements of this AC can also apply to new TC programs.

AC 91-82A also states that the evaluation of a cracking scenario for developing FMP at some point may need to include crack interaction. Under the original TAMCSWG tasking, the WG did not have time to discuss any specifics on how industry has applied the guidance from AC 91-82A for certification of transport category airplanes as part of the original activities captured in TAMCSWG 2018 Recommendation Report, including the subject of crack interaction. In the 2018 TAMCSWG Recommendation Report, the FAA states that there have been a variety of ways that applicants have complied with the requirements of the rule in establishing scheduled inspections and associated procedures. The WG acknowledged this as an important topic and believed there may be a need for the FAA to provide additional guidance. Based on this, the FAA has requested information from the WG on how to address crack interaction when establishing inspection programs, which the ARAC accepted as an extended tasking to this WG.

This report is in response to that tasking and provides the following:

- Recommendations on how an applicant may address crack interaction when establishing inspection programs.
- Documentation of other proposed recommendations that were considered by the WG but ultimately were not supported as a recommendation to the FAA (reference Section 2.2 for additional discussion on how agreement on proposals was reached by WG). Such proposals are included here for posterity with supporting and opposing rationale for the proposals.
- Additional technical material that the WG considered but similarly opted not to recommend incorporation into guidance material. Yet, the WG felt there is merit in including the information in this report strictly as reference material.
- Answers to specific technical and regulatory questions the FAA posed to the WG related to crack interaction. In some cases, those questions are addressed through either final or proposed recommendations. In other cases, the questions are purely technical (i.e., not regulatory) in nature, and the discussions are documented in this report for awareness and future reference.

1.3 Summary of Working Group approach to tasking

The WG reviewed § 25.571 and its associated guidance material to determine if either would benefit from clarification relative to the crack interaction assessment considerations. For proposed updates to guidance material, the WG did not focus on providing the exact text unless the WG deemed it to be vital to the recommendation (such as the case for introducing a new definition). Rather, the WG focused on capturing the intent of the recommendations in this report, along with any supplemental discussion to help reinforce the objective of the recommended revisions.

The ARAC tasking statement addressed in this report is related to crack interaction considerations in the context of developing inspection programs. However, as identified in existing guidance (AC 25.571-1D, 91-82A and 120-104 [7]), there are cases where DT-based repetitive inspections may not be effective in timely detection before the required residual strength capability is compromised. In such cases modifications or other operational limitations (also considered as "other procedures" in the rule) may be necessary. Therefore, the WG has not limited the review of consideration of crack interaction solely for the purpose of establishing inspections, but rather for DT-based maintenance programs more generally, which may include such "other procedures."

There are many aspects of a DTE used to develop inspections programs or procedures beyond crack interaction effects. For the extended tasking, the WG focused on crack interaction and how the rules and associated guidance material might be enhanced to better address this phenomenon in development of effective inspection programs without encroaching on other elements of a DTE (e.g., fatigue spectra, material properties, manufacturing quality, etc.).

Evaluation of PSEs to preclude WFD in a transport airplane's operational life is a subset of the general DTE requirement. AC 25.571-1D, Appendix 3 includes a process for determining if a PSE is susceptible to WFD, in which case the special WFD evaluation is required. Guidance for developing maintenance program requirements, including Limit of Validity (LOV)[3], Structural Modification Point (SMP) and Inspection Start Point (ISP), to preclude WFD is provided in AC 120-104. If the PSE or detail design point is not susceptible to WFD (i.e., a unique design feature) then the guidance in AC 120-104 is not normally used by applicants in developing DT-based programs.

The WG members all agreed that the existing guidance in AC 120-104 is adequate to address crack interaction and how an applicant should consider it when performing a WFD evaluation. Accordingly, the focus of the WGs effort was on crack interaction considerations for DTE of PSEs which is not part of a WFD evaluation. As described in Section 4.2, the WG did consider WFD AC 120-104 to be a good source of guidance to address crack interaction when the WG was considering potential change recommendations to AC 25.571-1D for local design details.

WFD includes two sources: Multiple Site Damage (MSD) and Multiple Element Damage (MED). Though the concept of MSD and MED are not unique threats to WFD susceptible structures, as multiple/concurrent cracks can occur in most any structural detail, industry typically uses these terms only in context of WFD evaluations. The WG recognized that using the terms MSD or MED for discussions of cracking in local design features (non-WFD susceptible structure) could be confusing. This was evidenced by comments from some WG members when MSD or MED were used in describing

[3] Sections 25.571, 26.21, and 26.23 refer to LOV as the limit of validity of the engineering data that supports the structural maintenance program.

cracking scenarios for unique design details. Accordingly, the WG does not use the term MSD or MED in this report when discussing multiple or concurrent cracks leading to interaction effects for the unique/local design detail. Furthermore, EASA has used the term "concurrent cracking" to describe the presence of multiple cracks within structural detail(s) in their AMC 25.571. Though the WG was careful to avoid using the terms MSD/MED, the WG uses both the terms "multiple" and "concurrent" cracks interchangeably; the damage scenarios described by these two terms have the same meaning to the WG in this report.

A significant part of the WG's focus was also on fatigue cracking and manufacturing defects that are often modeled as discrete cracks (e.g., "rogue flaw" as described in Section 4.5 of the FAA Damage Tolerance Assessment Handbook, Volume II [8]). The rule requires establishment of inspections or other procedures to ensure that the required residual strength of the PSE is maintained over the operational life in presence of fatigue damage, corrosion, manufacturing defects, or accidental damage[4]. Identifying the probable locations and modes for these four threats constitutes a threat assessment. The threat assessment drives the applicant to identify the physics of the problem, and there may be multiple ways to address the physics of the problem to achieve a maintenance program that ensures continued operational safety. If an applicant determines that probable locations and modes of damage due to these threats includes scenarios of multiple cracks in proximity such that their presence results in higher crack growth propagation than otherwise for single cracks, then the applicant should have a means to account for that effect. However, based on common practices of the WG members, explicit consideration of interaction of cracking with other forms of damage (such as corrosion or accidental damage) is not typically performed.

A similar concern was addressed, in part, by the Airworthiness Assurance Working Group (AAWG) in *Recommendations for Regulatory Action to Prevent Widespread Fatigue Damage in the Commercial Airplane Flee*t [9]. In Section 5.3.4 of that report, the AAWG discussed the interaction between Environmental Damage (ED) and Accidental Damage (AD) threats with WFD (a more extreme subset of fatigue damage threat) and concluded –

- for ED an effective corrosion control program will minimize interaction effects with MSD/MED; and
- for AD, there are two separate categories –
    - Local damage (such as dropped tool) which is addressed through maintenance programs generally structured to find such incidents or damage before they become critical. The AAWG noted that, as these incidents are local and isolated, in general they will never interact with MSD/MED damage scenarios; and

[4] § 25.571(a) identifies the requirement for establishing inspections or other procedures accounting for these four threats. § 25.571(b) states requirement for meeting residual strength, yet only for "fatigue, corrosion, or accidental damage." The 2018 report includes a recommendation to change "corrosion" to "environmental damage" and to add "manufacturing defects" as a damage threat to paragraph (b).

- Damage associated with unapproved methods or procedures used during manufacture or maintenance, such as scribe lines introduced when trimming adhesives or chemically milling marks. Though these types of threats may present a concern for interaction with other threats (such as fatigue damage) the existence and occurrence of these types of threats are rare and unpredictable and it is nearly impossible to account for all such potential threats as a certification activity. These threats are managed through aggressive investigation and corrective actions on all potentially affected airplanes when the threat is observed or suspected. Use of fail-safe design features should be adequate to contain this type of damage if the full-scale fatigue test (FSFT) with proper extended lifetimes is applied.

The current WG believes these conclusions from AAWG are still valid, and service and test findings since the publication of this report in 1999 have not revealed new concerns with current industry practices for addressing general threat interaction for compliance findings. Furthermore, as these AAWG conclusions are related to WFD, the notion of interaction between manufacturing damage (typically assumed in certification analysis activities as discrete and local) and ED or AD are less critical than potential of interaction with MSD/MED which, by definition, will be more widespread than the local manufacturing damage.

Lastly, this current extended tasking related to crack interaction is intrinsically a metal-centric concern and is not considered by the WG to be relevant to composite structures. Though solid laminate composite structures may include presence of very small cracks within the heterogenous composition, such cracking in composite structures is not presently analyzed or managed by industry in the same manner as the cracking in metallic structures. The current state of the industry for the development of maintenance programs in composite PSE is through significant reliance of the building-blocks approach to test-derived programs (described in AC 20-107B [10]). Effect of interacting damages (i.e., cracks, local delamination or disbonds) in a composite PSE is often addressed through a comprehensive test program in conjunction with analyses that properly envelopes expected damage threats. Consideration of interacting cracks for development of maintenance programs for composite materials is therefore considered beyond scope of this extension tasking. However, any metallic structural elements of a hybrid detail, consisting of the junction of metallic and non-metallic/composite structure, that also includes features susceptible to concurrent cracks should be applicable to the subject of this report as any other metallic structural details.

1.4 Technical background on potential crack interaction effects (Appendices B, C, D and G)

The presence of multiple cracks in either a single or adjacent structural member has been observed both in test and service articles ever since the earliest observations of fatigue cracking. This phenomenon of multiple or concurrent cracking is not a new damage scenario addressed by this WG. For the purposes of illustration, Appendix C presents both test and service findings demonstrating the presence of multiple cracks at structural details, either present in the same or adjacent structural elements where the observed cracks are expected to interact. The presence of two cracks may result in faster growth of each relative to the case where just a single, similar size crack is present.

This section provides relevant background on some technical aspects discussed by the WG of the effect of multiple cracks within PSEs, such as those illustrated in Appendix C, including:

- Effect of a lead crack on earlier initiation of secondary cracks;
- Effect of lead and secondary cracks on the stress intensity factor (SIF) solutions used in a linear fracture mechanics (LEFM)-based growth model;
- Effect of a lead crack on secondary cracks in adjacent details or adjacent structural elements in multiple load path designs due to potential redistribution of loads;
- Effect of interacting cracks is typically a greater concern for establishing repetitive inspection intervals than establishing inspection thresholds;
- Effect of crack interaction may not always be adverse with respect to crack growth rates; and
- Summary of the current state of crack growth software applications and some selected technical papers on the subject of crack interaction modeling.

Appendix D contains several examples showing separate analytical approaches to address crack interaction effects. Example AA shows a finite element model (FEM) to demonstrate how cracking of various lengths at a hole under a bearing and remote tension load will result in a local stress concentration at the opposing side of the hole. Such increasing stress concentration results in an expected associated reduction of fatigue life (earlier crack initiation) than otherwise expected for an uncracked hole. These effects should be considered in the development of the applicants continuing damage assumptions when such an approach is used for establishing inspection intervals. Example AA is an academic study and not a complete representation of all aspects of the fatigue performance of common structural details for which the stress concentration effect is being demonstrated. One such example is a compressive residual stress field around the hole due to fastener expansion for a mechanically fastened joint.

Appendix D also includes two examples demonstrating the comparative results for LEFM-based models of cracking at a fastener hole under cyclic bearing and remote (bypass) tension loads. Example BB shows comparative growth simulation results using two different NASGRO (a widely used crack growth computer program with many built-in SIF solutions) geometry models. Example CC shows a separate presentation from National Research Council (NRC) of Canada to the 2019 AFGROW User's Conference [11] (AFGROW is another crack growth simulation program, widely used by industry). Example CC similarly presents the comparative growth results of multiple cracks between a case with correction to the SIF solutions to account for the interaction effects and a case of similar cracking scenario where each crack is independently grown (no interaction effects explicitly considered). Example CC also illustrates this effect using a less widely available crack growth program [12]. Note, both Examples BB and CC in Appendix D present models based on fracture mechanics analysis of interacting cracks, and do not capture all the other methods an applicant may employ to develop repetitive inspection intervals, including, but not limited to, fail-safety design, initial (both primary and secondary) flaw size assumptions, higher design structural safety margin for fatigue, use of conservative fatigue spectra, or the actual performance of the structure in consideration recognized via testing or service experience, etc.

Though the WG members all agree on the underlying physics of multiple or concurrent cracking, including the technical content presented in Appendix D described above, the members also recognize there are various methods, approaches, and assumptions that can be employed to address this effect in establishing an effective maintenance program (reference Section 4.5 for additional discussion). The WG is not recommending nor endorsing any one method over others. The technical material contained in the appendices of this report is for information purposes only. As with any compliance data, applicants must ensure that the use of any method or assumption will result in reliable and effective maintenance programs, and must be accepted by their cognizant regulatory agency. While Appendix D includes several examples showing approaches to address this effect, additional comments shared by WG members reflecting a range of perspectives to address such cracking scenarios are also included.

Appendix 4 of AC 91-82A describes an effect of crack interaction for a Multiple Load Path (MLP) design; however, the term "interaction" does not explicitly appear in that discussion. This guidance describes a scenario involving MLP structure where local element failure with a relatively larger lead crack may accelerate the growth of smaller cracks in adjacent elements that experience higher loads redistributed from the prematurely failed element with the progressing lead crack. Though all WG members recognize this scenario, some members consider this scenario separately from crack interaction, describing it as "load redistribution." Nonetheless, all WG members recognize that it is a feature of multiple or concurrent cracking regardless of the classification terminology (i.e., "crack interaction" vs "load redistribution"). All WG members agreed such scenarios should be addressed in a DTE if it is expected.

Since the crack interaction influence on crack propagation rates is proportional to increasing crack sizes, and since the crack growth scenario under consideration here is the result of fatigue crack propagation (i.e., not accidental or discrete source damage) the effect of the interaction is also expected to be progressive. This expectation is also reflected in AC 91-82A through the statement that cracking may be complex and *at some point* include interaction. As a result, the WG considered that accounting for crack interaction may typically be an aspect of the DTE for structure after a period of life in terms of flight hours or cycles (i.e., for developing inspection intervals, analogous to an SMP or LOV as part of WFD evaluation, or another operational limitation/replacement period) and not necessarily typical for establishing DT-based inspection thresholds. The effect of interaction is less severe when the cracks (including adjacent cracks) are relatively small in the early service period of the airplane. Example CC in Appendix D shows one analytical evaluation where the interaction effect is demonstrated as more significant to establishing repeat intervals than for establishing an inspection threshold. Therefore, the WG largely considered crack interaction as it relates to the development of repeat inspection intervals. Yet modification/retirement is also an “other procedure” that may be used for aged structure when inspections are not effective. AC 91-82A uses the generalized term “damage-tolerance based inspection program” which normally includes a threshold and a repeat interval. As an extension of the notion that crack interaction is largely an issue which may need to be considered when establishing inspection intervals, the WG did consider options to propose new guidance material focused on how repeat inspection intervals may be established. However, the WG was unable to reach agreement on a recommendation to propose to the FAA on this and a summary of those discussions is presented in Section 4.6.6 of this report.

The primary perspective by this WG had been on considering the crack interaction effects as being adverse when establishing a structural maintenance program (i.e., resulting in faster crack growth in a structure than for a crack growth model without crack interaction effects). However, it should be noted for the completeness of technical discussion that there are cases in which crack interaction may provide a beneficial effect, such as the case for multiple parallel (or mostly parallel) cracks orthogonally aligned to a remote tension load; a condition described as “crack shielding.” Reference Appendix G for an illustrated case of parallel cracks at adjacent holes. While the terminology used by WG to describe “crack interaction effects” is largely understood and expected by WG to describe a detrimental effect, it is not necessarily the case for all possible crack interaction configurations. In all cases and configurations, the specific methodology selected by an applicant should yield accurate or conservative results.

To assist the FAA, the WG compiled a list of industry crack growth software packages and some commentary on the capability to model crack interaction effects, reference Appendix B, Table B-1. Additionally, Appendix B contains a partial list of publicly available technical papers an applicant may consider in their own development of SIF solutions for crack interaction scenarios, reference Appendix B, Table B-2. Note, such approaches are not an endorsement by WG as the only or preferred approach, simply documentation of existing technical papers which may be used as reference materials.

2 TAMCSWG Tasking

This WG has been tasked by ARAC through the TAE Subcommittee, to address the concerns raised by the FAA regarding industry use of crack interaction in establishing inspection programs (reference Section 1.2 for additional detail and background). The detailed extended task statement of the TAMCSWG on this subject accepted by ARAC and assigned to TAMCSWG is as follows:

> *Advisory Circular 91-82A provides evaluation considerations for establishing inspection thresholds and repeat intervals. It states that the evaluation of a cracking scenario at some point may need to include crack interaction. The working group did not have time to discuss any specifics on how industry has applied the guidance from AC 91-82A for certification of transport category airplanes. In the TAMCSWG Recommendation report, the FAA states that there has been a variety of ways that applicants have complied with the requirements of the rule in establishing scheduled inspections and associated procedures. The working group acknowledges this is an important topic and believes there may be a need for the FAA to provide additional guidance. Based on this, the FAA is requesting information from the working group on how to address crack interaction when establishing inspection programs.*

The original tasking, defined in January 26, 2015 Federal Register[5], is reproduced in Appendix A. The same elements for the original tasking (such as review of relevant regulatory materials, determination of need for updates, recommend updates and determining cost/benefits associated with the recommended updates) were applied to this extension subject.

During the WG deliberations on this extended tasking, the FAA raised additional specific questions related to the general topic which were presented to the WG to address. These questions and WG responses are contained in Appendix B.

[5] 80 FR 4029 January 26, 2015

2.1 Working Group Members

The Working Group membership consisted of voting members, subject matter experts and regulatory advisors and participants. The population reflected Original Equipment Manufacturers (OEMs), operators and both foreign and domestic regulatory agencies.

Voting members:

1.	William Browning	(Boeing)
2.	Chantal Fualdes	(Airbus)
3.	Pascal Lortie	(Bombardier)
4.	Benoit Morlet	(Dassault Aviation)
5.	Antonio Fernando Barbosa	(Embraer)
6.	Kevin Jones	(Gulfstream)
7.	Toshiyasu Fukuoka	(Mitsubishi)
8.	David Nelson	(Textron Aviation)
9.	Tom Eldridge	(British Airways)
10.	Doug Jury	(Delta Air Lines) – Chairperson
11.	Mark Boudreau	(FedEx)
12.	Eric Chesmar	(United Airlines)
13.	Walt Sippel	(FAA - advisor)

Subject matter expert:

1.	John van Doeselaar	(Airbus)
2.	Michael Gruber	(Boeing – retired)
3.	Thomas Harrison	(Textron Aviation)

Regulators:

1.	Michael Gorelik	(FAA)
2.	Patrick Safarian	(FAA)
3.	Larry Ilcewicz	(FAA)
5.	Richard Minter	(EASA - retired)
6.	Simon Waite	(EASA)
7.	Fabiano Hernandes	(Brazilian National Civil Aviation Agency (ANAC))
8.	Pedro Caldeira	(ANAC)
9.	Marco Villaron	(ANAC)
10.	Jackie Yu	(Transport Canada Civil Aviation (TCCA))
11.	Natasa Mudrinic	(TCCA)
12.	Hiroshi Komamura	(Japan Civil Aviation Bureau)
13.	Phil Ashwell	(United Kingdom Civil Aviation Authority (UK CAA))

2.2 Determination of Consensus

The Aviation Safety Quality Management System Report ARM-001-015: *The Office of Rulemaking Committee Manual* [13] states that each working group should establish a process by which it determines if consensus has been reached and encourages documentation of differing perspectives as providing value to the FAA in the rulemaking process. The activities documented in this report have been conducted under continuation of the TAMCSWG, which previously established a work plan that included a process for reaching consensus during the initial meetings held in 2015.

This report uses the terms full consensus and general consensus based on the definitions provided in the FAA ARM-001-015 Report which states *"full consensus"* is a situation where all voting members are in full agreement with the recommendations and *"general consensus"* as a situation where although there may be disagreement, the group has heard, recognized, acknowledged, and reconciled the concerns or objections to the general acceptance of the group. Although not every member fully agrees in context and principle, all members support the overall position and agree not to object to the proposed recommendation report.

Furthermore, the terms "full" and "general consensus" are applied to the report as a complete entity and not to the various items which are included in this report. The terms "agreement" and "disagreement" are used with respect to the detailed proposals and recommendations the WG considered.

Dissenting positions, where the entire group could not reach agreement on a proposal, are explained and captured in the report. As previously noted, this WG activity spurred much debate and discussion and in recognition of the value of dissenting positions to the FAA's potential future rulemaking activities the WG has taken care to capture all such dissenting positions completely.

Based on the TAMCSWG's original work plan authored in 2015, the WG for this extended tasking considered that a proposal subjected to a vote required two thirds of the voting member support (i.e., 8 or more of the 12 voting members) to be considered a recommendation to the FAA. Tallied votes of the WG members for the various proposals are included in Appendix E. However, this standard does not supersede the prior note that general agreement requires that those in the minority on a given vote may document their points of disagreement and otherwise have agreed to not object to the final recommendation moving forward. The FAA is a voting member of this WG in the sense that they may accept or reject the report in its entirety. However, for the purposes of considering specific proposals and whether those may be an actual recommendation by the WG, the FAA position is excluded from the vote count. Nonetheless, the FAA's stated positions are captured in Appendix E and their comments are documented in report where relevant.

3 Rule Recommendations

This section discusses the second element of the ARAC Tasking detailed in Appendix A for addressing crack interaction when establishing inspection programs. It focuses on Task 3 of the ARAC Tasking and summarizes the review, recommendations and supporting rationale. This task requires the WG to advise and make written recommendations on whether to change the damage-tolerance and fatigue evaluation requirements of Parts 25 and 26 to address crack interaction when establishing inspection programs.

In 2003, the Generalized Structures Harmonization Working Group (GSHWG) issued a recommendation report [14], which included recommended additions to § 25.571(a) related to inspection programs, though not specifically related to the consideration of crack interaction. These recommendations included the addition of § 25.571(a)(5) and (a)(6):

> *(5) When special inspections are required to prevent catastrophic fatigue failure, inspection thresholds must be established to ensure that cracking in a PSE will be detected before it results in catastrophic failure. The inspection thresholds must account for the variation in manufacturing quality.*
>
> *(6) Inspection programs for corrosion and service induced accidental damage must be proposed to protect the structure against catastrophic failure.*

The FAA did not incorporate these recommendations into § 25.571 at amendment 25-132[6] nor at amendment 25-148, but the TAMCSWG did address them in the 2018 report.

Section 3.5.1 of the TAMCSWG 2018 report includes a recommend rule change to "move toward a more material independent performance-based requirement building on what was suggested by the 2003 GSHWG effort." One recommendation was to remove the specific text from § 25.571(a)(3) that states, "Inspection thresholds … must be established based on crack growth analyses and/or test, assuming the structure contained an initial flaw of the maximum probably size that could exist as a result of manufacturing or service induced damage" with the following more performance-based requirement:

> *When inspections are required to prevent catastrophic failure, inspection thresholds must be established to ensure that damage in a PSE will be detected before it results in a catastrophic failure. The inspection thresholds must account for the*

[6] When the TAMCSWG started the tasking, § 25.571 was at amendment 25-132. All considerations and references in this report are related to amendment 25-132. The FAA adopted amendment 25-148 on 1/18/2023, which was near the completion date of this report. Amendment 25-148 only corrected a typographical error in § 25.571. As a result, the discussions and recommendations in this report are valid with respect to amendment 25-148.

expected range of damage threats to the structure and use methods substantiated by representative tests or in service data.

Similarly, the TAMCSWG 2018 report also recommend replacing the word “corrosion” with “environmental deterioration” to avoid metallic-centric language. For evaluation of the current rule in this extended tasking, all recommendations from the TAMCSWG 2018 report are considered valid and acceptable.

The evaluation criteria and rationale for final recommendation for changes to regulations generally fell within the following categories -

- Enforceability (does the rule provide explicit/implicit consideration of crack interaction);
- Performance-based vs. prescriptive requirements;
- Harmonization with EASA rules; and
- Cost/benefit evaluation

The results of that review follow.

3.1 Rule Changes

The WG reached general agreement that current rule text is sufficient for establishing the requirements for inspections or other procedures, § 25.571(a)(3), and consideration of crack interaction as part of the damage tolerance evaluation, § 25.571(b), and no changes are required.

The WG reviewed the current rule, including the changes recommended by the 2018 TAMCSWG Report, to determine if changes were needed to provide enforceability under the current regulations for the consideration of crack interaction in establishing inspection intervals or to address if a potential unsafe condition exists with current rule text in context of crack interaction. In the context of this review, enforceability is defined as establishing high-level performance-based criteria; that would direct an applicant to consider crack interaction as part of the evaluation when establishing repeat inspection intervals as part of the certification process.

The WG also reviewed the current rule based on performance-based vs prescriptive requirements. The current regulation, as discussed in Section 3.2, is considered to provide a high-level performance-based criteria. While the WG did identify the need to more clearly distinguish between cracking scenarios considered in the baseline DTE and those used in the WFD evaluation, the WG’s generally agreed position is that clarification is more appropriate for the associated guidance and not the rule itself (see Section 4 for detailed discussion on guidance).

The WG did consider changes to harmonize the current § 25.571 rule with language used in EASA CS 25.571. Several WG members found the requirements in § 25.571(b) to provide clearer and more concise language which provides a distinction between the performance of the DTE to establishing inspections and the “special consideration for widespread fatigue damage.” Two WG voting members preferred the current wording found in CS 25.571, Amendment 26 (introduced at Amendment 19), or slightly adjusted. Those dissenting positions are presented in Section 3.3.

Since neither the enforceability review, performance-based vs. prescriptive review, nor harmonization reviews resulted in recommended changes to the rule, there is no detailed cost/benefit evaluation needed (reference Section 5).

3.2 Rationale

Inspection requirements

In the 2018 report, the TAMCSWG recommended the § 25.571(b) rule to be changed from “inspection thresholds …must be established based on crack growth analyses” to “inspection thresholds must account for the expected range of damage threats to the structure and use methods substantiated by representative tests or in service data.” This would allow the applicant flexibility in the method used to establish the point at which inspections need to start, while the requirement that “inspection or other procedures must be established, as necessary, to prevent catastrophic failure” remains unchanged.

Consideration of crack interaction

The TAMCSWG 2018 report also recommended the following revised text for § 25.571(b): “The evaluation must include a determination of the probable locations and modes of damage due to fatigue, environmental deterioration, manufacturing defect[7], or accidental damage.” The majority of the WG considers the term “modes of damage” a high-level descriptor to cover a wide variety of damage occurrence and damage growth, which also implies crack interaction or other factors that may affect the damage extension rate. Overall, the current rule provides a high-level performance-based requirements to evaluate the damage tolerance capability of the aircraft and that detailed information related specifically to crack interaction is more appropriate for guidance materials covered in Section 4 of this report.

Review of safety concern

The FAA requested the WG review past airworthiness directive (AD) history of observed field issues to determine if there is evidence of a direct correlation between a lack of explicit crack interaction considerations in the DTE and if a known or observed safety

[7] The terms “environmental deterioration” (to replace the current term “corrosion”) and addition of “manufacturing defect” are presented as a recommended revision to § 25.571(b) made by TAMCSWG in 2018 report.

issue exists. A review of varying degrees was conducted by several OEM WG members to evaluate several AD's on their products related to fatigue cracking. All OEM WG members reported that their review had not revealed any safety issues that were directly related to inadequate inspection programs due to omission of crack interaction in the original analysis. There remains concern among operators and regulators that this review was not extensive nor provided adequate rigor to assure that consideration for crack interaction during the DTE is not necessary. The results did indicate that just as several factors influence the DTE, the observed in-service cracking was often influenced by several factors where the original certification DTE may not have adequately captured the actual service conditions. Such factors included, but were not limited to, load path and load distribution, points of stress concentrations, environmental considerations, etc. Based on this evaluation, the OEM WG members agreed that crack interaction is not an observed safety concern on its own. The position of the operator WG members and regulatory authorities is that a more detailed interrogation of field cracking would be required to eliminate the safety concern regarding current practices to address crack interaction effects completely. Additionally, the practices of some industry representatives not directly represented in this WG, such as supplemental type certificate (STC) holders or consultant designated engineering representatives (DERs) may need further review to ensure there is not an increased potential for safety concern yet to be revealed.

Harmonization

The majority of the WG members preferred the current FAA rule to the EASA rule. A comparison between the relevant language is shown below in Table 3.1, with added highlights which are relevant to this topic. The FAA rule specifically mentions "special consideration for widespread fatigue damage must be included where the design is such that this type of damage could occur." The EASA rule states, "Damage at multiple sites due to prior fatigue exposure (including special consideration of widespread fatigue damage) must be included in the evaluation where the design is such that this type of damage could occur." While there are some differences between FAA and EASA rule in § 25.571(a), it is the language "Damage at multiple sites due to prior fatigue exposure" that remains in CS 25.571(b) but is absent from the FAA rule which motivated the WG to consider if there is a need for crack interaction as a requirement (even implicitly) of the EASA rule while not for the FAA.

1. Development of FAA rule language: The FAA rule included the "damage at multiple sites" language from amendment 25-45, with the introduction of damage tolerance requirement, through amendment 25-86. It was revised to the current wording at Amendment 25-96 with the replacement of the explicit references to damage at multiple sites by the consideration for WFD by means of a full-scale test. A review of the comments published in the Federal Register, which addresses the changes at Amendment 25-96, shows the following discussion:

   > *"One commenter also suggested replacing the sentence in current 25.571(b) that states, 'Damage at multiple sites due to prior fatigue exposure must also be included where the design is such that this type of damage is expected to occur.' With the following sentence: 'Special*

consideration for WFD must be included where the design is such that this type of damage could occur.' Although the commenter provided no explanation of this suggestion, the FAA considers that is has merit. The FAA concurs that requiring 'special consideration of WFD' emphasized that in addition to demonstrating that WFD will not occur with the design service goal, the applicant for type certification must also control the effects of WFD that may occur beyond the design service goal. This is necessary to fulfill the objective of § 25.571(a) to avoid catastrophic failure due to fatigue throughout the operational life of the airplane."

While the commentary does not provide further explanation, most WG members consider the phrase "damage at multiple sites due to prior fatigue exposure" is interchangeable with MSD, which is closely associated with WFD. The FAA regulation is more general than the EASA counterpart and clearly applies to structure that has been determined to be susceptible to WFD, which includes damage at multiple sites. The FAA rule should not be revised to align with the EASA text.

2. Development of EASA rule language: EASA retained the "damage at multiple sites due to prior fatigue exposure" language when it inserted the "including special consideration of widespread fatigue damage" in its rule. The majority of the WG member position is that this language is not clear because multiple site damage is typically defined as a subcategory of WFD. A review of AMC 25.571 was conducted to determine if there is guidance to clarify the intent of the requirement. This review showed the following statement:

   … although FAR, (Joint Aviation Requirements) JAR, and CS 25.571 have, since 1978, required consideration of fatigue damage originating at multiple sites, the FAA AC was further revised on 29 April 1998 (revision 1C) to add guidance material whose objective was to preclude widespread fatigue damage (resulting from MSD and MED) from occurring within the design service goal of the aeroplane, and to aid in the determination of thresholds for fatigue inspection and/or other special fleet action. JAR/CS 25.571 were not harmonized with the 1998 amendment of 14 CFR 25.571.

   The reference to 1998 applies to changes introduced at FAA Amendment 25-96. The use of the term "damage at multiple sites" is not found in AMC 25.571. The closest use of the phrase is found in the definition of WFD, which "is the simultaneous presence of cracks at multiple structural locations." This definition matches those included in ACs 25.571-1D and 120-104. This also implies that "damage at multiple sites" and "multiple site damage" are used interchangeably and are closely related to WFD. Beyond WFD, there is no discussion in the AMC on how this damage should be included in the evaluation. The WG could not find any guidance or policy that shows this text is intended to be applied to the evaluation of "concurrent cracking" described in the AMC (see in Section 4.4 for discussion). Therefore, this statement in the regulation text is confusing, and the expectation of WG members is that such confusion would translate to FAA rule if this EASA language was adopted into § 25.571.

Though harmonization is a worthy goal, the WG preferred the current FAA rule as it clearly establishes that there are two distinct evaluations (WFD and non-WFD), which is further clarified in guidance through chart in Step 6 of AC 25.571-1D Appendix 3 (see following Figure 3.1 for the excerpt). The EASA rule does not offer that same clarity and possibly adds confusion by using the term “damage at multiple sites” without providing any clarity in guidance that this term is not synonymous “multiple site damage” typically associated with WFD. Therefore, the WG recommends the text in § 25.571(b) to not be harmonized with current text in EASA CS 25.571 for the noted reasons.

Table 3.1: Comparison of CFR and EASA CS

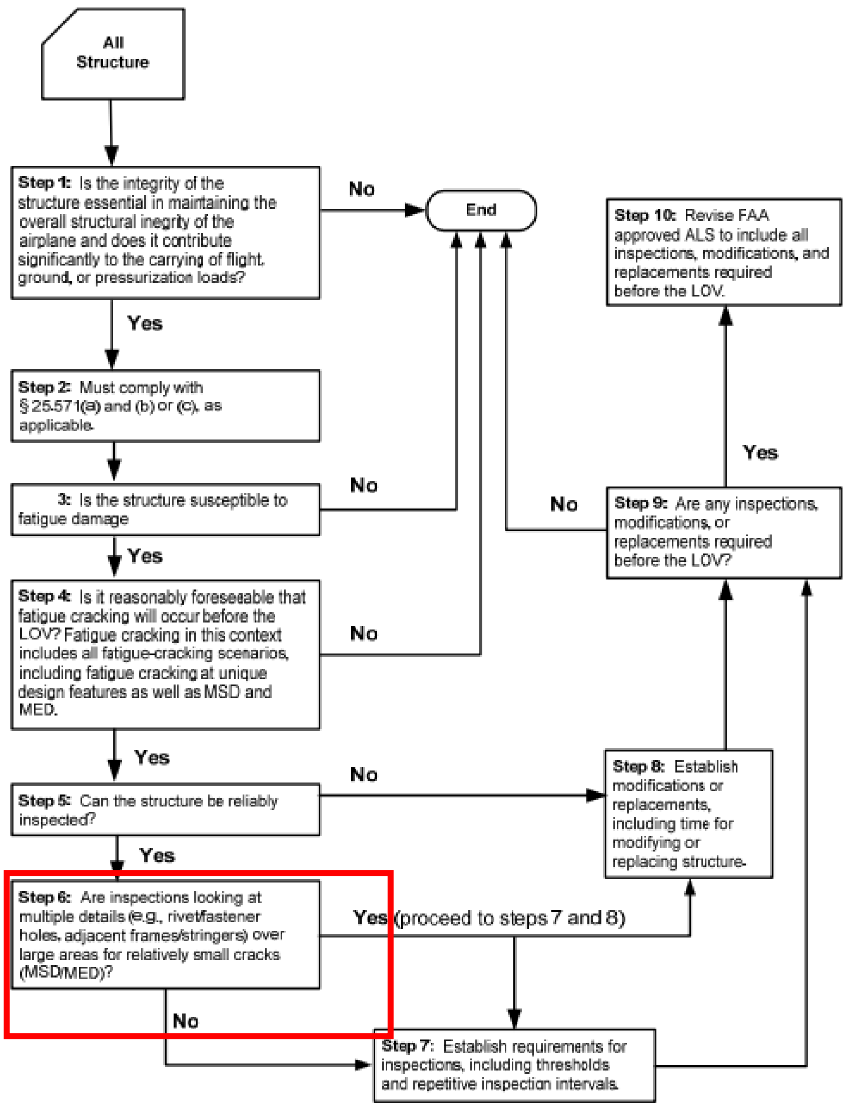
§ 25.571 Amendment 25-132	EASA CS 25.571 Amendment 19[8]
(b) Damage-tolerance evaluation. The evaluation must include a determination of the probable locations and modes of damage due to fatigue, corrosion, or accidental damage. Repeated load and static analyses supported by test evidence and (if available) service experience must also be incorporated in the evaluation. Special consideration for widespread fatigue damage must be included where the design is such that this type of damage could occur. An LOV must be established that corresponds to the period of time, stated as a number of total accumulated flight cycles or flight hours or both, during which it is demonstrated that widespread fatigue damage will not occur in the airplane structure. This demonstration must be by full-scale fatigue test evidence.	b) Fatigue and damage tolerance evaluation. The evaluation must include a determination of the probable locations and modes of damage due to fatigue, environmental deterioration (e.g. corrosion), or accidental damage. Repeated load and static analyses, supported by test evidence and (if available) service experience, must be incorporated in the evaluation. Damage at multiple sites due to prior fatigue exposure (including special consideration of widespread fatigue damage) must be included in the evaluation where the design is such that this type of damage could occur. An LOV must be established that corresponds to the period of time, stated as a number of total accumulated flight cycles or flight hours or both, for which it has been demonstrated by full-scale fatigue test evidence that widespread fatigue damage will not occur in the aeroplane structure.

[8] The highlighted text was introduced in EASA CS 25.571 at Amendment 19, though this text has remained constant through Amendment 27 (current amendment level at the date of this report).

1/13/11 AC 25.571-1D
Appendix 3

Appendix 3
Process for Compliance with 14 CFR 25.571(a), (b) and (c) for Fatigue Damage

This chart applies only to § 25.571(a), (b), and (c) for fatigue damage (FD), relative to LOV.



A3-1

Figure 3.1: Excerpt from FAA AC 25.571-1D, Appendix 3. Step 6 is highlighted to show FAA's distinction between a WFD and non-WFD evaluation.

3.3 Dissenting Positions

British Airways presented the following dissenting position

The EASA rule is more comprehensive and establishes the high-level requirement for an applicant to consider crack interaction in both the DTE and the WFD assessment. Therefore, the recommendation is to align, thus harmonizing, § 25.571(b) with the current CS-25.

Rationale: At a high level, the current EASA rule addresses crack interaction more comprehensively than the FAA rule. The opening two sentences in paragraph (b) are similar in both § 25.571 and CS-25.571 which include the phrase *"modes of damage."* The difference occurs in the third sentence, just prior to the LOV discussion, where the EASA explicitly mentions that *"damage at multiple sites dues to prior fatigue exposure (including special consideration of widespread fatigue damage) must be included in the evaluation….*"

The FAA rule, in contrast, does not mention damage at multiple sites, although it may be implied as part of the widespread fatigue damage demonstration but is never directly mentioned.

NOTE: The representative who provided this dissent had moved from British Airways to the Civil Aviation Authority during the WG tasking effort. The dissent remains valid for British Airways but is also adopted by the CAA.

FedEx presented the following dissenting position

The following line, with minor changes to differentiate it from WFD, should be reintroduced into the rule to emphasize that cracks that are not considered to be WFD can occur at more than one location. This would need to be reinforced with guidance that makes it clear that multiple cracks may need to be considered outside of a WFD assessment.

"*Damage at multiple sites due to prior fatigue exposure must also be included where the design is such that this type of damage is expected to occur.*"

Suggested alternate wording:

"Damage at more than one location due to prior fatigue exposure must be considered in a normal damage tolerance evaluation (localized cracking assessment) where the design is such that this type of damage is expected to occur."

Rationale: In addition to the previous dissenting position rationale, reintroducing something similar to the noted line provides a requirement that the damage tolerance evaluation must consider realistic cracking scenarios (one of the five facets, Eastin and Swift, International Committee on Aeronautical Fatigue & Structural Integrity 2005: *"Rough Diamond": Two Regulators Review Damage Tolerance* [15]) that may include multiple cracks outside of a WFD assessment. This change may improve safety since it will help limit analysis that may result in an unreliable inspection program.

This line was previously part of the rule from amendment 25-45 through amendment 25-86, was part of Docket No. 27358; Notice No. 93-9 recommendations and was removed without explanation on how it would affect non-WFD related evaluations.

The following is from Docket No. 27358; Amendment No. 25-96.

> "*One commenter also suggested replacing the sentence in current Sec. 25.571(b) that states, 'Damage at multiple sites due to prior fatigue exposure must also be included where the design is such that this type of damage is expected to occur,' with the following sentence: 'Special consideration for WFD must be included where the design is such that this type of damage could occur.' Although the commenter provided no explanation of this suggestion, the FAA considers that it has merit. The FAA concurs that requiring 'special consideration for WFD' emphasizes that, in addition to demonstrating that WFD will not occur within the design service goal, the applicant for type certificate must also consider ways to prevent or control the effects of WFD that may occur beyond the design service goal. This is necessary to fulfill the objective of Sec. 25.571(a) to avoid catastrophic failure due to fatigue throughout the operational life of the airplane."*

This line is also objective (not prescriptive) because it states that it is only required "*where the design is such that this type of damage can be expected to occur."* This allows applicants latitude in "*developing methods to demonstrate compliance*" as long as crack interaction is considered and, if required, mitigated with a conservative approach. There is no reason for not reintroducing the concept provided there is additional guidance.

The following is from Docket No. 27358, Notice No. 93-9 (bold text emphasis is added).

> *"The requirements for damage tolerance evaluation of structures contained in Sec. 25.571 are written in terms of* ***general objectives so as to allow manufacturers latitude in developing methods to demonstrate compliance****. Because the requirements are stated in objective terms, manufacturers have experienced difficulty in judging the scope of the evaluation necessary for certification. For instance, the rule requires consideration of damage at multiple sites due to prior fatigue exposure where the design is such that this type of damage can be expected to occur. This is an objective requirement that provides no specific guidance on what is required for showing compliance."*

NAA Member Positions

The FAA understands the range of considerations expressed by the members of the WG. However, as described in Appendix C of this report, there is evidence that more than one crack can nucleate in the vicinity of the same structural detail, which can in turn affect the crack growth rate and the establishment of repeat inspection intervals. In addition, the FAA believes a more thorough interrogation of the field (fleet) cracking experience would be required to better understand the safety risk due to crack interaction. While past performance is helpful in understanding the safety risk, it may not fully eliminate the safety concern for potential future applications which may entail gradual evolution of historical design practices, novel aircraft architecture, etc. Furthermore, the task of assessing the risk of crack interaction based on the limited survey of available airworthiness directives, service bulletins, and Special Airworthiness Informational Bulletins is inherently challenging because we are trying to make such an assessment based on a limited number of data points. The FAA purposely abstained from voting on a rule change since it will need to weigh the WG recommendations and underlying rationale, as well as other available information, as it internally deliberates potential future revisions to the rule and regulatory guidance materials following the publication of this report.

EASA notes that this process primarily addresses FAA rule text development and both FAA and EASA texts address the same intent. However, the WG discussion demonstrates some level of subjectivity regarding interpretation. Therefore, noting the current WG position and the limited remaining timescale for this rulemaking activity, it is understood that an FAA rule change for the purposes of this exercise may not be justified (or indeed a change to EASA text). However, there would be benefit from future development of harmonized text if the demonstrated scope for difference in interpretation exists and is considered to be significant).

ANAC, as a non-voting NAA member of the WG, shared in the dissenting positions above.

3.4 Majority WG member rebuttal to dissenting positions

The majority of the WG members who supported the proposal to not change the rule have recognized the dissenting positions. In review of the dissenting positions and associated rationale the WG members supporting the proposal for no rule change retain that position based on the following points, some of which are previously stated.

Majority WG member rebuttal to British Airways dissent:

- Since the EASA rule text does explicitly require evaluation of “damage at multiple sites due to prior fatigue exposure” it is understood by the majority of WG members that this is considered to be WFD.

- Since the FAA rule text does not explicitly mention damage at multiple sites, the associated guidance in ACs 25.571-1D and 120-104 clearly identify damage at multiple sites as a subcategory of WFD. The FAA rule is sufficiently broad while the EASA text could be potentially misinterpreted as previously discussed in paragraph 2 of prior harmonization discussion in Section 3.2.

Majority WG member rebuttal to FedEx dissent:

- The current FAA rule text already requires consideration of “modes of damage” and the proposed alternative wording is just one aspect of that. “Normal damage tolerance evaluation” is not defined in the rule and this suggested text is specific to metallic structures (hence too prescriptive). The WG 2018 recommendation proposed revising the rule to be general regarding material type and to be more performance-based. It is recognized that this effort is metallic-centric, however, the majority WG position is that the details for compliance should be in the AC rather than the rule to retain the intent of the 2018 recommendations.

- With respect to the comments about reintroducing the omitted text “damage at multiple sites due to prior fatigue exposure…” to the FAA rule — the quoted text essentially describes the concept of concurrent cracking at a single site or local detail, and this concept is not defined in the regulation. All guidance and policy from the pre-Amendment 25-96 era were focused on the effects of MSD/MED and their effect on fail-safety and the long lead crack (reference AC 25.571-1B). The MSD/MED guidance has been moved to Appendix 6 of AC 120-104.

- With respect to the cited excerpt from Docket No. 27358, Notice No. 93-9, stating that there is no specific guidance on what is required for a showing of compliance, the current revision of § 25.571 does require a full-scale fatigue test evidence. In this regard the current rule text is specific and unambiguous.

4 Guidance Recommendations

4.1 Introduction to guidance recommendations and final set of recommendations

In 1978 the FAA revised part 25 to require damage-tolerance evaluations of PSEs. Damage-tolerance analysis is a complex field, which has evolved significantly since 1978. Design approval holders (DAHs) have developed damage-tolerance evaluation methodologies, including tests and analyses methods, to establish inspections or other procedures to address fatigue cracking and other modes of damage in PSEs. These methodologies included criteria that DAHs have developed to address the range of cracking scenarios that could occur over the life of an airplane. While many of the approaches contain similar elements, each DAH has their own criteria to standardize its methodology to avoid catastrophic failure throughout the operational life of an airplane balanced with analytical simplifications and efficiencies based on engineering assumptions. Because of this, the WG had lengthy discussions, deliberating on what updates to the guidance material would benefit industry and regulators, and be cost-beneficial and practical to implement.

The WG identified detailed updates to the guidance material using a methodical approach by –

(i) Identifying the current guidance on crack interaction;
(ii) Ensuring WG members had the same understanding of the current guidance on crack interaction;
(iii) Identifying current industry practices; and
(iv) Developing recommendations to update guidance where the WG deemed appropriate (i.e., general agreement was reached).

Through this approach the WG identified seven topics for which proposed recommendations to revise guidance were considered. In some cases, alternative or supplemental proposals for a given topic were considered, which resulted in a total of eleven separate recommendation proposals considered by WG. Reference Section 4.6 for detailed discussions on the six topics for proposed revisions to AC 25.571-1D considered by the WG.

The positions of WG members on the eleven considered guidance recommendation proposals were not unanimous and the level of support and opposition varied for each proposal. Section 2.2 describes how the WG would determine when they have reached agreement or consensus, and Appendix E provides the vote tallies by WG members for each proposal. The outcomes of the voting are as follows:

- For two proposals, the WG was able to reach full or general agreement on the proposed revisions to AC 25.571-1X.

- For four proposals, more than 2/3 of WG voting members opposed the proposed revision recommendations. In these cases, the WG recommends the FAA to not incorporate the identified proposals into revisions of guidance or pursue the proposal.

- For the remaining five proposals, the WG member support was more evenly mixed. Accordingly, the WG could not reach agreement to either recommend the FAA to pursue or to not pursue these proposed revisions. Therefore, these five proposals are not included as recommendations by WG in either case yet are retained in this report for documentation.

For each of the proposals, except for two proposals which received unanimous member support, rationale in support of and in opposition to the proposed changes are provided along with the proposal in Section 4.6.

The WG focus for guidance recommendations was principally applied to AC 25.571-1D, however one proposal was to recommend the FAA charter an SDO to investigate development of a new guidance document as a means of compliance (MoC) apart from AC 25.571-1X.

The WG reached full or general agreement[9] on proposing the following changes to AC 25.571-1X:

1. Revise AC 25.571-1X, Paragraph 6.d (extent of damage) to add language similar to 91-82A stating "cracking scenarios can be complex, involve multiple sites, and at some point, include crack interaction." (reference proposal 4.6.1.1 for specific proposal language)

2. Revise AC 25.571-1X, Appendix 1 (References and Definitions), Paragraph 2 to introduce a new definition as follows (reference proposal 4.6.2.1):

   "Crack interaction - The effect on crack growth rate due to the simultaneous presence of more than one crack."

[9] While all members agreed on the two recommendations to change guidance material, the position of some members was that they were not sufficient alone and voiced a preference to include certain details from the other proposals. However, they did not oppose recommending them on their own because they do introduce incremental improvement to the guidance material. Final vote tallies are provided in Appendix E.

<u>The WG reached general agreement on the following recommendations:</u>

1. AC 25.571-1X should not be revised to simply reference AC 91-86A for guidance on developing inspection programs (reference proposal 4.6.1.2).

2. AC 25.571-1X should not be revised to add illustrations or lists of example cracking scenarios where interaction effects should be considered in the DTE (reference proposal 4.6.2.2).

3. AC 25.571-1X should not be revised to include acceptable means to address crack interaction, with either general or detailed approaches included (reference proposals 4.6.5.1 and 4.6.5.2).

4. The FAA should not charter a new SDO to further investigate this subject with objective to develop an industry recommended/optional means of compliance (reference proposal 4.6.7.1).

4.2 Review of existing guidance

The WG evaluated ACs 25.571-1D, 91-82A, and 120-104 to determine if that guidance for addressing crack interaction when establishing a structural maintenance program (inspections or other procedures) is clear. As part of this evaluation, the WG reviewed the current guidance to determine if the following four questions can be answered:

- What is crack interaction?
- Why does crack interaction need to be considered?
- When does crack interaction need to be considered?
- How does crack interaction need to be considered?

The WG members identified specific references to crack interaction in the guidance and discussed how those were addressed in their approach to the DTE. Based on these sections in guidance (excerpts provided below), the WG members sought to reach a common understanding of crack interaction. The WG then identified where clarification to the current guidance may be necessary. This effort resulted in six topics where the WG considered proposed revisions AC 25.571-1D for clarification on subject of crack interaction. The merits and disadvantages of each proposed clarification were discussed, and the results are presented here. These results form the basis of the final recommendation to the FAA, which is presented in Section 4.1.

The WG members all agreed that AC 120-104 provides relatively clear guidance on why (need for) and when to account for crack interaction when performing a WFD evaluation, though WFD assessment is only a subset of DTE performed for PSEs [note 6 in AC 25.571-1D, Appendix 3]. While the guidance provided in AC 120-104 pertains to performing WFD evaluations, the WG assessed whether this information could be applied to a non-WFD evaluation of a unique design detail.

The following are collection of excerpts from ACs 25.571-1D, 91-82A, and 120-104. The excerpts shown in bold are specific statements which are understood by WG members being either directly or indirectly associated with consideration of crack interaction for developing DT-based maintenance programs, and support answering the "what, why, when or how" questions.

Since any potential effect of crack interaction may only be a condition where multiple/concurrent cracks exist, the interest was in reviewing existing guidance that discusses DTE for cases involving multiple cracks. The WG is not suggesting that every appearance of the term "multiple cracks" in ACs necessarily explicitly establishes a need for a sophisticated analytical solution to address interaction effects. A WFD evaluation, as discussed in AC 120-104, is one scenario in which the guidance is particularly clear regarding the expectation for the evaluation (i.e., crack interaction effects are expected to be strong or weak in which type of details). The WG identified and reviewed instances where the term "multiple cracks" appeared in ACs 25.571-1D and 91-82A to determine if the guidance was clear regarding how to address crack interaction. If the guidance was not clear, the WG identified it as an item to consider recommending for clarification.

What is crack interaction?

To answer what is crack interaction, the WG identified the following sections from ACs 91-82A, 25.571-1D, and 120-104. The bold lettering is added to emphasize the text identified as most closely describing what crack interaction is and helping provide potential clarifications on the subject.

> AC 25.571-1D, Paragraph 6 (Damage-Tolerance Evaluation), d (extent of damage): *Each particular design should be assessed to establish appropriate damage criteria in relation to inspectability and **damage-extension characteristics**. In any damage detection, **including those involving multiple cracks**, it is possible to establish **the extent of damage** in terms of the following parameters:*
>
> - *detectability with the inspection techniques to be used,*
> - *the associated, initially detectable crack size,*
> - ***the residual-strength capabilities of the structure**, and*
> - ***the likely damage-extension rate.***

> AC 91-82A, Paragraph 10.b. Damage-Tolerance Based Inspections: *In considering a damage-tolerance based inspection program to address the demonstrated risk (paragraph 10a(1)), an applicant should complete a damage-tolerance evaluation. A thorough damage-tolerance evaluation will identify the crack location, **scenario**, critical crack size, the detectable crack size, inspection threshold, and the inspection interval (in number of flights or flight hours time in service) during which the crack grows from the detectable crack size to the critical crack size. AC 25.571-1D and the reference listed in paragraph 6c(3) provide additional information on performing a damage-tolerance evaluation.*

(1) *Evaluation Considerations. The damage-tolerance evaluation should consider the actual sites, **cracking scenarios**, and crack progression observed in the unsafe condition. Actual cracking scenarios can be complex, involve multiple sites, and at some point, include **crack interaction**.*

(a) *When performing a damage-tolerance evaluation to predict the residual strength and crack growth life, the applicant should address the most probable **cracking scenario** and appropriate loading conditions. **If the scenario includes cracks in multiple elements, or multiple cracks in one element**, the applicant must account for that in determining where, when, how, and how often to inspect for cracks.*

AC 120-104, Appendix 6 (Widespread Fatigue Damage Evaluation), Para. 1. (Predicting When WFD is Likely to Occur), c. (Cracking Pattern) (4): *Differences between multiple site damage and multiple element damage. We expect details of the approach used to characterize events leading up to WFD to be different. The differences will depend on whether you are considering multiple site damage or multiple element damage. **This is especially true for crack interaction.***

(a) Crack Interaction. Multiple site damage has the potential for strong crack interaction, and the effect of multiple cracks on each other needs to be addressed. Multiple element damage, in most cases, does not have the same potential for strong crack interaction. The differences between interaction effects for multiple site damage and multiple element damage are illustrated in Figure 6-2.

Figure 6-2

Difference between MSD and MED Interaction Effects

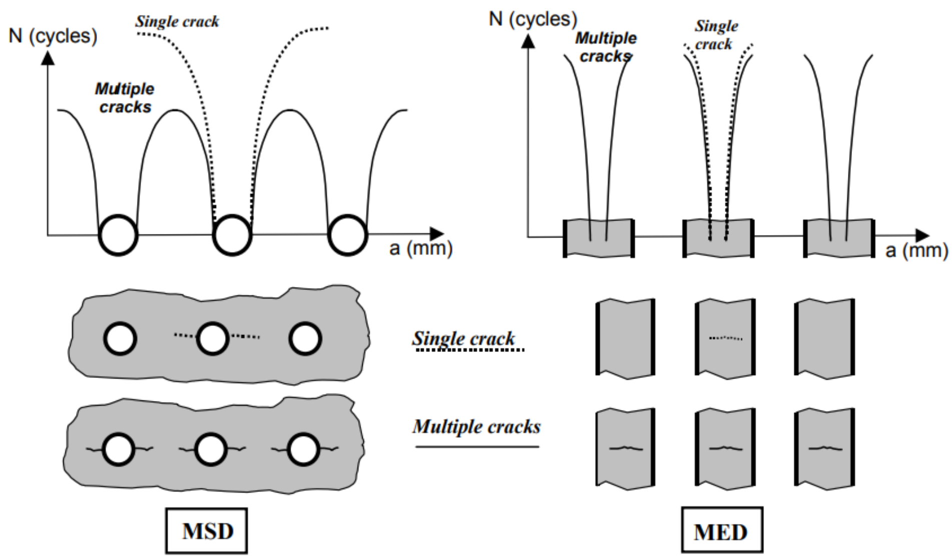


Figure 4.1: Excerpt from FAA AC 120-104, Appendix 6

(b) Multiple Site Damage and multiple element damage interaction. Some areas of an airplane are potentially susceptible to both multiple site damage and multiple element damage. Simultaneous occurrence of multiple site damage and multiple element damage is possible, even though it's not common. ***A comparison of inspection start points or modification start points might indicate the possibility of this occurring. If so, your evaluation should consider interaction between multiple site damage and multiple element damage****.*

Why does crack interaction need to be considered?

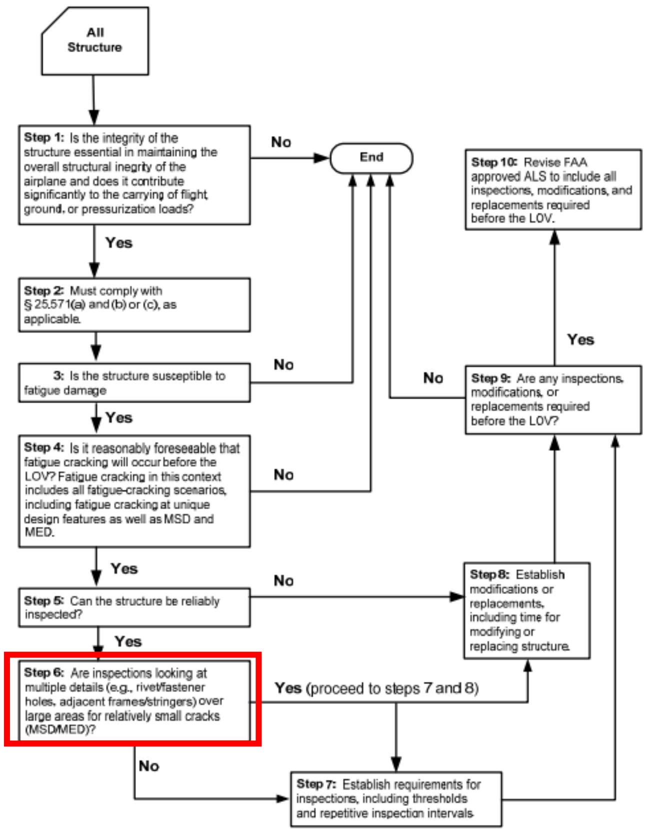
To answer why does crack interaction need to be considered, the WG identified the following sections from ACs 91-82A and 25.571-1D. The bold lettering and the box outlined in red are added to emphasize the text identified as helping provide potential clarifications on the subject.

AC 25.571-1D, Appendix 3 (Process for Compliance with 14 CFR 25.571(a), (b) and (c) for Fatigue Damage

1/13/11 AC 25.571-1D
Appendix 3

Appendix 3
Process for Compliance with 14 CFR 25.571(a), (b) and (c) for Fatigue Damage

This chart applies only to § 25.571(a), (b), and (c) for fatigue damage (FD), relative to LOV.



A3-1

Figure 4.2: Excerpt from FAA AC 25.571-1D, Appendix 3.

Step 6: This step determines whether inspections by themselves are adequate for precluding a catastrophic failure, or whether they are supplementary to modifying or replacing structure. When inspections are focused on details in small areas and have a high probability of detection, they may be used by themselves to ensure continued airworthiness, unless or until there are in-service findings. ***Based on findings, these inspections may need to be modified,*** *and it may be necessary to modify or replace structure.*

AC 91-82A, Para. 10. (Developing an FMP) b. (Damage-Tolerance Based Inspections) (b): ***The damage-tolerance evaluation should not use an easily***

> ***evaluated solution if it is not a representative scenario*** *(for example, a handbook solution for a single crack growing from a hole when the actual scenario involves multiple cracks).* ***Such an evaluation could result in an ineffective inspection program.***

<u>When does crack interaction need to be considered?</u>

To answer when does crack interaction need to be considered, the WG identified the following sections from ACs 91-82A, 25.571-1D, and 120-104. The bold lettering is added to emphasize the text identified as helping provide potential clarifications on the subject.

> AC 25.571-1D, 7.b. and AC 120-104, Chapter 1, 101. WIDESPREAD FATIGUE DAMAGE. ***Structural fatigue damage is progressive. It begins as minute cracks, and those cracks grow under the action of repeated stresses****. This can happen because of normal operational conditions and design attributes or because of isolated situations or incidents, such as material defects, poor fabrication quality, or corrosion pits, dings, or scratches.* ***Fatigue damage can occur locally, in small areas or structural design details****, or globally.*

> AC 91-82A, Para. 10.b.(1): *Evaluation Considerations. The damage-tolerance evaluation should consider the actual sites, cracking scenarios, and crack progression observed in the unsafe condition. Actual cracking scenarios can be complex, involve multiple sites,* ***and at some point, include crack interaction.***

> AC 91-82A, Appendix 4 (Methodology for Determining Repeat Inspection Intervals), Para. 2 (Multiple Load Path Structure): *Any benefits (e.g., less onerous inspection method and/or longer repeat inspection intervals) would depend on inspectability and the remaining life of the structure with the element failed. When this is done,* ***the likelihood of simultaneous cracking in multiple elements should be considered and accounted for as necessary.***

> AC 25.571-1D, Appendix 3 (Process for Compliance with 14 CFR 25.571(a),(b) and (c) for Fatigue Damage), Step 6: *When inspections are focused on details in small areas and have a high probability of detection, they may be used by themselves to ensure continued airworthiness,* ***unless or until there are in-service findings. Based on findings, these inspections may need to be modified****, and it may be necessary to modify or replace structure.*

<u>How does crack interaction need to be considered?</u>

To answer how does crack interaction need to be considered, the WG identified the following sections from ACs 91-82A and 25.571-1D. The bold lettering is added to emphasize the text identified as helping provide potential clarifications on the subject.

AC 91-82A, Para. 10.b.(5): *Inspection Repeat Interval. The inspection repeat interval is typically a fraction of the length of time for the crack to grow from the detectable crack size to the critical crack size.* **Appendix 4** *provides acceptable methods for determining the repeat inspection interval.* ***It is the applicant's option to determine how complex or simple the analysis should be. The applicant may determine that a simple analysis using conservative assumptions and scatter factors produces an acceptable inspection interval. An applicant may also use a more detailed analysis to justify a longer inspection interval.*** *The applicant should explain and justify all simplifying assumptions.*

AC 25.571-1D, 6. h. Damage-tolerance analysis and tests.

(1) ***Analysis, supported by test evidence****, should determine that:*

(b) *The* ***damage-growth rate*** *under the repeated loads expected in service – between the time the damage becomes initially detectable and the time the extent of damage reaches the value for residual-strength evaluation –* ***provides a practical basis for development of the inspection program and procedures described in section 6j of this AC****.*

….

(3) *The* ***damage-tolerance characteristics can be shown analytically by reliable or conservative methods****, such as the following:*

(a) *Demonstrating quantitative relationships with structure already verified as damage tolerant;*

(b) *Demonstrating that the damage would be detected before it reaches the value for residual-strength evaluation; or*

(c) *Demonstrating that the repeated loads and limit-load stresses do not exceed those of previously verified designs of similar configuration, materials, and inspectability.*

AC 91-82A, Appendix 4 (Methodology for Determining Repeat Inspection Intervals), Para. 2 (Multiple Load Path Structure): *When taking advantage of redundancy in a multiple load path structure there are two scenarios: when the inspection is for a completely failed load path, and when the inspection is for a cracked but not completely failed load path. In either case, the repeat inspection interval will be a function of the secondary load path remaining life (L_S) after primary load path failure.* ***It follows that the resulting interval is only valid out to the time that the cumulative fatigue damage and/or crack growth in the***

intact structure is accounted for. *This issue is illustrated in a crack growth context in Figure 4-2.*

AC 91-82A, Para. 10.b.(a)&(b): *When performing a damage-tolerance evaluation to predict the residual strength and crack growth life, the applicant should address* ***the most probable cracking scenario*** *and appropriate loading conditions. If the scenario includes* ***cracks in multiple elements, or multiple cracks in one element, the applicant must account for that in determining*** *where, when, how, and* ***how often to inspect for cracks****.*

The damage-tolerance evaluation should not use an easily evaluated solution if it is not a representative scenario (for example, a handbook solution for a single crack growing from a hole when the actual scenario involves multiple cracks). *Such an evaluation could result in an ineffective inspection program.* ***However, in many cases, it may be acceptable to evaluate a conservative, but easier to analyze, scenario than the actual scenario.*** *If an applicant uses such an approach, the applicant should explain and justify all simplifying assumptions.*

AC 25.571-1D, Appendix 3 (Process for Compliance with 14 CFR 25.571(a),(b) and (c) for Fatigue Damage), Step 6: ***When inspections are focused on details in small areas and have a high probability of detection****, they may be used by themselves to ensure continued airworthiness,* ***unless or until there are in-service findings.*** *Based on findings, these inspections may need to be modified, and it may be necessary to modify or replace structure.*

4.3 Review of prior recommended changes to FAA guidance

In 2003 the GSHWG provided a set of recommendations to the FAA for changes to AC 25.571-1C [14], which included, among many other proposed changes, new content to address development of inspection intervals, reproduced as follows. The bold lettering is added to emphasize the text identified as helping provide potential clarifications on the subject.

d. Inspection Intervals. The basis for setting inspection intervals is the period of time during which damage is detectable and the residual strength remains above required levels. The reliability of the repeat inspection program (i.e. frequency of inspections and probability of detection) should assure damage detection before the residual strength of the aircraft is compromised. Inspection intervals may be established by applying appropriate reduction factors to this period to ensure that the crack or failed load path will be found before the residual strength of the structure drops below the required level. Detectable crack sizes and shapes assumed to determine inspection intervals should be consistent with inspection method capabilities and the cracking characteristics of the structure being *evaluated.* ***If concurrent cracking in adjacent areas or surrounding structure is expected within the operational life of the airplane, then this should be accounted for in the cracking scenario assumed.*** *A discussion of how repeat inspection intervals are determined for the more common situations in aircraft structures is contained in Appendix 4.*

Appendix 4 of the 2003 GSHWG report is not included in this report because the FAA incorporated it into AC 91-82A, Appendix 4, in 2008. The FAA also adopted certain material on inspection intervals from the 2003 GSHWG report that capture the intent of that recommendation. The 2003 GSHWG report also included the recommendation for the FAA to adopt certain changes related to addressing WFD. When the FAA issued AC 91-82, they were completing the WFD rule with related changes to guidance and implementing the Aging Airplane Safety Rule (AASR). Those tasks did not include the incorporation of Appendix 4, nor the material on inspection intervals in AC 25.571-1 for various reasons. Those items are not directly related to the WFD and AASR rulemaking initiatives and the 2003 GSHWG report had many other recommendations to address. The Transport Airplane Directorate decided that they could address those items at a future date. Nonetheless, during this time, the Small Airplane Directorate had a need to publish much of the technical content from Appendix 4 and the discussion on inspection intervals as proposed by the GSHWG into AC 91-82. The Small Airplane Directorate had an immediate need to address safety concerns related to fatigue and issued the AC as a means for applicants to establish fatigue management programs to address those safety concerns. Before revising AC 25.571-1, the FAA tasked ARAC to receive input on this matter from industry. As an aside, the FAA reorganized such that policies on materials and structures are under the same organization instead of the Transport Airport Directorate or Small Airplane Directorate.

This TAMCSWG made a similar observation as GSHWG (reference Section 3.5 in 2018 report) and had agreed with the omission of a separate repeat inspection section in AC 25.571-1X at that time since, as was stated, the intent of the 2003 recommendation was effectively captured in AC 91-82A. The WG's stated concern to now adopt the 2003 GSHWG recommendation as written into AC 25.571-1X is that the result would be duplicate guidance in separate publications. In the 2018 report this WG also agreed there was no objection to adding a reference in AC 25.571-1D leading readers to 91-82A for additional information to establish inspection intervals. However, this was not pursued as a direct recommendation to the FAA in 2018 since the WG had run out of time when this topic was considered. This proposal was more recently considered by the WG in this extended tasking and is addressed in Section 4.6.6.2.

4.4 Review of EASA guidance

Recognizing an element of the tasking is to consider harmonization with EASA rulemaking, this WG also reviewed existing published guidance from EASA with an objective to identify where current EASA and FAA guidance differs on determining repeat inspection intervals. EASA AMC 25.571 Paragraph 8.(d) provides discussion on establishing inspection intervals. Additionally, EASA AMC 25.571 Paragraph 8.(d) language is similar to the proposed language presented by GSHWG in 2003 [6]. As noted in Section 4.6.6, FAA AC 25.571-1D does not include any directly comparable guidance. However, guidance presented in FAA AC 91-82A does include much of the similar guidance; though, it is recognized that AC 91-82A is not presently the prime source for establishing DT-based inspection programs for 25.571 certification activities. Nonetheless, the following table documents the identified excerpts from FAA AC 91-82A, which are understood to provide comparable guidance to EASA AMC 25.571 and the 2003 GSHWG Report. The intent of including this is to assist in understanding the degree of harmonization between EASA and FAA should the FAA consider adopting the GSHWG 2003 recommendation (which is a proposal discussed by this WG as noted in Section 4.6.6.1).

Table 4.1: Comparison of guidance text from EASA AMC 25.571 [6], recommended change to AC 25.571-1X from GSHWG [14], and FAA AC 91-82A [5]

EASA AMC 25.571, Para. 8.(d): “Inspection”	2003 GSHWG Report, d. Inspection Intervals.	Excerpts from FAA AC 91-82A
The basis for setting inspection intervals is the period of time during which damage is detectable and the residual strength remains above the required levels.	The basis for setting inspection intervals is the period of time during which damage is detectable and the residual strength remains above required levels.	10.b.(2) The critical crack size is the size of crack that degrades the strength of the structure to the minimum strength required. 10.b.(5) The inspection repeat interval is typically a fraction of the length of time for the crack to grow from the detectable crack size to the critical crack size
The reliability of the repeat inspection programme (i.e. frequency of inspections and probability of detection) should assure damage detection before the residual strength of the aircraft is compromised.	The reliability of the repeat inspection program (i.e. frequency of inspections and probability of detection) should assure damage detection before the residual strength of the aircraft is compromised.	10.b.(5) The inspection repeat interval is typically a fraction of the length of time for the crack to grow from the detectable crack size to the critical crack size. Appendix 4: The reliability of repeat inspections should assure crack detection before the residual strength degrades below the

		required level.
Inspection intervals must be established by applying appropriate reduction factors to this period to ensure that the crack or other damage or failed load path will typically be found well before the residual strength of the structure drops below the required level.	Inspection intervals may be established by applying appropriate reduction factors to this period to ensure that the crack or failed load path will be found before the residual strength of the structure drops below the required level.	10.b.(5) Appendix 4[10] provides acceptable methods for determining the repeat inspection interval. It is the applicant's option to determine how complex or simple the analysis should be. The applicant may determine that a simple analysis using conservative assumptions and scatter factors produces an acceptable inspection interval. An applicant may also use a more detailed analysis to justify a longer inspection interval. The applicant should explain and justify all simplifying assumptions. Appendix 4: The inspection method chosen will define the initial detectable crack that will be used to perform the damage-tolerance evaluation. Once the initial detectable crack is defined, crack growth and residual strength assessments must be performed to determine the time for the initial detectable crack (a_{DET}) to grow to a critical size (a_{CRIT}) that would result in failure if the required residual strength loads were applied.
Long periods of exposure to residual strength levels only just above the load limit should be avoided.	A discussion of how repeat inspection intervals are determined for the more common situations in aircraft structures is contained in Appendix 4. **Appendix 4 – Methodology for Determining Repeat Inspection Intervals** The applicant may face a number of different configurations that he will be required to evaluate and determine repeat inspection intervals. The reliability of the	8.b.(2) Cracking is a continued airworthiness concern because cracking can potentially reduce the strength of the structure. The loss of certificated ultimate load capability should be a rare event and the FAA does not knowingly allow the strength of airplanes to drop below the certificated ultimate load requirement.

[10] Appendix 4 provides prescribed inspection safety factors (opportunities for detection) for SLP or MLP designs

	repeat inspection program (i.e. frequency of inspections and probability of detection) should assure damage detection before the residual strength of the aircraft is compromised. Several of the more common situations are described below.	
This applies in particular to crack-arrest structure.	**Appendix 4 – Methodology for Determining Repeat Inspection Intervals** b. *Multiple load path structure*. (2) Evaluation by analysis. Figure 3 illustrates how inspection intervals could be established on the basis of crack growth and residual strength evaluation. The figure is for less than load path failure scenario but can also be used to discuss the case of a complete load path failure. The inspection interval is based on the life of the secondary load path(s) (L_r) subsequent to primary load path(s) failure at N_F plus the time (L_P) for a detectable crack (a_{DET}) in the primary load path(s) to grow to critical size under in-service loads. In order to do this within the context of a crack growth analysis it is necessary to assume some initial crack, of size ai, exists in the secondary load path at time zero. This initial crack size should be representative of normal manufacturing quality. Damage accumulated prior to load path failure is accounted for by calculating the amount of growth, (Δa_i), that occurs between time zero and N_F using "well" condition loading. The residual life, (L_r), then becomes the time for a crack of size	8.c.(3) Applicants who apply the fail-safe design approach to a demonstrated risk should fully understand and address the potential shortcomings discussed in the documents listed in paragraph 6. An applicant should also understand if cracks are expected to continue to develop in the fleet, which increases the likelihood that the strength of some airplanes' structure may deteriorate below design ultimate strength level, a fail-safe modification might not provide a solution to the demonstrated risk. In this case, the FAA will require the fleet-wide replacement or modification of the structure. As in the case of damage-tolerance, the schedule for completing these actions for a fail-safe design may allow a limited increase in operational life compared to the schedule for a structure with no demonstrated fail-safe characteristics.

	$ai+\Delta a_i$ to grow to critical size assuming a complete load path failure has occurred (i.e. "failed" condition loads used).	
It should be borne in mind that CS 25.305 is the principle requirement for strength of the airframe, and that CS 25.571 is primarily intended to provide an inspection programme that will ensure the timely detection and repair of damage in order to restore the aircraft to the required (CS 25.305) strength capability and preserve this capability throughout the majority of the aircraft's operational life.		8.b.(2) … service history has shown that the reliability of directed inspections is never sufficient to detect all cracks and as the number of crack reports increases, the likelihood that a number of airplanes in the fleet have undetected fatigue cracks also increases. Additionally, most damage tolerance based inspections are developed to ensure the structure always retains approximately design limit load capability. Therefore, for areas where fatigue cracks are reported, the likelihood increases with time that a number of airplanes in the fleet will have strength below the certificated ultimate load requirement. At some time during operation of the fleet, the likelihood that the strength of any given structure in a fleet is less than the certificated ultimate load requirement becomes unacceptably high and inspections must be modified (e.g., shorter intervals) or the problem must be terminated (e.g., fleet wide replacement/modification as a specified time in service).
Detectable crack sizes and shapes assumed to determine inspection intervals should be consistent with the inspection method capabilities and the cracking characteristics of the structure being evaluated. If concurrent cracking in adjacent areas or surrounding structure is expected within the operational life of the aeroplane, then this should be accounted for in the cracking scenario assumed.	Detectable crack sizes and shapes assumed to determine inspection intervals should be consistent with inspection method capabilities and the cracking characteristics of the structure being evaluated. If concurrent cracking in adjacent areas or surrounding structure is expected within the operational life of the airplane, then this should be accounted for in the cracking scenario assumed.	10.b.(3) The detectable crack size is the minimum size crack that an inspector can find reliably and repeatedly. The first prerequisite for an effective inspection program is that the detectable crack size must be smaller than the critical crack size. 10.b.(1) The damage-tolerance evaluation should consider the actual sites, cracking scenarios, and crack progression observed in the unsafe condition. Actual cracking scenarios can be complex, involve multiple sites, and at some point, include crack interaction.

Though EASA AMC 25.571 Paragraph 8.(d) content is presently covered in FAA AC 91-82A, by observation, the guidance in AC 91-82A Appendix 4 provides greater detail in establishing inspection intervals than what is provided in EASA AMC 25.571 Paragraph 8.(d). Accordingly, EASA may wish to consider adopting content shared in 91-82A for establishing inspection intervals in future updates to their AMC.

4.5 Methods to derive inspection intervals or otherwise account for crack interaction

The WG identified the following four categories of approaches that applicants have commonly used to account for crack interaction effects for local design details (including organizations represented by this WG). Three of these methods are related to establishing repeat inspections and the fourth is an operational limit/modification requirement. The WG also recognizes that other methods (not discussed here) used by industry may provide a similar level of safety, and therefore can be suitable for use in certification. Nonetheless, the four approaches identified below are those the WG considered in the course of this tasking.

If properly validated to be accurate or conservative, an applicant can effectively use one or a combination of approaches depending on the specifics of each case:

- **Default "rogue flaw" crack growth calculations using enveloping assumptions**
    - Described in AC 91-82A, Appendix 4.
    - The applicant would need to justify the assumptions and validate that they envelope test or service experience. Such validation evidence may support the assertion that the assumptions & analysis envelope potential effects of crack interaction within the airplane LOV and that complex or more detailed analysis may not be necessary.
    - Rogue flaw analyses typically include an assumed initial lead crack representing some potential relatively large undetected manufacturing defect (i.e., "rogue flaw") with array of secondary smaller cracks representing intrinsic and acceptable material and process flaws either at the same or adjacent details (i.e., "continuing damage").
    - WG members' experiences are that there has been commonality in using this approach across organizations, and that it is often employed by smaller DAH organizations (i.e., some STCHs, maintenance/repair organizations, etc.). It is considered portable between applicants, meaning different organizations may be able to use publicly available SIF solutions/tools and obtain similar results.
    - This general method is described in greater detail in the following publicly available sources:

- FAA's *Damage Tolerance Assessment Handbook, Volume II: Airframe Damage Tolerance Evaluation* (DOT/FAA/CT-93/69.II), Section 4.5 [8].
- United States Air Force (USAF) *Damage Tolerant Design Handbook: Guidelines for the Analysis and Design of Damage Tolerant Aircraft* (AFFDL-TR-79-3021), Section 2.7.16: Slow Crack Growth [16].
- *Verification of Methods for Damage Tolerance Evaluation of Aircraft Structures to FAA Requirements*, by Tom Swift, presentation to 12th International Committee on Aeronautical Fatigue, 1983 [17].

- **Complex crack growth calculations involving stress intensity models of multiple interacting cracks**
  - Similar to the methods described by AAWG in [9], Goranson's 2007 Damage Tolerance Analysis of Structures Keynote Presentation *Damage Tolerance: Facts and Fiction* [18], etc. Reference Appendix F for additional discussion on one OEM member employing this category of approach for local detail DTE which includes crack interaction considerations.
  - These require considerable development efforts to address the accurate or conservatively modeled behavior and relationship due to adjacent cracks of varying sizes and to establish initial flaw sizes.
  - These methods or detailed models may not be available to the general public via common industry-employed fracture mechanics-based tools or they may require a level of specialty not presently available at some organizations.
  - These methods and their conclusions are <u>not</u> "portable" between applicants.
- **Applying WFD-like evaluation methods to the analysis of the local detail**
  - Similar to the evaluation approach described in AC 120-104.
  - May employ simplification by assuming that all sites have identical crack array and analyze via simplified growth models. One common simplifying model is often described as a local strip model, where the interaction effects may be equal at every site using expectedly conservative assumptions about crack distributions, and therefore easier to apply in growth simulation.
- **Modify the structure before interaction effects become significant**
  - Described in AC 91-82A, Paragraph 10(c) & Figure 2 where applicant determines whether DT-based inspections are "safe or effective."
  - This may be considered as an "other procedure" as identified in 25.571(a)(3).
  - This approach is not a direct means to predict expected behavior of multiple cracks in proximity to each other. This approach is intended to mitigate the expected effect of interaction on crack growth or residual strength through an airworthiness limitation that prohibits operation of the

product beyond a period of time in which crack interaction effects are expected to occur. The limitations may include either modifying or replacing structure (similar to section 25.571(c), structural modification point, or an LOV, which is applied at airplane level).

While each approach can be properly applied to address crack interaction, there is no single source or description in the FAA guidance materials that outlines these methods or explicitly describes the process. The following summarizes the current guidance on crack interaction (reference Section 4.2 for detailed discussion on FAA guidance) -

- Crack interaction identified and discussed in AC 91-82A and tells applicants and design approval holders that you may need to consider it when developing DT-based inspections to address in-service findings.
- Crack interaction is discussed to a limited extent in AC 120-104 and is related to WFD evaluations.
- AC 25.571-1D has very limited guidance on crack interaction and it does not explicitly address repeat inspection intervals.

4.6 Items WG considered for recommendation

The WG deliberated on several different topics and/or approaches for recommendation as guidance changes (or the development of guidance changes) to the FAA. This was accomplished through the review of the current FAA guidance, prior recommendations, EASA guidance, and the identification of commonly applied approaches (not all possible approaches) as discussed in prior Sections 4.1-4.5. Six of these items are subjects where the WG considered whether updates to AC 25.571-1X would provide value to regulators and industry to ensure common understanding and expectations. These six items are briefly identified as well as the sections where these subjects are discussed in greater detail -

- Clearly state need for crack interaction consideration (reference Section 4.6.1);
- Define crack interaction (reference Section 4.6.2);
- Distinguish between WFD susceptible structure and local design features for purpose of crack interaction assessment (reference Section 4.6.3);
- Clarify the term “at some point” with respect to when crack interaction should be included in the DTE (reference Section 4.6.4);
- Identify sample approaches (example methods of compliance) for how crack interaction may be considered (reference Section 4.6.5);
- Clearly identify how to establish inspection intervals when crack interaction is a plausible scenario (reference Section 4.6.6)

A separate approach, not directly a means to clarify existing guidance, was also considered by this WG -

- Task a standards development organization (SDO) to develop technical guidance that can be referenced by regulators & industry as a potential acceptable means of compliance (reference Section 4.6.7).

Each of the areas above was considered by the WG members to determine if there is an agreed need for clarification to guidance (or value to further pursuit) and, if so, what the specific clarification should convey. In some cases, multiple or alternative proposals were considered within each subject. These areas of potential clarification and related proposals were largely drafted by a subteam of WG members and subsequently presented to the full WG. Each WG member and most NAA participants provided feedback to the items and proposals. The following sections provide the relevant discussion to the topics considered and the proposed changes related to the subject.

4.6.1 Need for crack interaction considerations

Proposal considered by WG -

4.6.1.1 Revise AC 25.571-1D, Paragraph 6.d (extent of damage) to add similar language from 91-82A stating “cracking scenarios can be complex, involve multiple sites, and at some point, include crack interaction” as shown below (in red & bold):

Current excerpt from AC 25.571-1D

d. Extent of damage. *Each particular design should be assessed to establish appropriate damage criteria in relation to inspectability and damage-extension characteristics. In any damage determination, including those involving multiple cracks, it is possible to establish the extent of damage in terms of the following parameters:*

- *detectability with the inspection techniques to be used,*
- *the associated, initially detectable crack size,*
- *the residual-strength capabilities of the structure, and*
- *the likely damage-extension rate.*

Proposed revision to AC 25.571-1X

d. Extent of damage. *Each particular design should be assessed to establish appropriate damage criteria in relation to inspectability and damage-extension characteristics.* ***Cracking scenarios can be complex, involve multiple sites, and at some point, include crack interaction.*** *In any damage* *determination, including those involving multiple cracks, it is possible to establish the extent of damage in terms of the following parameters:*

- *detectability with the inspection techniques to be used,*
- *the associated, initially detectable crack size,*
- *the residual-strength capabilities of the structure, and*
- *the likely damage-extension rate.*

<u>Proposal 4.6.1.1 discussion</u>

The reason ("why") an applicant should adjust or include additional consideration for crack interaction in their DTE should be clear in guidance material. AC 91-82A clearly states that design approval holders should consider crack interaction when developing an FMP as a result of in-service findings, which is a reactive effort to manage known cracking. However, the guidance material does not similarly note "why" applicants should consider crack interaction for proactive certification activities.

Advisory Circular 91-82A states: "<u>actual</u> cracking scenarios can be complex…." The WG is deliberate in omitting the term "actual cracking" in its recommendation. The primary intent of AC 91-82A is to address service findings, so it is appropriate to describe that scenario as "actual" cracking, or cracking that is observed in service, rather than cracking scenarios that are assumed in DTE for certification activities. The DTE performed in certification should not require assessment of the actual cracking scenario because the applicant may make conservative assumptions that result in enveloping solutions. The damage scenarios for certification are assumed and not actual. To avoid any confusion, the WG decided the recommendation to revise AC 25.571-1D does not need to include the word "actual" from the subject sentence in AC 91-82A to describe the cracking scenario. By just stating "cracking scenarios," the guidance would be more general and flexible. The resulting guidance would not imply that applicants would have to apply a specific cracking scenario in the DTE. As with any DTE, § 25.571 requires the analysis to be supported by test evidence.

<u>Vote for proposal 4.6.1.1</u>

Proposal 4.6.1.1 was supported by all WG members.

Some WG members (British Airways, Delta Air Lines, FedEx, Gulfstream, Mitsubishi, Textron and United Airlines) noted this proposal does not provide sufficient guidance on its own, and preferred proposals which provide more details. Accordingly, additional proposals discussed in Sections 4.6.2 through 4.6.6 provide additional guidance content that the WG considered supplemental to the proposed text of 4.6.1.1. Votes were collected for each of these separate proposals. Although these WG members preferred guidance updates with more details, these members also do not oppose this proposal 4.6.1.1 as a minimum recommendation.

Reference Appendix E for tabulated WG member votes.

Therefore, as stated in Section 4.1, the WG adopted proposal 4.6.1.1 as a recommendation to the FAA.

<u>Alternate proposal considered by WG -</u>

4.6.1.2 As noted in Section 4.3, the TAMCSWG stated in 2018 that the WG did not oppose to the addition of a reference or link in AC 25.571-1X to 91-82A. Accordingly, this proposal is to simply include a new reference in AC 25.571-1X to 91-82A in lieu of any duplicate text.

<u>Proposal 4.6.1.2 discussion</u>

Proposal 4.6.1.2 was based on previous discussions documented in the WG's 2018 report and served as a starting point for this extended tasking. Though not an explicit recommendation in 2018, the WG previously suggested a simple inclusion of a reference in AC 25.571-1X to AC 91-82A would be preferable to duplication of content. The WG also recognized in the 2018 report that they had not explored this proposal in any great depth. Under the extended tasking, the WG further deliberated the merits of either revising AC 25.571-1D to add a reference to AC 91-82A or to insert a similar sentence from AC 91-82A that addressed considering crack interaction in the DTE. The WG concluded it is preferable to add similar text from AC 91-82A to AC 25.571-1X to bring awareness to crack interaction as a consideration in a DTE. The WG generally did not prefer a reference to AC 91-82A as a means to bring awareness to the need for crack interaction consideration as part of a DTE because it could be simply stated as part of the "extent of damage" section in AC 25.571-1X. Adding this one sentence does not introduce extensive content duplication that creates a large concern for future revisions to either AC. British Airways also noted that other regulatory bodies (e.g., EASA) do not have corresponding guidance to the FAA's AC 91-82A, so their preference was to not simply refer to AC 91-82A for guidance.

<u>Vote for proposal 4.6.1.2</u>

Proposal 4.6.1.1 received unanimous support from WG members, while proposal 4.6.1.2 only received support by a few members (Delta Air Lines, Gulfstream, and Textron). British Airways also expressed support for 4.6.1.2, yet preferred proposal 4.6.1.1). Reference Appendix E for tabulated WG member votes.

Therefore, proposal 4.6.1.1 was recommended to the FAA.

And, although members preferred proposal 4.6.1.1 rather than 4.6.1.2, the WG did further consider the approach to create a reference in AC 25.571-1X to AC 91-82A with respect to the subject of developing recurring inspection intervals, and further discussion on that is provided in proposal 4.6.6.2.

4.6.2 Definition of crack interaction

Proposal considered by WG -

4.6.2.1 Revise AC 25.571-1X, Appendix 1 (References and Definitions), Paragraph 2 to include a new definition as follows:

"Crack interaction - The effect on crack growth rate due to the simultaneous presence of more than one crack."

Proposal 4.6.2.1 discussion

There is no definition for crack interaction in the published guidance even though the definition may be implied in the text. Therefore, the WG agrees that introducing such definition in the guidance would be beneficial to industry and regulators.

The WG deliberated on the proposed definition and variations, which elaborated on ways in which the effect of interacting cracks may be observed. This includes, but is not limited to, geometric beta factors in SIF solutions and load redistribution. However, the WG decided to not incorporate any of the variations because inclusion of various potential crack interaction effects becomes problematic and overly prescriptive for a definition. The potential crack interaction effects and the WG's understanding of crack interaction are summarized in Section 1.4. The WG agreed that the proposed definition in 4.6.2.1 is sufficiently general and that it captures all ways in which crack propagation can be influenced by presence of multiple cracks, such as those described in Section 1.4). It is the responsibility of the applicant to ensure all potential effects of interaction are properly considered in context of the requirement in 25.571(b) where probable locations and modes of damage are determined.

Vote for proposal 4.6.2.1

All WG members supported proposal 4.6.2.1. Some WG members suggested a preference that this definition be accompanied with discussion ensuring distinction between WFD and non-WFD assessments for crack interaction considerations (reference 4.6.3.1 additional discussion and WG members supporting this proposal). However, this preference had not resulted in their opposition of proceeding with this proposal being presented to the FAA as a recommendation.

Reference Appendix E for tabulated WG member votes.

As a result, the WG recommends proposal 4.6.2.1 to the FAA.

Proposal considered by WG (supplementing 4.6.2.1) -

4.6.2.2 Revise AC 25.571-1X as described in 4.6.2.1 to include additional illustrative examples of details where crack interaction would need to be considered as part of the definition. Example scenarios considered by the WG for this proposal are shown in Appendix G This proposal 4.6.2.2 is supplemental to 4.6.2.1.

Proposal 4.6.2.2 discussion

The position of four WG members was that the definition proposed in 4.6.2.1 is not sufficient on its own and that it should be supplemented by illustrative examples of structural details where crack interaction should be considered. Based on this, the four WG members created proposal 4.6.2.2 supplemental option for the WG to address.

Vote for proposal 4.6.2.2

Only British Airways, Delta Air Lines, United Airlines and FedEx supported proposal 4.6.2.2 as a supplement to proposal 4.6.2.1. The remaining voting WG members opposed this proposal. While the four members who supported 4.6.2.2 would prefer additional guidance, they agreed that the guidance material should include a definition of crack interaction and that an incremental change is better than no change. Thus, they are agreeable to the overall WG position of recommending 4.6.2.1 proposal without the supplemental 4.6.2.2 proposal option since their dissenting position is noted in this report (Appendix G).

TCCA members supported the general notion of including examples, such as this, in guidance, yet also agreed with the concern that examples may be overly prescriptive or cause confusion. TCCA supported the proposal as long as language is included that ensures examples do not comprise an exhaustive list and do not constitute all possible scenarios where crack interaction may need to be considered.

EASA members also supported proposal 4.6.2.2, though an examples list should not be considered to be all inclusive and this point should be clearly indicated in any examples supplement introductory text. Furthermore, such a supplement could be used to again highlight the differences/similarities between WFD and crack interaction considerations for design details etc., see also 4.6.3.

Reference Appendix E for tabulated voting results.

Due to the degree of opposition to this proposal, the WG recommends to the FAA to not include such illustrative examples in future revisions to AC 25.571-1X.

Rationale for supporting proposal 4.6.2.2

The WG members supporting proposal 4.6.2.2 suggested that there is precedence of including examples of structural details related to DTE in the current guidance material. They added that it is not clear that inclusion of such examples in guidance has necessarily caused appreciable challenges in certification activities. There has been reluctance by some members of TAMCSWG in similar subjects (including those addressed in 2018 recommendation report) to include lists or examples in guidance as being misinterpreted as being all-inclusive. However, the notion that if every conceivable scenario cannot be included examples appearing in guidance than no scenario should be included, leading to the risk of a shortcoming in an applicant's DTE, is not agreeable to the four members supporting this proposal.

Furthermore, due to the extent of discussion on this topic by the WG, it is apparent to the four members that there is value to the industry to illustrate scenarios in which crack interaction should be considered. As the FAA has tasked this WG to address a perceived concern of the lack of standardization and adequacy of industry's practices, the inclusion of example scenarios where crack interaction may require supplement to the "normal DTE" practices would help provide value to alleviate the FAA's concerns and to inform members of aviation industry with various levels of experience in this technical area. The inclusion of example cracking scenarios does not prescribe the way in which an applicant must address the scenario in their evaluations.

Per the FAA, regulatory guidance, whether an AC or policy, describes a method of compliance to the rule, or how the FAA intends to apply the rule going forward. Guidance is not binding on public. Applicants are able to propose other methods of compliance with the rule with the proper substantiation data. If examples were to be included in an AC, there could be a "disclaimer" preceding the examples to clearly explain their intended use (i.e., not in a prescriptive way). Offering several illustrative examples does not negate or remove the applicant's flexibility to establish their own scenarios. Having examples in guidance material does not imply the list is an exhaustive list of all possible options. There is precedence of including examples of structural details related to DTE in the current guidance material. The FAA will weigh the WG responses, as well as other available information, as it deliberates potential future revisions to the requirements or regulatory guidance materials.

Rationale for opposing proposal 4.6.2.2

The other eight WG members stated the supplemental option to the proposal is overly prescriptive and, thus, should not be recommended to the FAA for adoption into guidance. Gulfstream had noted that these examples created confusion as they appear to resemble WFD-susceptible details, which are presently addressed in AC 120-104.

4.6.3 Distinction between WFD and unique design details for crack interaction

Proposal considered by WG -

4.6.3.1 Revise FAA AC 25.571-1X by adding the following statement, with footnote (in red) after the sentence identified in proposal 4.6.1.1 (reference 4.6.1 for the current AC 25.571-1D text):

d. Extent of damage. *Each particular design should be assessed to establish appropriate damage criteria in relation to inspectability and damage-extension characteristics. Cracking scenarios can be complex, involve multiple sites, and at some point, include crack interaction. Crack interaction has a significant influence in the behavior of WFD (MSD and MED) as discussed in AC 120-104. However, crack interaction can also affect the behavior of cracking at unique design features or details[X]. In any damage determination, including those involving multiple cracks, it is possible to establish the extent of damage in terms of the following parameters:*

- *detectability with the inspection techniques to be used,*
- *the associated, initially detectable crack size,*
- *the residual-strength capabilities of the structure, and*
- *the likely damage-extension rate.*

[X] AC 25.571-1X, Appendix 3, Steps 4 and 6 are available to assist the applicant to determine if their structure being evaluated is WFD susceptible or is a local, unique design detail.

Proposal 4.6.3.1 discussion

Crack interaction has a significant influence in the behavior of WFD (MSD and MED) as discussed in AC 120-104. However, crack interaction can also affect the behavior of cracking at unique design features or details, as defined below -

- AC 25.571-1D: Fatigue damage can occur locally, in small areas or structural design details, or globally; and
- "Unique Design Features", i.e., small areas or structural design details, which are described in AC 25.571-1D, Appendix 3, Step 4 and 6. These scenarios are typically addressed by a standard damage tolerance evaluation (i.e., not a WFD evaluation).

The definition introduced in 4.6.2.1 is intended to apply to scenarios involving both local, unique design feature fatigue damage and WFD, but the current guidance does not highlight this.

EASA members encouraged the use of the term design detail point (DDP) which appears in CS 25.571, which potentially has the same definition as unique design detail as used by WG for this proposal. Detail design point (DDP) is defined in AMC 25.571 as an "area of structure that contributes to the susceptibility of the structure to fatigue cracking or degradation such that the structure cannot maintain its load carrying capability, which could lead to a catastrophic failure."

Vote for proposal 4.6.3.1

British Airways (with a proposed change – see following discussion), Delta Air Lines, FedEx, Gulfstream, Mitsubishi, Textron and United Airlines all supported this proposal to be a recommendation to the FAA. Airbus, Boeing, Bombardier, Dassault, and Embraer all opposed this proposal. The FAA supported this proposal, with a minor suggested change – see following discussion. All other NAA participants, including CAA, ANAC, TCCA and EASA, supported this proposal.

Reference Appendix E for tabulated voting results.

Since this proposal did not receive enough votes the WG did not recommend it to the FAA.

Rationale for supporting proposal 4.6.3.1

A statement to clarify that "crack interaction is not only for WFD but also for unique design features" is considered necessary to ensure the recommended guidance changes discussed in this report are applied properly to both types of structure. The added statement would make the intention discussed in Section 4.6.1 clear, that interaction is a consideration for the evaluation of both WFD and local details and highlight the different evaluation criteria for each category of structure.

It is well recognized that crack interaction effects are a key element of the WFD process and there are ample discussions of those effects in AC 120-104. WFD always involves multiple cracks. However, it is less clear that terms such as "multiple cracks" or "concurrent cracking" are also intended to be applied to the typical damage tolerance analysis of local details (i.e., “Normal DTE”) used to develop inspection intervals. Several WG members expressed concern that crack interaction may be applied only to WFD evaluations unless the guidance is clarified.

As evidenced by the initial WG discussions on this topic (reference Section 1.3), there was confusion on the description of and distinction between interaction effects for local details and those for WFD. Some WG members use terms like “multiple site damage” to describe both scenarios, while many other WG members believe that the term MSD is to be applied to WFD only. The WG clarified that this report was to be specific to the evaluation of local details, and seven WG members agreed that this clarification should also be extended to the guidance. This statement would clarify that the term “crack interaction” as used in the recommended guidance in Section 4.1 is applicable to the evaluations of both WFD-susceptible structure and local structural details -

- The evaluation of crack interaction effects for details that are susceptible to WFD must be based on full-scale fatigue test evidence and generally follow the process described in AC 120-104.
- The evaluation of crack interaction effects in local details and unique design features would follow the recommended changes to AC 25.571-1D as discussed in Section 4.1 in this report.

The FAA recommended the proposed statement should be further clarified using the definition of local fatigue damage already given in AC 25.571-1D[11]:

> *Crack interaction has a significant influence in the behavior of WFD (MSD and MED) as discussed in AC 120-104. However, crack interaction can also affect the behavior of cracking* ***locally, in small areas or*** *at unique design features or details****.***

This clarification adds additional information that already exists in the AC without changing the intention of the proposal. There were no comments opposed to this clarification and so it is considered to be accepted by the seven WG members who supported the original proposal. This suggested clarification to proposal 4.6.3.1 did not influence the opposing position of the five OEM WG members, and therefore was not included in the recommendation to the FAA from the WG.

British Airways also recommended the statement should be expanded to include an evaluation by analysis and/or testing to determine the likelihood of crack interaction in the fatigue performance of the feature/detail to arrive at a suitable inspection threshold and regime. Several WG members did not agree with this proposal primarily in that this aspect is addressed in Section 4.6.4 and that it adds a prescriptive element that is intended to be a clarification. This proposed change was not adopted.

[11] AC 25.571-1D 7.b.(1): Fatigue damage can occur locally, in small areas or structural design details, or globally.

Rationale for opposing proposal 4.6.3.1

Some WG members opposed proposal 4.6.3.1 because the proposal presented in Section 4.6.1 is generic and, as such, encompasses both WFD and small areas or details; it does not exclude unique design features or details. The applicant should determine whether crack interaction is applicable or relevant for a given type of damage tolerance evaluation. The shared view amongst the opposing WG members is that there is no need for such a clarification.

4.6.4 Clarify "at some point" with respect to crack interaction

Proposal considered by WG -

4.6.4.1 Revise FAA AC 25.571-1X by defining (or rephrasing altogether) the term "at some point" (reference 4.6.1.1) as suggested below (new text for this proposal in red) with other revision proposals 4.6.1.1 and 4.6.3.1 (reference 4.6.1 for the current AC 25.571-1D text):

d. Extent of damage. *Each particular design should be assessed to establish appropriate damage criteria in relation to inspectability and damage-extension characteristics. Cracking scenarios can be complex, involve multiple sites, and at some point, include crack interaction. Crack interaction should be considered in the DTE when the fatigue reliability[x] within the LOV/DSG has fallen to a level where multiple cracks are expected in the unique design features or details[y], which can be established by fatigue/durability analysis, or established by test or service findings, or both. Crack interaction has a significant influence in the behavior of WFD (MSD and MED) as discussed in AC 120-104. However, crack interaction can also affect the behavior of cracking at unique design features or details[y]. In any damage determination, including those involving multiple cracks, it is possible to establish the extent of damage in terms of the following parameters:*

- *detectability with the inspection techniques to be used,*
- *the associated, initially detectable crack size,*
- *the residual-strength capabilities of the structure, and*
- *the likely damage-extension rate.*

[x] As proposed by WG in the 2020 SLP report (initial revision, and revised in 2021): The ability of the structure to perform its function without failure due to fatigue throughout the operational life of the airplane.

y AC 25.571-1X, Appendix 3, Steps 4 and 6 are available to assist the applicant to determine if their structure being evaluated is WFD susceptible or is a local, unique design detail.

Proposal 4.6.4.1 discussion

As discussed in Section 4.1, the WG recommends that AC 25.571-1X be revised to include similar wording to what is currently in AC 91-82A (emphasis added):

> *"cracking scenarios can be complex, involve multiple sites, and at some point, include crack interaction."*

The point at which crack interaction could be a factor in the DTE is not explicitly defined in AC 91-82A, although the concept is discussed. Furthermore, the WG could not uniformly interpret when "at some point" is. Several members identified their individual approaches to establish this threshold and they generally follow the methods used to derive inspection intervals, as discussed in Section 4.5. "When" each WG member applies these methods is based on their interpretation of current ACs 25.571-1D, 91-82A and 120-104 discussed in Section 4.2. The existing guidance suggests the notion that "at some point" is associated with the fatigue life of the structure (i.e., not a random event such as accidental damage).

A sub-team of WG members attempted to develop proposed guidance to clarify when crack interaction effects may be significant in local details (Section 4.6.3 discusses what is meant by local details). If fatigue analysis, testing, or service findings indicate concurrent cracking is likely within the LOV / Design Service Goal (DSG), then the effects of crack interaction should be addressed. This proposal is an attempt to use the concept of "fatigue reliability" introduced as a recommendation in the WG's SLP Structures Recommendation report issued in 2020 and revised in 2021 to establish this point in time:

> *When the fatigue reliability[12] within the LOV/DSG has fallen to a level where multiple cracks are expected in the design detail, then interaction is likely and should be considered in the DTE. This can be established by fatigue/durability analysis, or established by test or service findings, or both.*

Consistent with the general presentation in WG's SLP structures report, the fatigue reliability in this context is intended to mean the residual strength requirements of § 25.571(b) is still maintained (i.e., "perform its function") in presence of concurrent cracking associated with the structure's initial normal manufacturing quality ("normal" fatigue damage) existing at the end of the operational life with an associated level of confidence. A single fatigue reliability target for all structural details is not endorsed by the WG. Please see the WG's initial 2018 and SLP reports ([1], [2], respectively) for

[12] As proposed by WG in the 2020 SLP report (initial revision): The ability of the structure to perform its function without failure due to fatigue throughout the operational life of the airplane.

additional discussions on the challenges to reaching agreement on recommending fatigue reliability target values. The applicant should establish the target reliability and confidence values for the structure based on testing, construction, accessibility for inspection, etc. Conceptually, in the case where fatigue reliability at the end of the operational life is high, the normal fatigue damage is likely to still be small relative to an assumed large lead crack (i.e., a “rogue flaw”) for the period in which the DT-based inspections are based on timely detection of the lead crack. This evaluation is typically addressed in the analysis by the applicant’s “continuing damage” assumptions and independent crack tips. In cases where normal fatigue damage may occur within the operational life (e.g., LOV), the applicant may need to consider concurrent cracking or show that their continuing damage assumptions still envelope the likely cracking scenario.

The following chart illustrates the notion for a simplified case. The green curve represents a common assumption of a lead crack growing from a rare manufacturing flaw. This assumption (green curve) is often used by applicants for establishing the inspection program of a local detail (not part of a WFD evaluation). The grey curves represent typical, expected fatigue cracking growing under expected operational loads initiated from defects associated with normal manufacturing process, which may exist, of varying sizes, in the presence of the assumed lead crack. This set of curves from normal fatigue illustrates a case where the fatigue reliability at the end of the operational life is high, and that the size of associated normal fatigue damage is relatively small compared to an assumed lead crack commonly used for DT-based inspections. Therefore, the crack interaction effects are not expected be appreciable during the operational life in this illustrated scenario.

For some details, the normal fatigue reliability, and associated residual strength curve drawn in black, may be inferior to that shown in Figure 4.3. In the context of the below figure, inferior fatigue reliability may be conceptually understood such that the growth life of the fatigue cracks (curves shown in grey) is shorter, and the curves translate to the left. The corresponding residual strength curve (in black) will also translate accordingly and may intersect the required residual strength curve (red) before reaching the operational life (blue). In such a case the normal fatigue damage may be of a size where interaction effects would need a more rigorous investigation and/or maintenance program change (see Section 4.5 for various approaches).

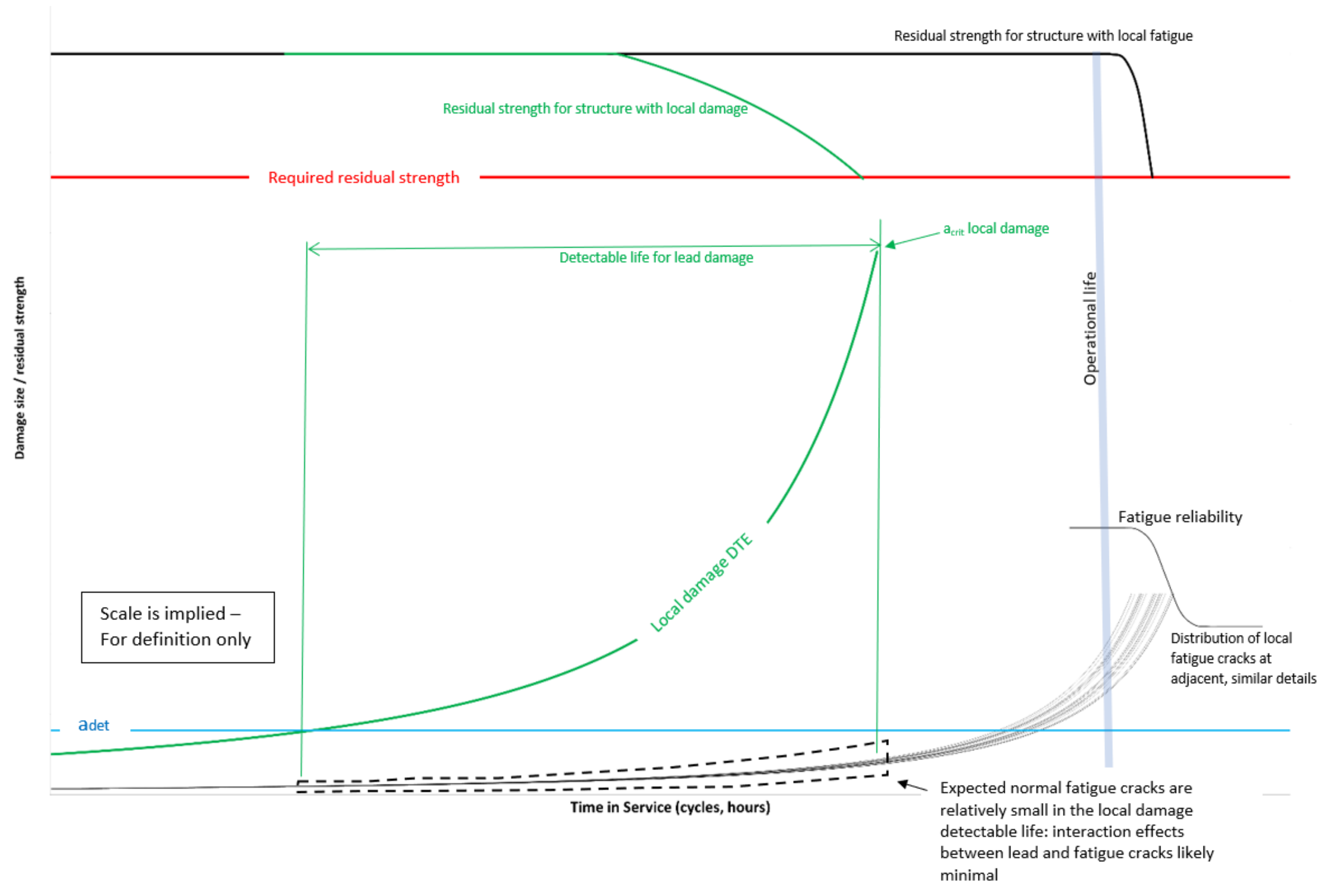


Figure 4.3: Illustration of typical crack growth curve and notional normal fatigue reliability

The proposed text contains two proposals as an attempt to further provide a recommendation on guidance. Those are "at some point," the topic of this section (4.6.4) and "unique design detail," the topic of section 4.6.3. As stated in that section, the WG could not agree on the proposal to further define what is meant by "unique design detail."

<u>Vote for proposal 4.6.4.1</u>

The WG members were evenly split on recommending this proposal to the FAA. This proposal was supported by British Airways, Delta Air Lines, FedEx, Gulfstream, Textron and United Airlines. This proposal was opposed by Airbus, Boeing, Bombardier, Dassault, Embraer, and Mitsubishi.

The FAA expressed support for this proposal, with some noted feedback (see the following supporting rationale discussion). Non-voting NAA participants from EASA, CAA, ANAC and TCCA also supported this proposal.

Reference Appendix E for tabulated voting results.

As this proposal did not receive enough support the proposal was not recommended by the WG.

Rationale for supporting proposal 4.6.4.1

The statement added in Section 4.6.1 provides a list of key considerations but does not provide evaluation criteria. While these considerations would reasonably be applied by most applicants to WFD evaluations described in AC 120-104, it is not clear that they would be properly incorporated into the DTE for local, unique design features. ACs 25.571-1D (Appendix 3, Step 6) and AC 91-82A both provide some information on how an applicant might perform this evaluation when there are service findings. Despite this fact, the guidance should clearly address scenarios where fatigue testing, such as the full-scale fatigue test required to address WFD, or analysis results, typically for design changes and STCs, indicate that multiple cracks are likely within the operational life[13] of the airplane.

Furthermore, clarifying the term "at some point" would also provide applicants a means to justify simplified crack growth methods and assumptions by performing a fatigue evaluation of the design and demonstrating that crack interaction is unlikely.

The FAA also agreed with the proposal but preferred removing the term "fatigue reliability" as defined in the single load-path report. Instead, the text would simply state the performance objective: the ability of the structure to perform its function without failure due to fatigue throughout the operational life of the airplane. This could be done by defining the point in time when crack interaction should be considered using the proposed text below:

> *The term "at some point" is defined in the context of structural damage progression within the LOV/DSG and refers to the state when multiple cracks are expected to occur or to form in the unique design detail, which can be established by fatigue/durability analysis, or by test or service findings, or a combination of these.*

[13] The current EASA AMC 25.571 text "if concurrent cracking in adjacent areas or surrounding structure is expected within the operational life of the aeroplane, then this should be accounted for in the cracking scenario assumed" is recognized as being related to this notion. As noted in Section 4.4, there is similar FAA guidance, though it is presented in AC 91-82A for FMP development, and not necessarily in 25.571-1D for certification efforts.

The FAA expressed the following concerns with the terminology “fatigue reliability” in the proposed text:

- “target reliability” can be interpreted as a conventional reliability metric used by most companies (unrelated to fatigue assessment); and
- Even if “fatigue reliability” were to be rephrased as “fatigue reliability target and confidence interval,” such a concept is not well defined (mathematically and otherwise), and so enforcement of any such metric is problematic.
- Defining such a requirement is not needed to clarify the concept of “at some point.”

In general, this alternative wording provided by the FAA results in the same objective as the proposal 4.6.4.1 wording and conveys the same intention: the DTE should address crack interaction if multiple cracks are likely within the operational life of the airplane (i.e., LOV/DSG).

The introduction of a fatigue reliability concept in AC 25.571-1X was earlier proposed by this WG in both the 2018 report for establishing inspection thresholds, and in 2021 recommendation report specific for considerations with single load path structures. One objective of introducing fatigue reliability into AC 25.571-1X in SLP report (reference Section 4.2.1 of SLP report) was to convey a hierarchy of robustness in various structural designs (e.g., SLP hidden & visible vs. fail-safe integrally stiffened panel vs. MLP hidden). The WG members supporting proposal 4.6.4.1 are agreeable to the FAA’s proposed alternative text, yet note the rationale for the WG preference for the use of the term “fatigue reliability” or “reliability” documented in the two prior reports is not changed as a result of the WG members agreement here. It is noted, however, that the term “unique design detail” is the subject of the discussion in Section 4.6.3 and incorporation of proposal 4.6.4.1 into AC 25.571-1X would need to consider those arguments. Otherwise, none of the WG members who supported proposal 4.6.4.1 indicated opposition to this revised wording proposed by the FAA.

ANAC participants expressed agreement with those in WG who had identified crack interaction as presenting a concern more in the case of inspection intervals than thresholds. ANAC participants also pointed out that there is no clarification on the guidance materials of when crack interaction should be included as part of the DTE.

<u>Rationale opposing proposal 4.6.4.1</u>

Airbus, Boeing, Bombardier, Dassault, and Embraer opposed this proposal because “at some point” is simply a reminder that crack interaction may be initially irrelevant but may become relevant as cracking progresses. The shared position amongst the opposing WG members is “at some point” is sufficient to address the meaning above, and do not think the language change is necessary.

Moreover, the definition is not satisfactory since the idea of a fatigue reliability "level where multiple cracks are expected” is vague and debatable. Each applicant should determine when crack interaction is expected and relevant, based on its unique knowledge and experience.

4.6.5 Examples of means of compliance

Proposal considered by WG -

4.6.5.1 Revise AC 25.571-1X to include a general description of current industry practice for establishing inspection intervals or other procedures and addressing crack interaction (reference the four separate items listed in Section 4.5).

Proposal 4.6.5.1 discussion

As specified in § 25.571(b), the damage tolerance evaluation must include an analysis that is supported by test evidence and (if available) service experience. The analysis may include simplifying assumptions that envelope complex behavior (with adequate justification), however, this is not explicitly stated in AC 25.571-1D. Advisory Circular 91-82A includes specific language around inspection repeat intervals that allows applicants to employ simplifying assumptions for complex cracking scenarios (again, with adequate justification).

Vote for proposal 4.6.5.1

Appendix E provides the voting tally on this item. Only four of the voting WG members supported proposal 4.6.5.1 (British Airways, Delta Air Lines, FedEx, and United Airlines). The remaining voting members opposed this proposal.

The FAA expressed support for this proposal. Non-voting NAA participants from EASA, CAA, ANAC and TCCA also supported this proposal.

Due to the degree of opposition to this proposal, the WG recommends to the FAA to not include such example methods in future revisions to AC 25.571-1X.

Rationale for supporting proposal 4.6.5.1

Based on discussions within this working group, it is clear that WG members have different viewpoints of what it means to consider crack interaction as part of a DT. Two prevailing thoughts emerged as acceptable methods of compliance approaches. One approach would involve a rigorous analytical endeavor, which requires extensive testing.

The other approach would involve the sizing of structure such that crack interaction effects are not expected or predicted within the operational life of the structure or involve implementation of a modification or replacement program before potential cracking reaches a size when interaction may lead to an ineffective inspection program (one unable to timely detect damage before becoming critical). These different viewpoints reveal that applicants may account for the effects of crack interaction in very different ways. As a result, the four operator working group members who supported proposal 4.6.5.1 recommended that the different approaches should be clearly documented for industry and regulator awareness.

Furthermore, WG members supporting this proposed recommendation believe the four broad approaches summarized in Section 4.5 are well-balanced and provide an adequate level of detail without being prescriptive in which approach an applicant should use.

This WG is expected to represent interests of all potential applicants, including smaller STCHs, other new-entry TCH applicants or other independent FAA designees. In particular, there should be awareness that there are simplifying approaches that can be utilized instead of un-conservatively ignoring the physics of crack interaction because a set of analytical solutions may not be readily available or too arduous.

This proposed recommendation does not include specifically crafted language, rather it is presented as more notional with a stated objective, with specifically crafted language to be developed by the FAA. However, it is the intention of the WG members supporting this proposal that any such content describing means to address crack interaction include a statement that these are example approaches and may not be the only acceptable ways to address the potential effects, where the overall objective of the DTE is unchanged (development of effective maintenance program relying on inspection or other procedures). Including options in guidance material does not preclude any presently employed methods to be used, provided the methods are valid and acceptable to the local regulators, which is always the case. Furthermore, these four approaches help illustrate a wide variety of acceptable means applicants may opt to use (not mandated to use), some of which are not necessarily obvious as acceptable means to “consider” the effects of interaction (such as operational limits, modification points, etc.).

There is precedence for including optional means to address specific damage threats in advisory circulars, and examples of structures which may be of a category requiring evaluation as directed by rule. AC 120-104 presently includes examples of WFD susceptible structural details (Appendix 5), and acceptable options for determination of final cracking scenarios for WFD prediction (Appendix 6, Para. 1.c.(2)). Though the subject of AC 91-82A is for the development of FMP related to in-service damage findings, Appendix 4 also includes descriptions of how applicants may develop inspection intervals and how they may simplify analysis assumptions, such as assuming MLP structures may be treated as SLP for analytical simplicity as an optional, but potentially conservative approach. The members supporting this proposed recommendation are not aware that either such optional or example material in ACs as published, such as these noted examples, have resulted in excessive burden to applicants presently performing these evaluations.

The FAA reinforced that it may be useful to include the four examples in the AC as guidance. However, the text should include a clear statement that these approaches may not be the only acceptable approaches, which is consistent with the WG members supporting this proposal rationale. EASA agreed with FAA position, and further noted the example four approaches do not need to be all inclusive or too prescriptive and could benefit a significant part of the community that the regulators need to address beyond certain TCHs.

Rationale for opposing proposal 4.6.5.1

The reasoning for opposition to this proposal is consistent with existing FAA guidance in AC 91-82A and the WG recommendations in 2018 TAMCSWG Report.

Interpreted as prescriptive

While the intent in presenting examples may not be to provide a prescriptive approach or methodology for crack interaction, there is a concern that this is how it will be interpreted by applicants or used by regulators, reducing flexibility.

AC 91-82A states "the applicant may determine that a simple analysis using conservative assumptions and scatter factors produces an acceptable inspection interval. An applicant may also use a more detailed analysis to justify a longer inspection interval" when discussing establishing inspection intervals. Further, in Appendix 4, *Methodology for Determining Repeat Inspection Intervals,* "It is the applicant's option to determine how complex or simple the analysis should be. The applicant may determine that a simple damage tolerance analysis using conservative assumptions and inspection safety factors produces an acceptable inspection interval."

The 2018 TAMCSWG report, Section 3.5, states "the proposed guidance does not define specific details of either a crack growth or fatigue method used by an applicant, but it specifically mentions the importance of validation and all of the aspects needed in the analysis." While this was specific to threshold discussion, the overarching principle applies to inspection intervals as well. The guidance should ensure the methodology chosen produces results reflective of the many variables involved as well as providing visibility on all the important variables that must be considered yet the expected effects may be bound within an enveloping solution.

Limitations of examples

Examples covering a wide range of structure and loading are often hard to define and may require an in-depth knowledge of the assumption and limitations. Without first-hand knowledge of an approach, there is a risk of examples being misused. Also, when a reader looks at the broad range of approaches that can be utilized to account for crack interaction, the idea of a complete set of examples, that include all assumption, limitation, design details, and philosophy is challenging. This is especially true of complex crack growth calculation involving stress intensity models for multiple cracks.

Additionally, most WG OEM members use a combination of in-house as well as commercially available tools. Those in-house tools are likely unavailable to all applicants.

Confusion created by examples

While examples have been used in guidance in the past, there is evidence that these examples have not resulted in a better understanding. For example, paragraph 4.b of AC 25.571-1 introduced a list of examples for PSE. This list was modified in AC 25.571-1A, and again in AC 25.571-1C. While this list remained unchanged in AC 25.571-1D, the term Fatigue Critical Structure (FCS) was introduced, and as stated in Appendix 5 of the same AC, "The lack of standardization of the usage and understanding of the term 'PSE,' and the resultant diversity that exists between type-design PSE lists, have required the FAA to introduce a new term, 'fatigue-critical structure,' in the *Aging Airplane Safety—Damage Tolerance Data for Repairs and Alterations* found in 14 CFR part 26, subpart E, and corresponding advisory material." While this is not necessarily an endorsement of omitting examples, it does provide some justification that the use of example may not provide additional clarity or direction.

In summary, the opposition to include the proposal of 4.6.5.1 is as follows -

- Excluding examples and methodology while including high-level performance goals in guidance reflects the intent of the recommendations from the 2018 TAMCSWG report. Furthermore, the current AC does not provide detail examples for performing crack growth analysis.
- A comprehensive list of examples that captures all the nuance, assumptions, and variation is challenging. The result could be applying a methodology that is not fully understood.
- The inclusion of examples that illustrate details of detailed design standard have resulted in confusion in the past.

Proposal considered by WG (alternative to proposal 4.6.5.1) -

4.6.5.2 Revise AC 25.571-1X, Paragraph 6 or a potential new appendix to include a more comprehensive and detailed list of potential design, analysis and/or operational limits (i.e., other procedures) which an applicant may apply as means to account for effects of crack interaction for a local (i.e., non-WFD susceptible structure) DTE when the fatigue reliability is such that cracks adjacent to the lead assumed crack are expected. Reference Appendix H for list of analysis assumptions.

Proposal 4.6.5.2 discussion

The principal difference between proposals 4.6.5.1 and 4.6.5.2 is the extent of detail contained in each. Proposal 4.6.5.1 is general and includes the items identified in Section 4.5. Proposal 4.6.5.2 expands on the information in proposal 4.6.5.1 by including details on a means of compliance example (reference Appendix H).

The content presented in Appendix H was part of an early attempt by some WG members to identify various analysis assumptions that may be employed as a part of a DTE as a method to consider the effect of crack interaction. The material in Appendix H was an answer to the FAA how crack interaction may be considered when applicants are developing an inspection program, or what are some mitigating assumptions that alleviate the need for a complex evaluation.

This list was shared and deliberated amongst the WG. The items in this list were subsequently captured and simplified into the generalized four categories identified in Section 4.5. Since proposed recommendation 4.6.5.1 captures these four broad categories, the proposal 4.6.5.2 was subsequently dismissed as unnecessary as the same members who expressed support for 4.6.5.2 also supported 4.6.5.1. The members supporting the earlier attempt to address methods preferred the simplicity of the proposal 4.6.5.1. The items in Appendix H are more prescriptive than the four general approaches in 4.5, and it is recognized that one objective of the WG is to promote performance-based guidance over prescriptive when appropriate. Furthermore, no member who opposed proposal 4.6.5.1 also supported proposal 4.6.5.2. That is, those who opposed the less detailed approach also did not prefer the more detailed approach for the same reasons.

Vote for proposal 4.6.5.2

The WG member votes for proposal 4.6.5.2 were identical to proposal 4.6.5.1. Appendix E provides the voting tally on proposal 4.6.5.1.

Only the four operator representative members in the WG supported either 4.6.5.1 or 4.6.5.2 proposals. All OEM representative members opposed both 4.6.5.1 and 4.6.5.2 proposals.

Rationale for supporting and opposing proposal 4.6.5.2

The arguments in support of and in opposition to proposals 4.6.5.1 and 4.6.5.2 are essentially the same. That is, those who supported the idea of including acceptable methods of how to consider crack interaction were less concerned with the extent of detail captured. Conversely, those who opposed the inclusion of acceptable methods into guidance were not concerned with any extent of detail of how to consider interaction effects, but rather prefer simply raising awareness of the need to consider interaction without further elaboration.

4.6.6 Add inspection interval guidance in AC 25.571-1X

Proposal considered by WG -

4.6.6.1 Revise AC 25.571-1X to add a new sub-section under Paragraph 6 (*Damage-Tolerance Evaluation*) to address inspection intervals which captures the following elements:

- Recommended revision proposed by GSHWG: paragraph d. on page 36 of 2003 report.
- Include considerations for various new and conventional technologies with respect to meeting the overall probability of detection objectives of establishing repeat intervals (see following discussion). The development of such content is beyond the scope of tasking for this WG.
- Incorporate the intent of the changes from proposed recommendations 4.6.1.1, 4.6.3.1, 4.6.4.1, 4.6.5.1/4.6.5.2 into this new section. Incorporation of these noted proposals would then supersede the other proposed revisions to paragraphs 6.d or 6.h. These noted proposals are expected to be more meaningful for assisting applicants in establishing inspection intervals than in a general discussion for DTE.

Proposal 4.6.6.1 discussion

As previously discussed in Sections 1.4 and 4.6.4, the WG recognized the effect of crack interaction in establishing inspection programs is largely during the period later in an airplanes life as fatigue cracking is a progressive threat and interaction effects are related to relative crack sizes. The point at which interaction is expected to be more significant is when the structure is in its recurring inspection period (e.g., point at which potential cracks would be reliably detectable) in contrast to the early life of the structure when the cracks are relatively small, and not yet progressed to a reliably detectable size. Accordingly, the WG considered recent history of guidance recommendations related to inspection intervals and whether potential crack interaction guidance should be linked to or captured within guidance material under the subject of establishing inspection intervals.

As discussed in Section 4.3 the content of the 2003 GSHWG recommendation for inspection intervals was largely adopted into new AC 91-82A, but as frequently noted in this report this AC is specific to the subject of in-service issues and FMP. There is presently no direct link from 25.571-1D to 91-82A, so that the guidance content in 91-82A on inspection intervals is not considered directly applicable to 25.571-related certification activities. Note, the WG recommended in the 2018 report to update 25.571-1D by adding reference to AC 91-82A to address both fatigue test cracking and in-service findings. The WG had also already reviewed this question of inspection intervals in 25.571-1X in 2018 and suggested that a simple reference to 91-82A was acceptable.

Vote for proposal 4.6.6.1

Appendix E provides the voting tally on this item.

The WG did not reach agreement that AC 25.571-1D should be updated to address inspection intervals. Four of the WG members (British Airways, Delta Air Lines, FedEx and United Airlines) supported proposal 4.6.6.1; the remaining members opposed the proposal.

The FAA supported proposal 4.6.6.1. The other non-voting NAA members, CAA, ANAC, TCCA and EASA, also supported proposal 4.6.6.1.

Based on the voting member responses the WG is not recommending this proposal to the FAA.

Rationale supporting proposal 4.6.6.1

Supplementing the first five proposals (4.6.1 through 4.6.5), a discussion of inspection intervals in AC 25.571-1X and a reference to AC 91-82A would sufficiently provide an applicant with the information necessary to consider multiple cracking in a damage tolerance evaluation. This recommendation also provides a better context on guidance related to inspection intervals and greater crack interaction awareness than would any references to an AC (91-82A) that may be overlooked by applicants because the AC includes “for In-Service Issues” in the title. These changes make it clear that the effects of interaction need to be considered if multiple cracks are likely as a result of analysis, test or service experience.

Delta Air Lines recognizes the general benefit of further guidance on establishing inspection intervals, but also believes that this recommendation is beyond the tasking of the group. If the approach is simply to refer to 91-82A, then there can be clarification that these approaches are acceptable even if applied to certification activities (not just reactive to service findings).

FedEx supported this proposal despite the AC duplication because some future proof generalized duplication (that is the physics of the problem is not expected to change) in ACs is acceptable if it increases awareness of crack interaction.

Some WG members supported this proposal because it provides some harmonization with EASA guidance (reference Appendix E and Section 4.4). However, several WG members that supported this proposal also noted that harmonization should be addressed on a larger scale and that this harmonization should be focused on how guidance in FAA AC 91-82A does or does not harmonize with other NAA guidance which is beyond the subject of crack interaction or inspection intervals.

Additionally, WG members who supported this proposal recognize there are other elements that should be considered by the FAA if they introduce a new section in AC 25.571-1X dedicated to recurring inspection intervals. The objective of the inspection interval section is to ensure there is sufficiently high probability of detecting damage prior to the reduction of the structure's residual strength below required levels. It was acknowledged that various technological advancements, such as passive structural health monitoring, may introduce new concerns (e.g., damage detection objectives are not diminished relative to conventional inspection techniques). This broad topic of various influencing factors that may affect inspection intervals is beyond the tasking of this WG focused specifically on crack interaction. Thus, in recognition of this, proposal 4.6.6.1 includes an itemized point for the FAA to consider emerging inspection technologies and the impact on probability of detection in any new section on inspection intervals in AC 25.571-1X if this proposal were to be pursued.

EASA members expressed support for this proposal from a harmonization "tidying up" perspective. Proposal 4.6.6.1 is preferred for the main purpose of this exercise, but distinction between intents for certification and in-service experience needs to made clear with respect to the use of AC 91-82A. EASA agrees that a broader harmonization exercise might be appropriate.

Rationale opposing proposal 4.6.6.1

Airbus, Boeing, Bombardier, Dassault and Embraer opposed this proposal because the development of repeat inspection intervals is a generic damage tolerance issue and is not specifically about crack interaction. For this reason, it is considered beyond the scope of the extended WG task. Additional concerns are that the recommendations from either GSHWG 2003 or AC 91-82A on the determination of repeat inspection intervals do not fully address crack interaction issues and AC 25.571-1D Appendix 3 already suggests that an inspection program needs repeat inspection intervals, which does not imply that additional guidance is needed. There is no need for a new section in AC 25.571-1D, or a new sub-section in its Paragraph 6, or a reference to AC 92-81A in Appendix 3 of AC 25.571-1D.

Some WG members have suggested there is merit to proposed recommendation 4.6.6.1 in particular, due to the benefit of harmonization in text between FAA AC 25.571-1X and EASA AMC 25.571 (reference Section 4.4 for comparison between text in EASA AMC 25.571 Paragraph 6 and the proposed text in GSHWG 2003 recommendation). However, since the guidance from FAA and from EASA are not in conflict, the lack of guidance harmonization is not an issue and does not represent any burden for a dual certification process. Moreover, both EASA and FAA publish a list of Significant Standards Differences (SSD) between a pair of U.S. Code of Federal Regulations (14

CFR) part 25 and EASA CS 25. The only mention in any SSD of 25.571 is paragraph (e) with reference to AC 25.571-1D/ Policy PSANM100-1993- 00041/AC20-128 for uncontained rotor and fan damage to structure. Establishment of inspection intervals has not been identified as such. Taking all the above into account, there is no observed benefit in recommending or promoting a harmonization effort for guidance on inspection intervals as part of damage tolerance related publications.

Proposal considered by WG (alternative to 4.6.6.1)

4.6.6.2 Revise AC 25.571-1X to add some details of this history to the Background section of AC 25.571-1X.

The connection to AC 91-82A should be further reinforced by adding a reference (red text) in Appendix 3, Step 6, of AC 25.571-1X:

When inspections are focused on details in small areas and have a high probability of detection, they may be used by themselves to ensure continued airworthiness, unless or until there are in-service findings. Based on findings, these inspections may need to be modified, and it may be necessary to modify or replace structure. ***See AC 91-82A as a means to make this determination***[15]*.*

Proposal 4.6.6.2 discussion

The FAA incorporated the 2003 GSHWG recommendation on repeat intervals in AC 91-82A. This proposal 4.6.6.2 is intended to align with the prior action by the FAA. So, in lieu of creating a new section in AC 25.571-1X to address inspection intervals, a simple update to AC 25.571-1X to add a reference to the current guidance in AC 91-82A that already achieved the objective of 2003 GSHWG is all that is needed.

Vote for proposal 4.6.6.2

Appendix E provides the voting tally on this item.

The WG did not reach agreement that AC 25.571-1D should be updated to address inspection intervals. This proposal 4.6.6.2 received more support by WG members than 4.6.6.1. Seven members supported proposal 4.6.6.2 (British Airways, Delta Air Lines, FedEx, Gulfstream, Mitsubishi, Textron, and United Airlines). The remaining voting members objected this proposal.

[15] This recommendation was also proposed in the 2018 TAMCSWG report, Section 3.12.

The FAA also supported this proposal 4.6.6.2. NAA non-voting member CAA supported this proposal. NAA non-voting members ANAC and TCAA opposed this proposal. EASA supported this proposal, with the same rationale provided for proposal 4.6.6.1.

Rationale supporting proposal 4.6.6.2

This proposal would raise awareness by providing information on the GSHWG recommendation and the associated method to derive repeat intervals in AC 91-82A, and provides consistency with prior position stated by the TAMCSWG. The WG previously discussed repeat inspection intervals and a summary of those conclusions is provided in the 2018 report, Section 3.5. The WG supported adding a reference to AC 91-82A in 25.571-1X with some added context to make the content of 91-82A more generally applicable to TC projects for transport category airplanes. The WG did not recommend any further changes to address repeat intervals at that time.

The conditions outlined in the 2018 report still apply and are not significantly affected by the discussions on crack interaction covered in this report. The most expedient means to ensure crack interaction is included in the DTE for local design details is through the incorporation of the changes proposed in this report (4.6.1 through 4.6.4) and adding a discussion and reference to AC 91-82A. This change requires no new information to be developed.

The added discussion and references to AC 25.571-1X would provide an applicant with the information necessary to include consideration of multiple cracks in the DTE. These changes would make it clear that crack interaction effects should be considered in the derivation of the intervals if multiple cracking is likely within the service life as determined by analysis, test or service experience.

As discussed in Sections 3.3 and 4.4, the current FAA and EASA damage tolerance rules and guidance are not harmonized. Typically, the differences are resolved by Methods of Compliance Issue Papers (IP) or Certification Review Items (CRI) for significant design projects. Due to the complexity of damage tolerance certification and the desire by NAAs to understand the compliance approach, this practice is expected to continue. AC 91-82A provides guidance on developing inspection intervals that is comparable to the content provided in EASA AMC and a comparison table is provided in Section 4.4. This table provides information that could be used by an applicant to draft an acceptable compliance approach in an IP/CRI. Adding a discussion and reference in AC 25.571-1X would provide sufficient awareness of the information concerning repeat intervals in 91-82A to facilitate that effort.

Rationale opposing proposal 4.6.6.2

Airbus, Boeing, Bombardier, Dassault, and Embraer opposed this proposal 4.6.6.2 for the same reasons presented in opposition to proposal 4.6.6.1.

4.6.7 Delegating additional guidance development to Standards Development Organization (SDO)

Recommendation proposal considered by WG

4.6.7.1 A third-party SDO may be engaged to determine optional means of compliance for applicants to address effects of crack interaction using, but not limited to, the recommendations to AC 25.571-1X contained herein.

Discussion of proposal 4.6.7.1

FAA representative participants of this WG presented a potential transition by the FAA to adopt less prescriptive guidance in ACs and to instead enable industry organizations to derive detailed, prescriptive optional means of compliance. If such transition is executed by the FAA then much of the proposals considered by this WG (particularly those not reaching the general agreement level to be a final recommendation) may not meet the standard of more general guidance in ACs and these details may be reserved for industry organizations-managed standards.

Such an SDO would likely comprise a larger representation than this WG, including representatives from manufacturers, operators, maintenance/repair organizations, STC holders, consultant DERs, and academia. And, if this proposed recommendation is pursued by FAA, then any supplemental tasking should be clearly defined by FAA. Because WG members did not widely support this proposed recommendation effort, they did not draft specific tasking language. The WG recognizes that for an SDO to be successful, clear focused tasking is essential.

Vote for proposal 4.6.7.1

Only a minority (British Airways, Delta Air Lines, FedEx and Textron) of the WG members supported this notional proposal, recognizing additional work would be required to better define the tasking as noted. The remainder of the WG (eight remaining voting members) opposed this proposal. Reference Appendix E for tabulated vote results. Because the majority of the WG opposed this proposal, both as a notional proposal or in consideration of a potential detailed charter, the WG opted not to invest time in crafting a charter for WG to consider.

Based on the degree of opposition to this proposal by the WG members the WG recommends the FAA not pursue this proposal (reference 4.1).

Rationale supporting proposal 4.6.7.1

If the noted transition to less prescriptive guidance material is truly adopted by the FAA then reliance on SDO for additional specific guidance to complex certification activities would be standard and this subject may be well-suited for management by a highly technical organization with diverse representatives beyond those included in the present WG, including, but not limited to academia, STCHs, etc.

EASA noted the SDO approach will become an increasingly relevant possibility as the regulators move further towards performance-based regulations. Furthermore, although EASA agrees with some of the following comments in opposition to this proposal that no one approach may be valid for all applicants or scenarios, an SDO development could be beneficial by providing increased awareness/discussion/documentation of issues impacting the subject across the broader industry. However, as mentioned, the tasking will need to be clearly defined.

Rationale for opposition of proposal 4.6.7.1

The charter for any SDO would need to include an investigation of the four (at a minimum) approaches WG members identified as being used to address multiple cracks in their derivation of repeat intervals. Most of the WG discussions on SDO activity appear to be related to only the “complex crack growth” approach and how to simplify it. This proposal does not provide a detailed charter.

The WG identified potential areas where clarification in existing guidance material may have value and have made recommendations herein that are expected to ensure improvement in awareness and to achieve a common understanding amongst industry and regulators. Based on the discussions held by this WG, it is not clear that an SDO would achieve much more significant progress to reaching acceptable “one-size fits all” prescriptive methods due to the variety of analysis and maintenance program development methodologies employed by various applicants. Furthermore, the development of prescriptive approaches is not considered necessary or beneficial.

5 Cost & Benefit Analysis

This section addresses the third element of the ARAC Tasking detailed in Section 2 for crack interaction. It focuses on Task 3 of the ARAC Tasking and summarizes the estimated costs and benefits of the proposed changes. As the WG was unable to identify any specific benefit to improving safety through any change to the existing rule text, there is no expected mandatory actions to require new costs to industry. The recommended changes would provide clarifications in the guidance material by identifying crack interaction as a mode of damage to consider in a DTE.

Because advisory circulars are not mandatory, applicants may propose alternative methods of compliance with the regulation. Furthermore, the WG's recommended changes to guidance are minimal and are for clarification purposes. Therefore, there are not expected to be new or appreciable costs to applicants resulting from implementation of the WG's recommendations in this report.

6 References

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Appendix A TAMCSWG Tasking

This appendix provides an excerpt of the specific tasking taken from the January 26, 2015 Federal Register identifying the 3 main elements:

Element #1 - Evaluate current § 25.571, subparts C and E of part 26, and guidance material

1. Evaluate § 25.571, subparts C and E of part 26, and associated regulatory guidance material (*e.g.,* advisory circulars and policy statements) to determine whether any changes to the airworthiness standards and/or guidance material are required to address transport airplanes being constructed of metallic, composite, and hybrid structures. The working group is also tasked to evaluate whether any changes to part 25 and the associated regulatory guidance material are required to provide consistency with the damage-tolerance and fatigue airworthiness standards and associated guidance material for parts 23, 27, and 29. The working group is requested to include in its evaluation a review of the following advisory circulars (AC) and policy statements (PS):

   a. Advisory Circulars: AC 25.571–1, Damage Tolerance and Fatigue Evaluation of Structure; AC 20–107, Composite Airframe Structure; AC 120– 93, Damage Tolerance Inspections for Repairs and Alterations; AC 120–104, Establishing and Implementing Limit of Validity to Prevent Widespread Fatigue Damage; AC 27–1, Certification of Normal Category Rotorcraft (specifically, Subpart C—Strength Requirements); and AC 29–2, Certification of Transport Category Rotorcraft (specifically, Subpart C— Strength Requirements).
   b. Policy Statements: PS–ANM100–1989–00048, Policy Regarding Impact of Modifications and Repairs on the Damage Tolerance Characteristics of Transport Category Airplanes; PS– ACE100–2001–006, Static Strength Substantiation of Composite Airplane Structure; PS–AIR–100–120–07, Guidance for Component Contractor Generated Composite Design Values for Composite Structure; PS–ACE100– 2002–006, Material Qualification and Equivalency for Polymer Matrix Composite Material Systems; PS–ANM– 100–1991–00049, Policy Regarding Material Strength Properties and Design Values, § 25.613; PS–ANM100–1993, Compliance with § 25.571(e) Discrete Source Damage (Uncontained Engine Failure).

Element #2 - Recommend Rule or Guidance changes

2. Advise and make written recommendations on whether to change 14 CFR part 25, subparts C and E of 14 CFR part 26, and related regulatory guidance material, such as ACs 25.571– 1, 20–107, 120–93, and 120–104, to address the use of metallic, composite, and hybrid structures in transport airplanes. In developing the recommendations, the working group is requested to consider:

   a. The threats associated with fatigue, environmental exposure, and accidental damage that must be addressed per § 25.571.
   b. Applicability to emerging technology materials.
   c. The recommendations contained in the 2003 General Structures Harmonization Working Group (GSHWG) report entitled, ''Damage Tolerance and Fatigue Evaluation of Structures, FAR/JAR § 25.571.'' You can find the GSHWG report at *http://* [*www.faa.gov/regulations_policies/*](http://www.faa.gov/regulations_policies/) *index.cfm/document/information/*

documentID/384. The working group recommendations should include whether it is appropriate to:

i. Require applicants to assume the structure contains an initial flaw of the maximum probable size that could exist as a result of manufacturing or service- induced damage.
ii. Add a requirement for showing structural capability in the presence of damage, so that even if the structure fails partially, there will still be enough structure remaining to be safe.

d. The continued operational safety of composite and hybrid structures as they age, including any airworthiness limitations in the structural maintenance program.
e. The testing of hybrid structure, including, but not limited to, addressing thermal effects, test duration, load enhancement factors, and crack-growth retardation.
f. The bonding or bolting of repairs to metallic, composite, and hybrid structures.
g. The certification of large structural modifications on transport airplanes constructed of composite or hybrid structures.
h. The EASA rulemaking activity on aging aircraft for harmonization purposes.

3. Provide recommendations on appropriate performance-based requirements to address the results of the evaluations above, with consideration of applicability not only to metals and known composites, but also other emerging technology materials.
4. Provide recommendations on any new guidance or changes to existing guidance, including AC 25.571–1D, and AC 20–107B to address the results of the evaluations above.

Element #3 - Estimate the Cost and Benefit associated

5. Provide initial qualitative and quantitative costs and benefits. Based on the recommendations, perform the following:

a. Estimate the costs to implement the recommendations;
b. Estimate the benefits of the recommendations in terms of potential fatalities averted;
c. Estimate any other benefits (*e.g.,* reduced administrative burden) that would result from implementation of the recommendations.

Appendix B WG response to specific questions posed by FAA regarding crack interaction

During the period of this task extension the FAA identified specific questions to the WG to assist the FAA in their understanding of current industry practices. The request made by the FAA to the WG was to ensure that these questions, at minimum, are addressed. This appendix documents the FAA's posed questions, and the WG responses. To an extent, these questions are addressed within the main body of the report. In other cases, the WG detailed responses are provided directly in this appendix. The FAA recognized the WG responses to these questions, and comments from FAA are documented here.

1. FAA – EASA harmonization considerations

a) Amdt. 25-45/54/72/86: The previous wording of the rule and AC is as follows: Damage at multi-sites due to prior fatigue exposure must be included where the design is such that this type of damage can be expected to occur.

   - This text was omitted at Amendment 25-96 and later. EASA's regulation still includes this text. *The requirements are not harmonized* as stated by some WG members.
   - Do we need to reconsider dissenting position, and does the WG need to provide a better response why not being harmonized is okay?

WG response:

The WG addressed this question from multiple perspectives as described in Sections 3, 4.4 and 4.6.6.2 of this report.

- Section 3 of the report identifies relevant differences between § 25.571 (amendment 25-132) and EASA CS 25.571 (amendment 27) about concurrent cracking. The WG considered these differences and was in general agreement that the language in CFR is preferrable (with some additional revision to guidance) as discussed in Section 3. Dissenting positions are also included in that section of the report. While the rule texts between the EASA and FAA are different, the intent of each rule is the same. Compliance to each has not required applicants to provide different compliance data to each regulator.

- Section 4.4 of the report details the difference in guidance text between the current EASA AMC 25.571, AC 91-82A and the recommended text from GSHWG on establishing inspection intervals.

- As discussed in both Sections 4.4 and 4.6.6.2 the WG concluded that though there is not direct alignment of text between AC 25.571-1D and EASA AMC 25.571, there is significant commonality in guidance text between EASA AMC 25.571 and AC 91-82A. The WG concluded that a path exists for applicants to address any perceived non-harmonization, which is described in Section 4.6.6.2.

FAA response:

The FAA understands the range of considerations expressed by the members of the WG. However, the FAA historically has strived to harmonize key regulatory requirements with EASA and other regulatory agencies. The FAA will weigh the WG responses, as well as other available information, as it deliberates potential future revisions to the requirements or regulatory guidance materials.

2. Clarification of the concept of crack interaction

a) Define what crack interaction is. Does it include load redistribution or interaction at the local level or both?

WG response:

The WG proposal 4.6.2.1 introduces the following new definition to crack interaction that is relatively generic. Reference that section for additional discussion into the development of this definition.

“**Crack interaction** - The effect on crack growth rate due to the simultaneous presence of more than one crack”.

This generic, performance-based definition is intentional such that it is the WG position that either load redistribution or local crack interaction (i.e., adjacent and aligned crack tips in same element) would be considered an example of an interaction effect of one crack on another. The effect of increased crack rate may be result of: (1) adjacent cracking in the same member at same or nearby details (effects at local level) and/or (2) in adjacent members at same or adjacent details (load redistribution from one member to another). Reference Section 1.4 for additional discussion.

b) Clarification questions on the scope of the activity: (1) What is the effect of a long crack on accelerating the “initiation” of a secondary crack? And (2) What is the effect of a long crack on accelerating the “propagation” of a secondary crack?

WG response:

Section 1.4 and Appendix D provides discussion and material presented to WG members to motivate discussion about the effects of crack interaction on two scenarios:

- interaction of a long crack on accelerating the initiation of a secondary crack, and
- interaction of a long crack on accelerating the propagation of a secondary crack.

While the WG members recognized the results of these physical models, the WG members had not agreed that either of these approaches to demonstrate relative effects are necessary or applicable to every applicant's DTE methodology. Establishing these specific approaches in guidance would be overly prescriptive as addressed by WG in Section 4.6.5. Section 4.5 provides various approaches applicants have used which may include accounting of crack interaction effects.

For some applicants, these interaction effects have typically been addressed as "continuing damage," for example based on the definitions in the USAF requirements [16], or as discussed in Section 4.6.3.2.2 of the FAA DT Handbook [8] and in 4.6.4.1 of this report. Though the USAF may embody the results of a DTE in a different manner (e.g., for structural sizing) than what Part 25 applicants may (e.g., for inspection programs), the physics of the problem is uniform between the product types. Simplified assumptions, such as cracks growing independently, have been applied in conjunction with conservative estimates, such as initial flaw size. Different versions of these scenarios have been adapted by applicants based on their individual test and service experience (reference Section 4.5). The size and distribution of secondary cracks is dependent on many parameters and is related to the overall fatigue reliability (as defined and discussed in Section 4.6.4 of this report) of the design.

All of these scenarios described in the questions above can be relevant. However, each applicant should show how their continuing damage assumptions represent or envelope the likely possible scenarios and fatigue performance of their design.

Section 1.4 is intended to provide the reader with better understanding of the WG members perspective of potential effects of interacting cracks all included in the generic proposed definition. As described in Section 4.6.2, introducing a definition of crack interaction with additional specificity beyond what the WG recommended text is challenging to address all possible effects and accordingly, the definition then becomes overly prescriptive.

FAA response:

The FAA understands the range of considerations expressed by the members of the WG. However, as described in Appendix C of this report, there is evidence that more than one crack can nucleate in the vicinity of the same structural detail, which can in turn affect the crack growth rate and the establishment of repeat inspection intervals. The FAA will weigh the WG responses, as well as other available information, as it deliberates potential future revisions to regulatory guidance materials.

3. Potential elements of the report's technical summary

a) What are the engineering criteria that a company should consider in order to define if an applicant needs to account for crack interaction in the DT evaluation?

WG response:

The WG did not reach agreement on criteria that would define when applicants should address crack interaction in their DT evaluation. However, the WG did identify four general approaches to account for crack interaction (reference Section 4.5 in the DT evaluation). In addition, the WG considered two prescriptive approaches, which are discussed in this report as follows.

- Section 4.6.4: Using fatigue reliability data to demonstrate when additional engineering analysis or other operational limitation/part replacement may be required to address crack interaction.
- Section 4.6.5.2 and Appendix H: Using a detailed list of engineering assumptions or design/operational limitations.

Examples of two test articles and one in-service finding in which crack interaction effect is observed are shared in Appendix C . Section 3 briefly summarizes a limited review of ADs performed by several WG TCH members used by the WG to assess the potential safety concerns with the current state of the industry practices to address interaction and to identify any shortcomings, if present, based on combined experiences of WG member companies and product performance.

Appendix C presents examples where crack interaction effects are expected to be significant due to relative size of multiple cracks within a structural detail, or adjacent details from test and service. Gulfstream also discussed with WG evidence in a test article where multiple adjacent cracks were present. While the actual crack behavior in the test article was expected to be influenced by the same physical phenomena (i.e., change in stress field ahead of crack tips), their use of a continuing damage model for developing of inspection program and consideration of part modification at some point (both approaches presented in Section 4.5) had demonstrated that inspection program to be reliable. The position reinforced by Gulfstream for this discussion is that validation of the engineering assumptions (criteria), including accounting for crack interaction, through testing is expected and should clearly demonstrate that the engineering assumptions in total (including how crack interaction is addressed) are valid and/or conservative.

FAA response:

As discussed in Section 3.2, the FAA believes a more thorough interrogation of the field (fleet) cracking would be required to better understand the safety risk due to crack interaction. While past performance is helpful in understanding the safety risk, it may not fully eliminate the safety concern for potential future applications. Furthermore, the task of assessing the risk of crack interaction based on the limited survey of available airworthiness directives, service bulletins, and Special Airworthiness Informational Bulletins is inherently challenging because we are trying to disprove a hypothesis based on a limited number of data points.

b) There are currently no cracking scenarios identified in AC 25.571-1D. Should the AC include cracking scenarios?

WG response:

As discussed in Section 4.6.2.2, the majority of WG members determined that the AC should not include cracking scenarios, and, based on the number of WG members opposing this proposal, the WG recommends the FAA not include examples in guidance. Their rationale for not including examples in AC 25.571-1D is summarized as follows:

- The AC would be overly prescriptive.
- The AC provides flexibility for applicants to establish the physics of the damage modes and locations.
- Using the definition proposed in Section 4.6.2.1, applicants should be able to determine the cracking scenarios that result in crack interaction.
- The list of examples may be incomplete and result in applicants being overly focused on only these example scenarios.
- Some examples may appear to be a repeat of WFD scenarios, which may generate more confusion than clarification.

The examples the WG considered are described in Appendix G.

FAA response:

Regulatory guidance, whether an AC or policy, describes a method of compliance to the rule, or how the FAA intends to apply the rule going forward. Guidance is not binding on public. Applicants are able to propose other methods of compliance to the rule with the proper substantiation data. If examples were to be included in an AC, there could be a “disclaimer” preceding the examples to clearly explain their intended use (i.e., not in a prescriptive way). Offering several illustrative examples does not negate or remove the applicant’s flexibility to establish their own scenarios. Having examples in guidance material does not imply the list is an exhaustive list of all possible options. There is precedence of including examples of structural details related to DTE in the current guidance material. The FAA notes that Section 4.6.2.2 provides more details on this topic, including the rationale behind both the majority and dissenting positions. The FAA will weigh the WG responses, as well as other available information, as it deliberates potential future revisions to the requirements or regulatory guidance materials.

c) What industry-wide analytical tools exist in the public domain related to crack interaction and damage tolerance evaluation? If there are significant gaps, would ARAC recommend research activity to address them?

WG response:

To maintain readability the WG did not explicitly address this question in the main body of the report, yet this response is referenced in 1.4. The detailed, tabulated summary and discussion are included here.

The following Table B-1 summarizes the current state of publicly available tools to industry for crack analysis. Some tools are available to general public at no cost, others require fee(s) and may be subject to other usage agreements. Of these analytical tools there is a wide variety of modeling flexibility available to users, which is generally proportional to the user's knowledge or experience.

Public domain software that would be easily usable to help aid in DTE and assess crack interaction effects during crack propagation was difficult to find and none were identified in the survey. Table B-1 contains a table of many private and some public software/programs that was found during the survey. Use of the terms "private" and "public" in Table B-1 is intended to reflect the users access to the source code for each application. Except as noted, these software packages are available to the general public, but most require some fees for use.

Some programs seem to mainly use existing closed-form solutions for 2D cracks and employ a graphical user interface for the user. Others are more complex 3D crack growth software that utilize existing FEA models and results (as inputs), re-meshing the sub-model to insert an initial crack, grow the crack with adaptive re-meshing techniques, and perform a J-integral (strain energy release rate) to determine the SIFs at each step of iteration. This method theoretically accounts for crack interaction if multiple cracks can be inserted simultaneously.

The only notable public domain program with flexibility to address general crack interaction effects is Warp3D. However, it is only a finite element solver that can compute SIFs. The user would need a pre- and post-processor to incorporate Warp3D and its capabilities. FEACrack (private) is a pre- and post-processor that contains

Warp3D in its package. As above, crack interactions are theoretically already included in the FE solution.

Though existing crack growth software tools are the most expedient manner for industry to have a set of fracture mechanics solutions to employ for an evaluation, there are various technical publications available in the general domain that provide additional technical background on various crack interaction problems and related fracture mechanics methodologies, and some of them may be used by applicants to develop their own solutions rather than relying on existing software. Some members of WG provided a sample list of available technical publications to assist in such an effort, which are provided in Table B-2. The list of references in Table B-2 exemplifies some public-domain articles and reports on the topic of analytic assessment of crack interaction. These references represent a small fraction of the total body of work published in this field. They have not been vetted by the WG members, and their inclusion in the report does not imply a buy-in of or endorsement by this WG.

The referenced documents in Table B-2 are just a sample of available technical content that may be of use to industry/applicants in modeling effect of crack interaction. Some of the referenced documents address crack interaction when evaluating MSD/WFD scenarios, either growth or residual strength. While the primary focus of the WG has been on crack interaction effects for local design details, results provided in technical documents including crack interaction effects in a WFD evaluation are still beneficial to an applicant when modeling crack interaction in a local design detail as noted in Section 4.5 (i.e., a MSD/WFD approach may be appropriate and desirable for evaluating a local design detail).

Though there are significant gaps in the public domain software, there is enough publicly available data for applicants to write their own software or use FEM to calculate simple SIFs with interaction. Therefore, since published solutions are generally available to industry and applicants may be capable of developing their own software/FEM using these solutions, the WG does not recommend further research activities to address this.

Table B-1 lists the crack growth software that may have capabilities to explicitly analyze various crack interaction scenarios.

Note: inclusion of certain software packages in this table and/or commentary notes do not reflect an endorsement, prioritization, or rejection of any of these programs. It also not a comprehensive list, but a reflection of a limited survey of available software tools to generically account for interaction effects of concurrent cracking in a fatigue crack growth simulation.

Table B-1: Crack growth Software

Name	Domain	Description	Notes
NASGRO	Private (Southwest Research Institute)	Fracture Mechanics and FCG Software	**Suite of several computer programs:** 2D crack growth analysis; fatigue crack growth (FCG) life, SIFs from library of solutions, critical crack size, fits FCG and fracture toughness equations to test data, SIF for 2D bodies using boundary element method
BEASY	Private (BEASY)	Fracture and FCG Software	3D crack growth analysis (tied with ABAQUS, ANSYS, NASTRAN), SIF (calculated using J-integral or crack opening displacement), crack growth rates, crack growth paths, critical crack sizes, integrated with NASGRO 2-3 material database and can link to later versions of NASGRO
AFGROW	Private (LexTech)	Fracture and FCG Software	2D crack growth, mostly LEFM methods, plug-ins to 3rd-party FE code to feed AFGROW stress inputs for crack growth, SIFs with library of solutions, spectrum management tool, Fracture Mechanics Database (da/dN vs ΔK, da/dt vs Kmax, fracture toughness)
BAMF	Private (Hill Engineering)	3D FCG Software	Combines AFGROW with StressCheck software to simulate crack growth in 3D model, actual results are in text format and plotted using Excel
CCGS	Private (Materials Center Leoben)	Predicts FCG in test specimens only	
Zencrack	Private (Zentech)	FCG software that interfaces with ABAQUS, ANAYS, or Simcenter Nastran	3D crack growth analysis; Grows cracks in user's 3D model (with initial crack meshed by user) and generates new meshes (adaptive remeshing) as the crack propagates, calculates crack fronts at each iteration, requires material data (from user or other database)
Fastran	Private (FractureLab)	FCG under variable-amplitude loading, originally developed by	*may be discontinued*

		James Newman Jr.	
FRANC3D (sometimes referred to as FRANC3D/ng)	Private (Process Optimization Corp)	FCG software that interfaces with ABAQUS, ANAYS, or Simcenter Nastran	3D crack growth analysis using FEA; Grows cracks in user's 3D model (with initial crack meshed by user) and generates new meshes (adaptive remeshing) as the crack propagates, calculates crack fronts at each iteration, requires material data from user but includes NASGRO 3 material data
FRANC2D	Public (Cornell Fracture Group)	FE-based to simulate crack propagation in 2D structures	Unsupported programs but freely distributed, includes pre-processor, cannot compute fatigue life; will need to do manually using Excel or similar
FRANC3D/Classic	Public (Cornell Fracture Group)	FE-based to simulate crack propagation in 3D structures	3D crack growth analysis (using boundary elements method); Unsupported program but freely distributed, will likely no longer work on modern computers because it was developed as 32-bit with Xwindows graphics
FEACrack	Private (Quest Integrity Group)	3D FE pre- and post-processor software for cracks	3D FEA pre- and post-processor with Warp3D (see below) solver to grow cracks, automatic mesh generation as crack propagates
Warp3D	Public (University of Illinois)	FE analysis engine that includes crack growth, no GUI	Continuing development as a ready-to-run research code for solution of large-scale 3D solid models, requires input data from a pre-processor -> Warp3D performs the calculations -> can use post-processor to interpret the results from Warp3D
Z-Cracks	Private (Z-Set)	Fracture mechanics module for post-processing FEA results	
LIFING	Private (AIR-WORKS)	Fatigue solver with optional crack growth module (GROWTH)	FE model and results import -> remesh with LIFING -> crack growth -> post-processing, SIF calculated with J-integral
CRACKS2000	Private (University of Dayton R.I.)	Similar to AFGROW	
CanGROW	Public (NRC Canada)	Fracture mechanics code developed at NRC Canada that includes crack interaction analysis capabilities	A special crack growth analysis program developed at NRC-Canada for MSD evaluation. CanGROW has the capability to grow multiple cracks simultaneously and to calculate the SIF by compounding a set of β-factors from the β-factor library and/or the FE based β-factor tool.

Table B-2 provides a partial list of publicly available crack growth and fracture mechanics analysis books and articles; some discuss crack interaction modeling, or provide some guidance on crack interaction analysis. This list is not comprehensive and included for reference only.

Table B-2: Available Technical Literature on Crack Interaction

Aksel, B., and Erdogan, F., "Interaction of Part-Through Cracks in a Flate Plate." Lehigh University, NASA Contractor Report 177926 (April 1985). https://ntrs.nasa.gov/api/citations/19850013382/downloads/19850013382.pdf
Anderson, B., et al., "Evaluation and Verification of Advanced Methods to Assess Multiple-Site Damage of Aircraft Structure." The Boeing Company. Report DOT/FAA/AR-04/42 (October 2004). https://www.tc.faa.gov/its/worldpac/techrpt/ar04-42all.pdf
Anis., S.F., et al., ""Simplified stress field determination for an inclined crack and interaction between two cracks under tension." Theoretical and Applied Fracture Mechanics, Volume 107, June 2020, 102561.
Bakuckas, J.G., Jr., Chen, C.C., Yu, J., Tan, P.W., and Bigelow, C.A., "Engineering Approach to Damage Tolerance Analysis of Fuselage Skin Repairs." Report DOT/FAA/AR-95/75 (November 1996). https://www.tc.faa.gov/its/worldpac/techrpt/ar9575.pdf
Boduroglu, H., and Erdogan, F., "Internal and Edge Cracks in a Plate of Finite Width Under Bending." Lehigh University. NASA Contractor Report 166094 (March 1983). https://ntrs.nasa.gov/api/citations/19830013118/downloads/19830013118.pdf
Broek, D., Jeong, D., and Thomson, D., "Experimental and Analytical Investigation of Multiple Cracking in Various Types of Test Specimens". 19950008046.pdf (nasa.gov)
Chang, R., "On crack-crack interaction and coalescence in fatigue", Engineering Fracture Mechanics, Volume 16, Issue 5, 1982, Pages 683-693.
Dai., J., Creager, M., Odian, K., Safarian, P., "Significance of Local Multiple Crack Growth Consideration on Aging Aircraft Structural Damage Tolerance Analysis." International Committee on Aeronautical Fatigue, Lucerne, Switzerland (May 2003).
Dawicke, D.S., and Newman, J.C., Jr., "Analysis and Prediction of Multiple-Site Damage (MSD) Fatigue Crack Growth." NASA Technical Paper 3231 (August 1992). https://ntrs.nasa.gov/api/citations/19920022035/downloads/19920022035.pdf
De Rijck, J.J.M., and Fawaz, S.A., "Stress intensity factors and crack interaction in adjacent holes", Engineering Fracture Mechanics, Volume 68, Issue 7, May 2001, Pages 963-969.
Erdogan, F., and Boduroglu., "Surface Cracks in a Plate of Finite Width Under Tension or Bending." Lehigh University. NASA Contractor Report 172309 (March 1984). https://ntrs.nasa.gov/api/citations/19840011858/downloads/19840011858.pdf
Grandt, A.F., Jr., "Analysis of Fatigue Crack Growth from Countersunk Fastener Holes." Purdue University, Report DOT/FAA/AR-08/21 (August 2008). https://www.tc.faa.gov/its/worldpac/techrpt/ar0821.pdf
Kachanov, M., "Elastic solids with many cracks: a simple method of analysis", Int. J. Solids & Structures, Vol. 23, No. 1, pp. 23-43, 1987.
Lam, K.Y., and Phua, S.P., "Multiple crack interaction and its effect on stress intensity factor", Engineering Fracture Mechanics, Volume 40, Issue 3, 1991, Pages 585-592.
Liao, M., et al., "Advanced damage tolerance and risk assessment methodology and tool for aircraft structures containing MSD/MED", Congress of International Council of the Aeronautical

Sciences (ICAS 2010), pp. 1863-1872, 2010-09-24.
Madia, M., et al., "Multiple crack initiation and propagation in weldments under fatigue loading", 3rd International Symposium on Fatigue Design and Material Defects, FDMD 2017, 19-22 Sept. 2017, Lecco, Italy.
Murikami, Y., et al., "Stress Intensity Factors Handbook.", Committee on Fracture Mechanics, The Society of Materials Science, Japan, 1987.
Newman, J.C., Jr., "An Improved Method of Collocation for the Stress Analysis of Cracked Plates with Various Shaped Boundaries." NASA Langley Research Center. NASA Technical Note D-6376 (August 1971). https://ntrs.nasa.gov/api/citations/19710022830/downloads/19710022830.pdf
Newman, J.C., Jr., and Raju, I.S., "Stress-Intensity Factor Equations for Cracks in Three-Dimensional Finite Bodies." NASA Langley Research Center. NASA Technical Memorandum 83200 (August 1981). https://ntrs.nasa.gov/api/citations/19810023035/downloads/19810023035.pdf
Newman, J.C., Jr., and Raju, I.S., "Stress-Intensity Factor Equations for Cracks in Three-Dimensional Finite Bodies Subjected to Tension and Bending Loads." NASA Langley Research Center. NASA Technical Memorandum 85793 (April 1984). https://ntrs.nasa.gov/api/citations/19840015857/downloads/19840015857.pdf
Raju, I.S., and Newman, J.C., Jr., "Methods for Analysis of Cracks in Three-Dimensional Solids." NASA Langley Research Center. NASA Technical Memorandum 86266 (July 1984). https://ntrs.nasa.gov/api/citations/19840022261/downloads/19840022261.pdf
Raju, I.S., and Newman, J.C., Jr., "Stress-Intensity Factors for Corner Cracks at the Edge of a Hole." NASA Langley Research Center. NASA Technical Memorandum 78728 (June 1978). https://ntrs.nasa.gov/api/citations/19780018548/downloads/19780018548.pdf
Steadman, D., "Destructive Evaluation and Extended Fatigue Testing of Retired Transport Aircraft, Volume 5: Data Analysis Report." Delta Air Lines. Report DOT/FAA/AR-07/22,V5 (October 2007). https://www.tc.faa.gov/its/worldpac/techrpt/ar07-22-5.pdf
Tsang, D.K.L., Oyadiji, S.O., and Leung, A.Y.T., "Multiple penny-shaped cracks interaction in a finite body and their effect on stress intensity factor", Engineering Fracture Mechanics, Volume 70, Issue 15, October 2003, Pages 2199-2214.

4. Crack interaction considerations in the context of DT assessment

a) What role does the threat assessment play in establishing a need to address crack interaction in the analysis?

WG response:

Section 1.3 of this report briefly describes the role of a threat assessment in establishing a need to address crack interaction in the analysis.

b) Do applicants consider environmental or handling effects in fatigue-critical areas that contribute to cracking in multiple features? (e.g., areas of the aircraft that are more exposed to environmental factors or accidental damage, such as door surround structure)

WG response:

Appendix G of the 2018 Recommendation Report [1] addresses the following:

- ALS maintenance requirements;
- the differences between DTE-based, MSG-3 derived and conditional (unscheduled) maintenance programs; and
- some historical background regarding the expectations of DTE to address Fatigue Damage (FD) as special damage tolerance-based inspections/replacements and MSG-3 process to address Environmental or Accidental Damage (ED or AD) as baseline scheduled maintenance.

The WG provided this material in [1] as supplemental discussion to support the recommendation to revise AC 25.571-1X to clarify how to address escalation of any ALS task.

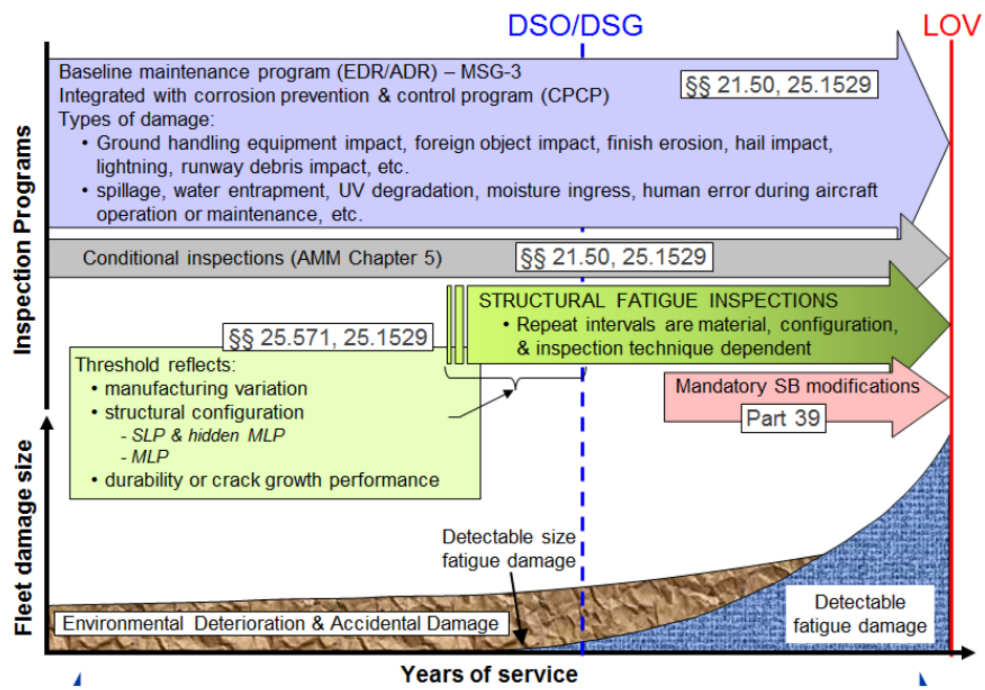
Section 1.3 of this report provides additional discussion regarding the typical approach to address interaction when other different damage threats are present. The WG used the information from the Recommendation Report for WFD by AAWG in 1999 [9].

One specific approach for addressing door-related structures, as an example, is to control the operating stress levels and design for large cracks (fail safety) in these locations with the understanding that they are prone to AD/ED. This approach should establish DT-based inspections that account for the AD/ED evaluation performed per the MSG-3 process.

c) What steps should companies take to ensure the structural maintenance program is adequate to address the threats defined in § 25.571 (most notably fatigue)? Examples?

WG response:

The WG previously addressed the importance of a structural maintenance program having multiple elements to prevent catastrophic failure due to fatigue, corrosion (environmental deterioration), manufacturing defects, or accidental damage (four threats) throughout the operational life of an airplane, as required by § 25.571. This is discussed in 2018 recommendation report (reference figure in Section 3.7.4.2 and additional discussion in Section 3.8 of [1] and reproduced below).



Elements of the maintenance program contributing to the safety objectives include MSG-3 derived inspection programs, corrosion prevention & control program, conditional inspections, structural fatigue inspections (e.g., crack growth-based programs), and in-service finding programs (e.g., ADs, service bulletins).

The TAMCSWG does not recommend a single approach to ensure effectiveness of a maintenance program for the safe continued operation in presence of the four categories of threats. However, the WG recognizes the current processes as ensuring a maintenance program is effective over the product's life, as listed below.

- Full scale fatigue testing & teardown inspections
- Addressing in-service damage findings as established in existing rules and guidance when potential short-comings of the maintenance program exist, such as:
  - § 21.3 (Reporting of Failures, Malfunctions, and Defects)
  - § 121.703 (Service Difficulty Reports (SDR) - Operators)
  - § 145.221 (SDR – Repair Stations)
  - Part 39 (Airworthiness Directives)
  - AC 91-82A (Fatigue Management Programs for In-Service Issues)

- Strong OEM, industry and regulatory partnerships, such as Structural Task Groups

When these elements are properly executed, effective structural maintenance programs should be achieved. The second bullet (addressing in-service damage findings) identifies requirements and guidance to address known safety issues, which occur due to a threat not being properly addressed, yet also come into play even if the maintenance program is reliable (i.e., even though the threat was envisioned and properly addressed). Regardless of the intervals, if cracks are discovered during a prescribed inspections the second bullet point actions are required.

Proper execution of the above is expected to include a feedback loop. For instance, when service experience reveals that manufacturing issues are not captured in a fatigue test article, they should be addressed as part of the SDR/Part 21/39 activity (reference WG's 2018 report section 3.12 on recommendations for addressing findings from FSFT). Preferentially, manufacturers should adopt any changes into later builds of the existing airplane model or new products based on any lessons learned from an in-service finding. An effective way to introduce these types of changes is through industry partnerships.

This response was not directly included in the main body of the report, as the question and response are generic to the overall effectiveness of a maintenance program, and not specific to crack interaction. Just as there is no single way to account for the effect of crack interaction in a DTE, there is no single mechanism (or prescribed steps/procedure) in place to measure the effectiveness of each engineering assumption/analysis technique employed in a DTE.

c) 1. Is crack interaction being properly taken into account when investigating the range of threats used to define an inspection program? Or, is the rogue flaw approach sufficient (as allowed for over 30 years)?

WG response:

An improper accounting of crack interaction as part of the threat evaluation for the development of an inspection program could result in a safety concern, which may be eventually revealed in service or through full-scale fatigue test evidence. The WG addressed this in Section 3.2.

As discussed in Section 4.5, there are several methods that can be used to address concurrent cracking when developing the fatigue management program. The "rogue flaw" approach is one of the methods discussed and it is outlined in AC 91-82A. However, as cautioned in 91-82A and discussed in Section 4.6.4, inspections based on this approach may need to be supplemented with part replacements based on the overall fatigue performance of the detail. In other words, the rogue flaw approach has limitations, and those limitations need to be understood to provide the correct inspections or other procedures as part of the structural maintenance program. Simplifying assumptions may be used if they envelope the likely cracking behavior as discussed in Section 4.6.5.

c) 2. Is addressing fatigue with "manufacturing damage" adequate, or is this a gap in complying with § 25.571?

WG response:

The WG largely focused on the threat of manufacturing damage in presence of fatigue damage as a scenario of threats recognized to likely be the most significant to the concern about crack interaction as discussed in Section 1.3. This is, in part, due to the AC 91-82A as a means to develop a fatigue management program which was presented as context for the extended tasking activity for how to address crack interaction when establishing inspection programs. This is also based on experiences of WG members, based both in test and service findings.

c) 3. Do the assumptions used in the F&DT analysis reflect the actual cracking behavior of the structure subject to fatigue?

WG response:

The WG had considered this notionally as part of recommendation 4.6.1.1. The language in AC 91-82A states "The damage-tolerance evaluation should consider the actual sites, cracking scenarios, and crack progression observed in the unsafe condition. Actual cracking scenarios can be complex, involve multiple sites, and at some point, include crack interaction." However, AC 91-82A is addressing the topic of developing a FMP to address a known problem. The purpose of the DTE as addressed in § 25.571 is to develop necessary maintenance programs to address probable damage.

Because all possible damage modes cannot be precisely modeled the objective of the DTE is then to develop solutions (i.e., maintenance programs) which effectively capture the performance of the expected worst-case scenarios which may occur. This is the notion captured by the term "enveloping assumptions" in Section 4.5.

The WG was deliberate in omitting the term "actual" from recommendation as described in Proposal 4.6.1.1 discussion.

Appendix C Multiple Cracks in Structural Components

Examples of two structural components with multiple crack nucleation sites before failure

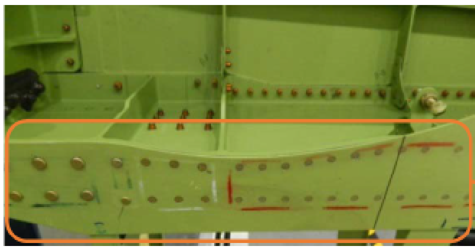
This appendix is intended to document the crack interaction examples and crack growth analysis presented by Dr. Patrick Safarian, FAA Fatigue and Damage Tolerance Technical Specialist, to the WG that was utilized in working group discussions. In some cases, WG members provided pointed contrary views, and those are noted within the presentation material captured in this Appendix.

Introduction

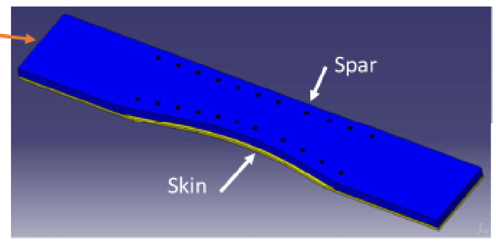
- A TC holder conducted major component fatigue tests and a full-scale fatigue test for the certification of a derivative airplane model.
  - Increased gross weight of the airplane resulted in increased loads in affected structures
- Fatigue test results shown for two structural components.
  - Rear Spar Notch Detail (6 specimens)
  - Center Line Mid Spar Splice (8 specimens)
  - All test specimens were cycled to failure.
  - Each test specimen had multiple cracks at many details before final failure.
- This presentation also contains an in-service example with multiple cracks.

1. Rear Spar Notch Detail

Rear Spar Notch Detail

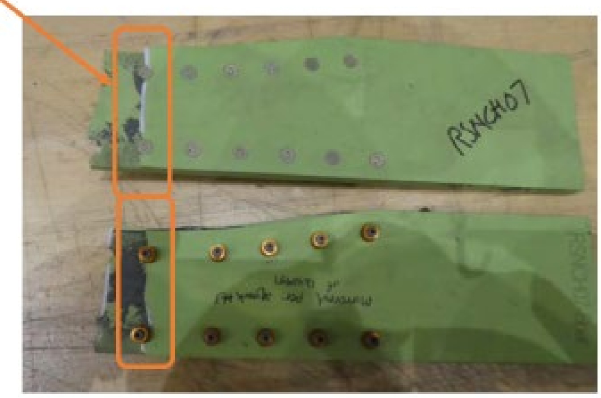


There are total of 6 test specimens all showing cracks at multiple locations before complete failure of the components.

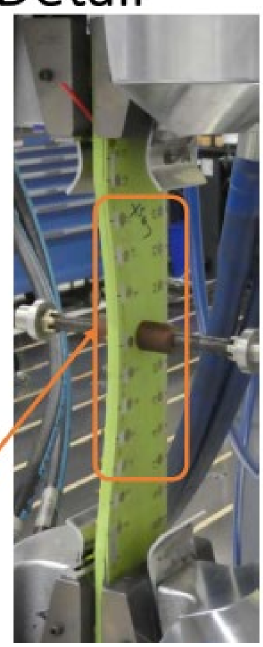


Failed Rear Spar Notch Detail

See next slide for cracking pattern



Critical Fasteners



Multiple Cracks in Rear Spar Notch Detail

Note that there are cracks at <u>ALL</u> 8 detail design points of this component, which led to the complete failure of the structure.

TC holder's comment: *There are numerous different sized cracks on the specimen– Cracks are highlighted*

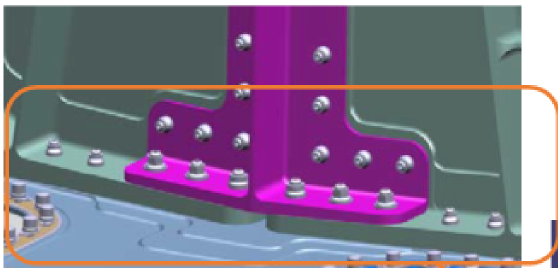
Here is the sample without the highlights

For TAMCSWG activities only. Please do not share.

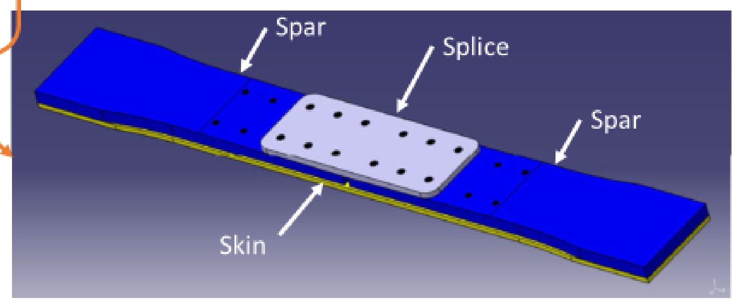
6

2. Center Line Mid Spar Splice

Center Line Mid Spar Splice



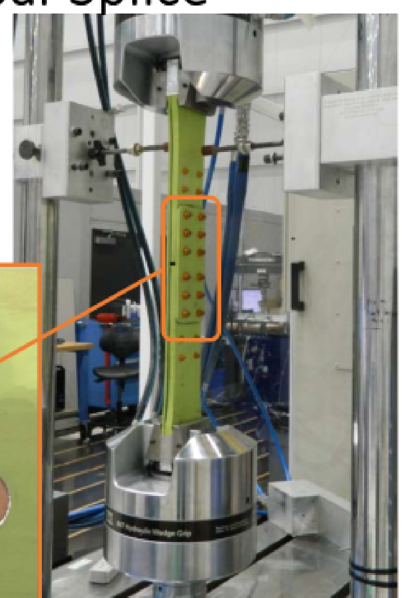
There are total of 8 test specimens all showing cracks at multiple locations before complete failure of the components.

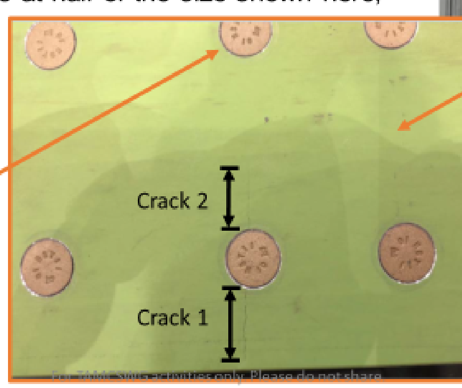


Cracked Center Line Mid Spar Splice

TC holder's note: There are 2 cracks at one of the fastener locations in the splice plate. Crack 2, the crack farthest from the edge, is at a substantial length while crack 1, the crack closest to the edge, is not yet broken to the edge. <u>Crack 1 was not visually detectable</u> when the crack length was half of the size shown in this picture. At this length, crack 1 was only visually detectable when the specimen was under load. In addition, when crack 1 was at half of the size shown here, crack 2 was there too. As with crack 1, crack 2 was only visually detectable when the part was loaded.

This hole has 2 invisible cracks at this time. These cracks were confirmed by HFEC inspection.



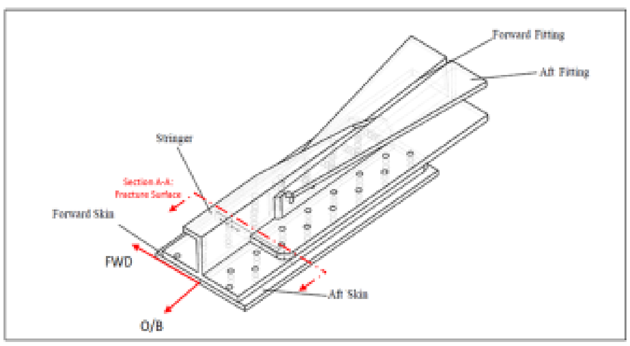


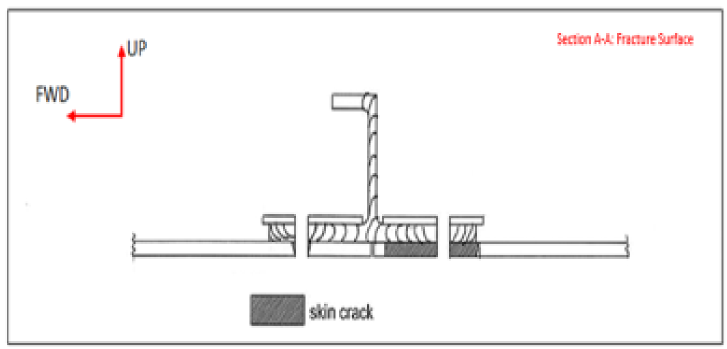
9

Multiple Cracks on Wing Stringer Splice and Lower Wing Skin Stack-Up

- This is an in-service example of multiple cracks at a structure with few "detail design points." The stringer was discovered completely severed and visible cracks were discovered in the lower skins. The location of the severed stringer was also noted to coincide with the end of the FWD/AFT tension fittings connected to the main lower centerline beam. Further investigation revealed that the forward skin panel had also started cracking.
- The striations are an indication of fatigue cracking and were shown to have originated from the two fastener holes on the outer flange of the stringer and grow inwards where they continue up the vertical web of the stringer until eventually the stringer could not carry the required load and completely fractured.

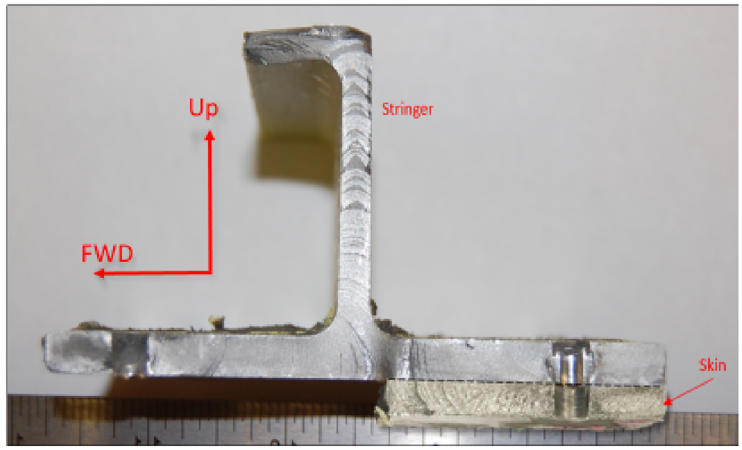
Multiple Cracks on Wing Stringer Splice and Lower Wing Skin Stack-Up





Multiple Cracks on Wing Stringer Splice and Lower Wing Skin Stack-Up

- The material around both the forward and aft skin cracks were removed by maintenance.
- The forward skin crack is only visible on faying surface side. The aft skin crack had broken through to the lower surface. The two pieces are on separate skin panels (FWD/AFT wing skins), conjoined by the stringer acting as splice strap.



<u>Gulfstream perspective:</u> This damage is indicative of the structure having reached its fatigue limit and a repeat inspection based on normal DTE is not appropriate.

This specific example is given in AC120-104, figures 5-14 and 5-16. It should be evaluated as WFD following those methods. Gulfstream believes it to be WFD and not applicable to this discussion.

<u>Additional comment:</u> For this example, Gulfstream suggests: approaches as noted in Section 4.5 may be applicable to this case, including the use of guidance in AC 120-104 as a means to address crack interaction. Consideration of crack interaction may include part modification or a significantly different crack growth simulation approach beyond what may be considered normal DTE at the point which the detail contains many equal size cracks, regardless if it is classified as WFD susceptible structure in AC 25.571-1D, Appendix 3, step 6 or not.

Appendix D Example Analyses Illustrating the Potential Effect of Interacting Cracks

This appendix includes examples of ways to analyze crack interaction. They show the potential effects of crack interaction and the influence it may have on the establishment of an effective inspection program (i.e., determining inspection method or frequency). Dr. Patrick Safarian, FAA Fatigue and Damage-Tolerance Specialist, presented examples AA and BB in this appendix to the WG. Example CC is an excerpt from a presentation made by the National Research Council Canada which addresses comparative examples of LEFM-based analytical crack growth simulations with and without explicit consideration of interacting cracks for a single structural detail using a less-widely available crack growth simulation tool (CanGROW) [11], [12]. Included in example CC are some supplemental observations of these results presented by a WG member as part of a discussion on potential sensitivity of thresholds and repeat inspection intervals by explicit inclusion of crack interaction effects to the SIF in a crack growth analysis.

WG discussion pertaining to these examples is provided in Section 1.4 of the report.

As this presentation material was shared as a means to spur discussion, different perspectives provided by WG members are noted where appropriate.

EXAMPLE AA: Fatigue Analysis of Material on the Opposite Side of a Plate with a Single Cracked Offset Hole

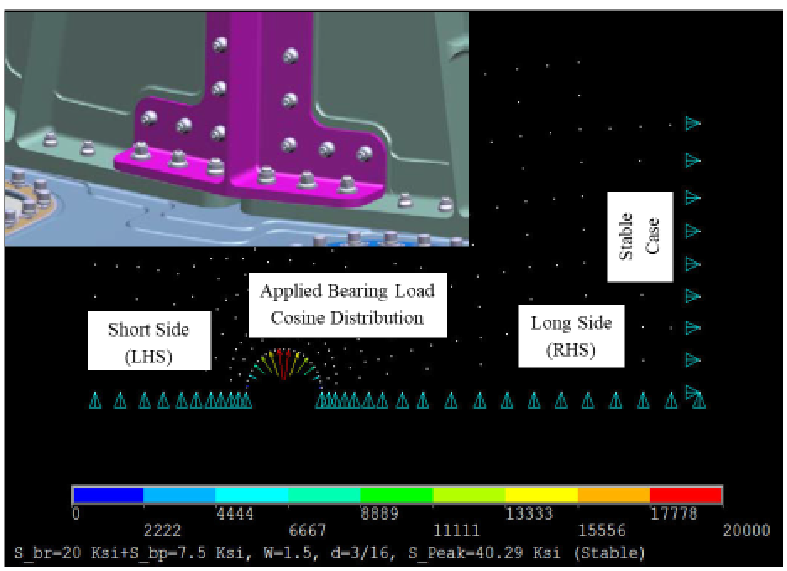
Introduction

- A stress and fatigue analysis is presented to show how the fatigue life of a panel is effected as an assumed crack on the short ligament of a plate with an offset hole propagates.
- The K_t at the hole on the opposite side of the ligament with crack increases as the crack propagates. The fatigue life of the uncracked ligament due to increased K_t is calculated.
- The plate is subject to bearing load and tension load.
- Plate dimensions are: W=1.5", H=8", t=0.05", d=3/16", Short ED=2.5D=0.468", and the load transfer is 17.5%.
- Applied Stresses are Bearing Stress=12.73 Ksi + By-Pass Stress=7.5Ksi

Finite Element Analysis

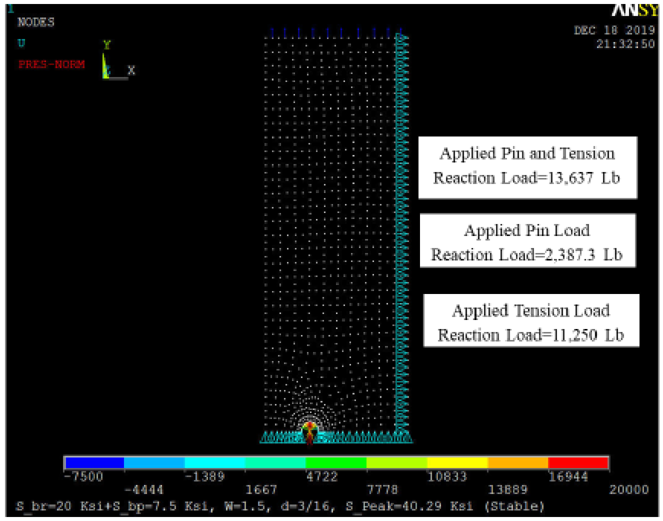
Finite Element Model- Description

- The model is half symmetric.
- Bearing loads are applied as cosine distributed load.
- Two cases are considered: stabilized and unstabilized (Ux on RHS edge of the part is set to zero or it's unconstrained)



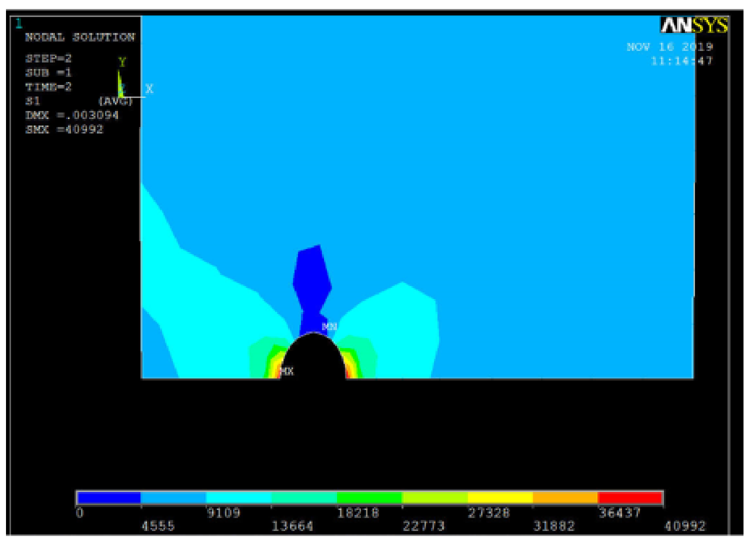
Finite Element Model- Loads & BC

- Detail of applied stresses to the FEM
- For accuracy the chosen element are quadratic elements with mid-side node.
- This is the nodal plot of a Stabilized model.



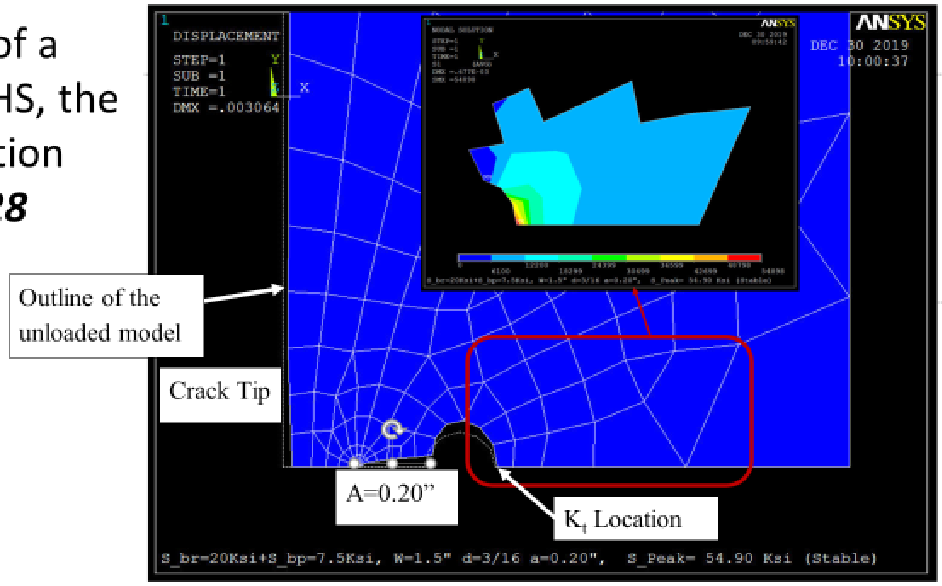
Finite Element Analysis Results- No Cracks

- Stabilized: Stress concentrations on both sides are ***3.88***
- Unstabilized: Stress concentration on RHS is ***3.93*** and on LHS is ***3.95***.



Finite Element Analysis Results- Crack on LHS

- In the presence of a 0.20” crack on LHS, the stress concentration on the RHS is ***5.28***



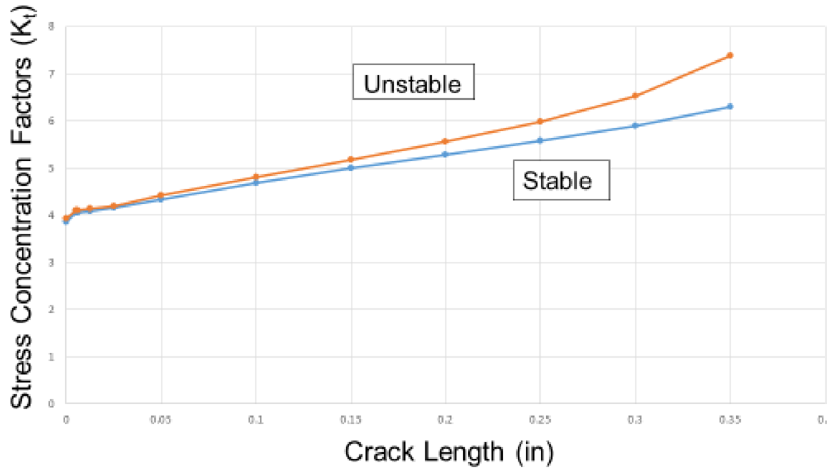
Finite Element Analysis Results- Crack on LHS

- Table of Stress Concentration factors for the RHS of the hole as a function of various Crack Lengths on the LHS.

a	Kt_Stab	Kt_Unstab
0	3.88	3.93
0.0050	4.0573	4.1137
0.00625	4.0577	4.1144
0.0125	4.09	4.14
0.0250	4.16	4.23
0.0500	4.34	4.42
0.1000	4.68	4.81
0.1500	5.00	5.18
0.1600	5.05	5.25
0.2000	5.28	5.56
0.2500	5.58	5.98
0.3000	5.90	6.52
0.3500	6.29	7.38

Finite Element Analysis Results- Crack on LHS

- Plot of Stress Concentration factors for the RHS of the hole versus various Crack Lengths on the LHS.



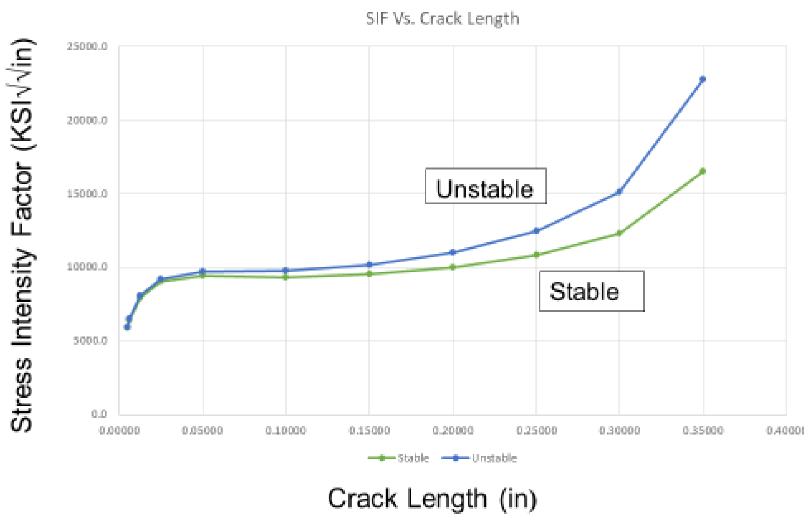
Finite Element Analysis Results- Crack on LHS

- Table of Stress Intensity Factors and their associated Geometric Factors
- All values are provided in English units
- These values are for reference and are not used in the analysis. Nasgro software was used for crack growth analysis.

Crack Length (in)	SIF Stable	SIF Unstable	Beta Stable	Beta Unstable
0.00500	5859.8	5962.2	5.14	5.23
0.00625	6363.6	6476.0	5.00	5.08
0.01250	7923.2	8070.2	4.40	4.48
0.02500	9035.3	9224.2	3.55	3.62
0.05000	9438.1	9693.0	2.62	2.69
0.10000	9339.6	9749.7	1.83	1.91
0.15000	9534.0	10181	1.53	1.63
0.16000	9582.0	10289	1.49	1.60
0.20000	9977.2	10992	1.38	1.53
0.25000	10813.0	12442	1.34	1.54
0.30000	12310.0	15109	1.39	1.71
0.35000	16532.0	22792	1.73	2.39

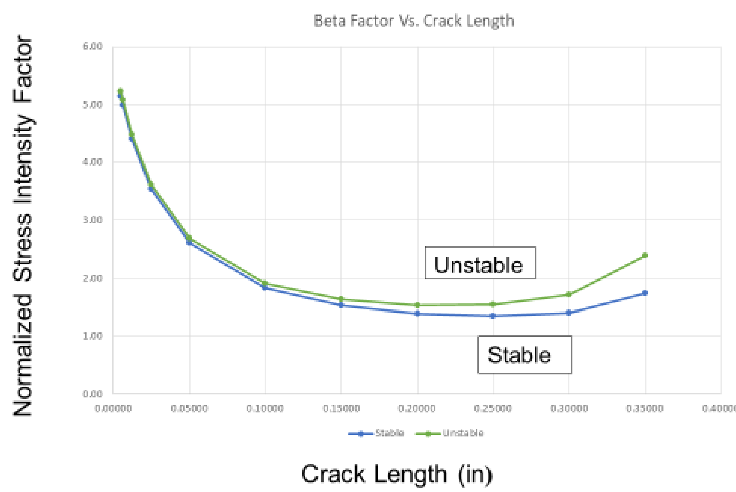
Finite Element Analysis- Crack on LHS

- Plot of Stress Intensity Factors versus various Crack Lengths



Finite Element Analysis- Crack on LHS

- Plot of Normalized Stress Intensity (Geometric) Factors versus various Crack Lengths



Fatigue Analysis of the RHS

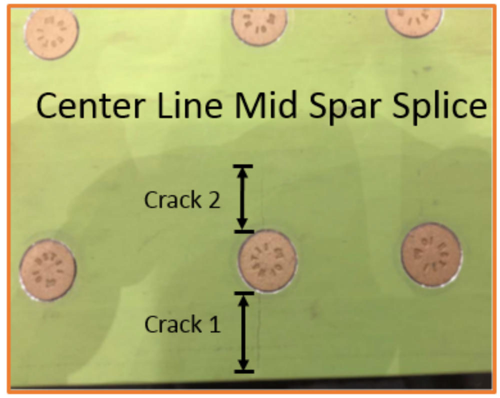
- Conducted fatigue analysis of the material on the RHS of the hole as the crack propagated on the LHS to its critical length.
  - Used Nasgro software to grow the crack incrementally
  - Used the average K_t value for each increment
  - Calculated the fatigue damage for each increment until critical crack length of LHS reached
  - Calculated the accumulated fatigue damage using Palmgren-Miner rule [Typically $\sum(n/N) < 1$ to be acceptable]
  - Used MMPDS S-N curves
  - Used fatigue life of 95%/95%
  - Used an empirical factor of 0.872 to adjust the K_t values from the model, which is an open hole to a filled hole.

Fatigue Analysis of the RHS

Δa (a1 to a2)	K_{t_a1}	K_{t_a2}	K_{t_Ave}	$N_{f\ Open\ Hole}$	$N_{95/95}$	K_{t_Ave} x 0.872	$N_{f\ Filled\ Hole}$	$N_{95/95}$	CG Life	S(n/N)
0.05 to 0.10	4.34	4.68	4.51	262,455	61,729	3.93	550,082	129,379	29,792	0.230
0.10 to 0.15	4.68	5.00	4.84	183,344	43,122	4.22	372,597	87,635	23,762	0.271
0.15 to 0.20	5.00	5.28	5.14	136,453	32,094	4.48	271,048	63,750	18,208	0.286
0.20 to 0.25	5.28	5.58	5.43	104,958	24,686	4.73	204,664	48,137	12,871	0.267
0.25 to 0.30	5.58	5.90	5.74	80,993	19,050	5.01	155,301	36,527	8,106	0.222
0.30 to 0.35	5.90	6.29	6.10	61,595	14,487	5.31	116,197	27,329	4,696	0.172
										1.448

Conclusion

- RHS material fatigue life does not support a **0.05"** crack[1] growing on the LHS to its critical length of **0.388"**
  - ∑(n/N) ≥ 1 (or 100%) is not acceptable
  - RHS material accumulated fatigue damage is **145%**.
- These test specimens appear to support the assumptions made in this analysis, however a fractographic analysis should to confirm this conclusion.



1. 0.05" crack size is typically used in DT evaluations

Fatigue Analysis Summary of RHS 0.005" Crack on LHS

- Conducted another fatigue analysis except assumed an 0.005" crack on the LHS of the hole.
- Determined the final crack length on LHS of hole when the accumulated fatigue damage resulted in failure of the RHS material.
- Similar to the analysis described above, the fatigue life of the RHS was calculated as the crack on the LHS propagated incrementally.

Fatigue Analysis of the RHS

Δa (a1 to a2)	Kt_{a1}	K_{t_a2}	K_{t_Ave}	$N_{f\_Open\ Hole}$	$N_{95/95}$	K_{t-Ave}*0.872	$N_{f\_Filled\ Hole}$	$N_{95/95}$	CG Life	S(n/N)
0.005 to 0.00625	4.06	4.06	4.06	460,384	108,282	3.54	1,020,862	240,107	13,715	0.057
0.00625 to 0.0125	4.06	4.08	4.07	454,171	106,821	3.55	100,5585	236,514	35,847	0.152
0.0125 to 0.025	4.08	4.16	4.12	424,693	99,888	3.59	933,510	219,561	25,504	0.116
0.025 to 0.050	4.16	4.34	4.25	358,890	84,411	3.71	77,5167	182,319	15,150	0.083
0.05 to 0.10	4.34	4.68	4.51	262,455	61,729	3.93	55,0082	129,379	29,792	0.230
0.10 to 0.15	4.68	5.00	4.84	183,344	43,122	4.22	37,2597	87,635	23,762	0.271
0.15 to 0.166	5.00	5.09	5.045	149,409	35,141	4.40	29,8802	70,278	6,422	0.091
									150,192	**1.001**

This analysis indicates that the fatigue life of the RHS ends when the 0.005" reaches 0.166".

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Conclusion

- Calculations show that, by the time the primary crack on the LHS reaches its failure length, the RHS ligament will fail.
- The accumulated fatigue life of RHS in this example ends when the crack on the LHS grows from a material defect of ***0.005"*** to ***0.166"***, which is less than the critical length of ***0.388"*** shown in the previous analysis.
- The probability of detecting cracks is lower than the probability of detecting cracks when no-crack interaction is assumed. Crack growth analysis shows that after the LHS ligament fails, the RHS crack is large enough to cause a panel failure in only ***285*** cycles.
- The analysis should not ignore the presence of a crack on the RHS while the crack propagates on the LHS because—
  - From fatigue damage accumulation perspective: Fatigue analysis shows that the K_t in the RHS increases as the primary crack continues to grow on the LHS.
  - From crack growth perspective: Effectively we are saying that after ***97,432*** cycles, when the LHS ligament fails, suddenly a crack appears on the RHS with a ***0.04"*** size, which causes the entire panel to fail in very low number of cycles (e.g., ***285*** cycles). This is unrealistic and cannot be substantiated by any test evidence or service experience. Every test evidence and service experience indicates an opposing crack to the primary crack.
- For these reasons, if no-crack-interaction is assumed in setting inspection intervals, the other assumptions must be shown to be well substantiated or show that a model that omits the interaction effect is conservative.

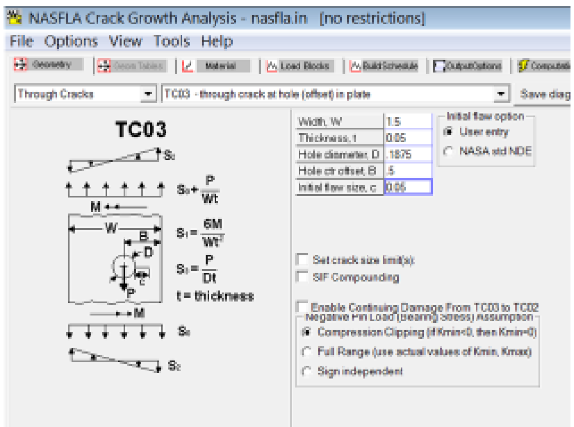
Gulfstream perspective: The factored (95/95) fatigue life of this detail was reported to be 129,000 cycles. The DT results indicate a threshold at 97,000/2 = 48,500 cycles (factor on mean fatigue life of 11) with a repeat inspection of 24,000-26,000 cycles depending on interaction model used.

Assuming that the LOV is reasonably set below the point of generalized cracking (100,000 cycles for example), FD is not likely within that LOV. I contend that the 'no interaction' model is already very conservative, and no additional tweaks are necessary. Adding the assumed interaction effects just make it more conservative.

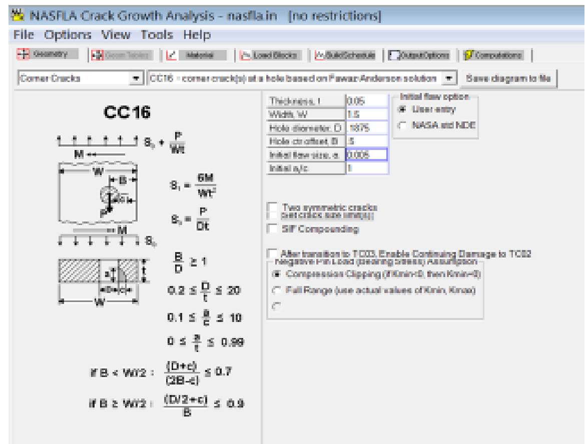
The inspection method should consider that both, or either, sides of the hole may be cracked, but the associated interval is already conservative.

EXAMPLE BB: Analytical Examples of Crack Growth Analysis with and without Crack Interaction Models using NASGRO

Analytical Example 1- Non-Interactive Model



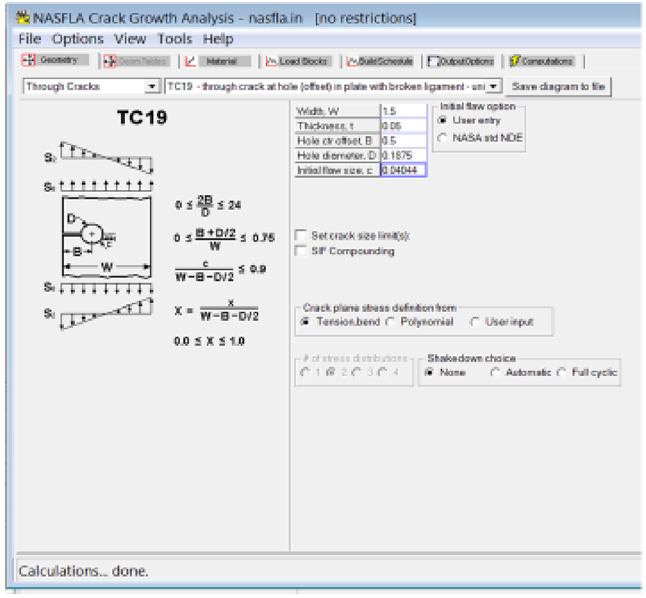
Stage 1A: Crack growth analysis of a single 0.05” crack to failure using TC03 leads to 97,432 Cycles.



Stage 1B: Crack growth analysis of a single 0.005” crack using CC16 in 97,432 leads to an 0.0404”.

Analytical Example 1- Non-Interactive Model

<u>Stage 2:</u> Crack growth analysis from end of Stage 1 using TC19 leads to additional 285 Cycles.

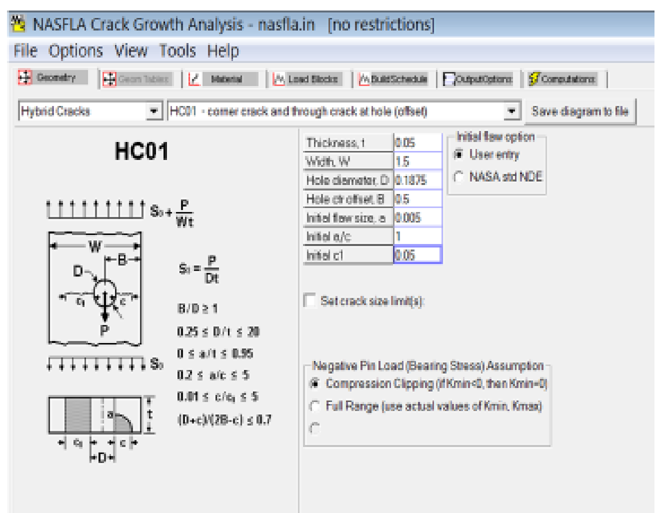


The total crack growth life of this plate without the effect of interaction is 97,717 cycles.

Analytical Example 1- Interactive Model

Using HC01 an 0.05" crack with a secondary 0.005" crack is grown to failure with the crack interaction

The total crack growth life is 94,975



Comparison of Analytical Example 1

<u>Without crack interaction:</u>
Using a factor of 2: (97,717 – 45,000)/2 = 26,400 cycles
Using a factor of 3: (97,717 – 45,000)/3 = 17,600 cycles

<u>With crack interaction:</u>
Using a factor of 2: (94,975 – 46,000)/2 = 24,500 cycles
Using a factor of 3: (94,975 – 46,000)/3 = 16,300 cycles

In this example it is evident that there are not much difference in Inspection intervals using the two models. However, in the non-interactive model the resulting inspection will be visual, while the interactive model will required inspections using NDT technique, such as HFEC.

Comparison of Analytical Example 2

If the offset of the hole is changed from <u>0.50”</u> to <u>0.65”</u> the following will be the analysis results:

<u>Without crack interaction:</u>
Using a factor of 2: (154,985 – 56,000)/2 = 49,500 cycles
Using a factor of 3: (154,985 – 56,000)/3 = 33,000 cycles

<u>With crack interaction:</u>
Using a factor of 2: (121,509 – 50,000)/2 = 35,700 cycles
Using a factor of 3: (121,509 – 50,000)/3 = 23,800 cycles

In this example the differences between inspection intervals are greater. This leads to shorter intervals as well as requirement of use of NDT technique.

Conclusion

- The simultaneous presence of multiple cracks can occur in local details.
- At some point, cracks may affect the crack growth rate of other cracks in local details.
- Crack growth analysis should in some way account for the effects of crack interaction.
- Crack lengths at time of inspection may be smaller than predicted by analysis if crack interaction is not considered.
- Not accounting for crack interaction may result in an unreliable inspection program
  - Repeat inspection interval may be unrealistically long (reference Appendix C, Page 99)
  - Inspection method may be unreliable (e.g., the critical crack size may be smaller than a visual inspection can reliably detect.) (reference Appendix C, Page 100)
- Crack interaction is seen in tests components and in-service structural failures

EXAMPLE CC: Simultaneous Crack Growth Using CanGROW

The following is excerpt from “Continuing Damage Case Study” presented by Yan Bombardier & Guillaume Renaud to AFGROW Users Workshop 2019 held in Clearfield, UT, 9/10-11/2019 (https://www.afgrow.net/workshop/documents/2019/Guillaume-Renaud-Continuing-Damage-Case-Study-2019.pdf) [11]

Introduction

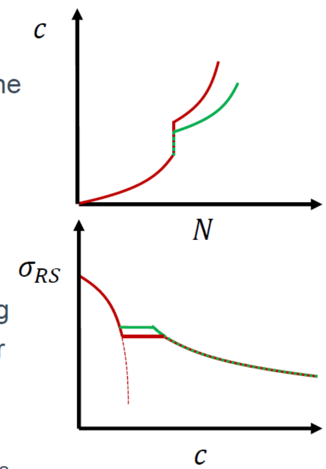
Motivation and Objective

Life and Residual Strength for a Ligament Failure Scenario

- The life and residual strength after ligament failure depends on the continuing damage size.
- Traditional damage tolerance practices may underestimate the continuing damage size for some scenarios.

Objective

- Using CanGROW, compare crack growth characteristics resulting from independent (sequential) and simultaneous crack growth for a demonstration problem provided by USAF A-10 ASIP.
  - Compare Cangrow sequential analysis to AFGROW sequential analysis
  - Compare Cangrow sequential analysis with Cangrow simultaneous analysis



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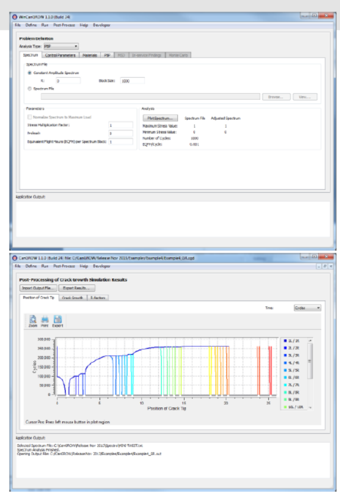
Canada

Introduction

CanGROW

- NRC in-house code developed to analyze multiple hole/crack scenarios
  - Phase-by-phase (**PBP**) (sequential crack growth)
  - Multi-Site Damage (**MSD**) (simultaneous crack growth)
- Many built-in K-solutions
- MSD analysis based on compounding method
- Regression of in-service findings for EIFS calculations
- Monte Carlo simulations
- NDI/Repair simulations



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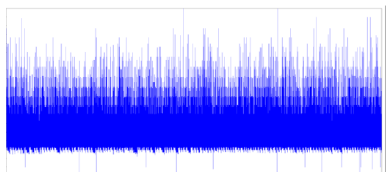
Canada 5

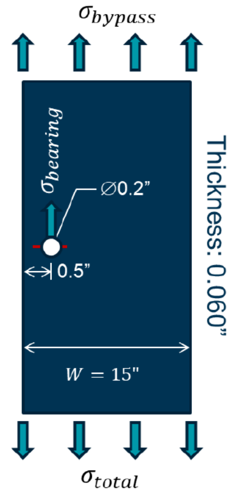
Problem Definition

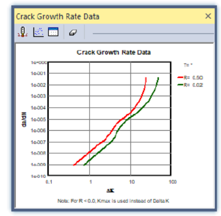
Geometry, Loading, Material

Offset hole in a plate

- Material: 7075-T6, Tabular Lookup (R = 0.02, R = 0.5)
- Retardation: Willenborg (SOLR = 1.7)
- Spectrum: Variable amplitude (A-10)







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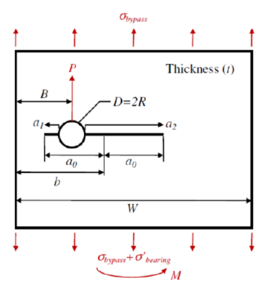
Canada 7

Simultaneous Crack Growth

CanGROW's Core β-Solution

- Offset hole in a finite plate
- Crack(s):
  - Radial (single crack)
  - Diametrical (double cracks)
- Loads:
  - Bypass remote stress
  - Bearing stress (fastener loads)
- Assumptions:
  - Mode I only
  - Uniform bypass stress
  - Empty hole

Crack Size Definition:



Reference: Bombardier, Y., Liao, M. (2010) *A New Stress Intensity Factor Solution for Cracks at an Offset Loaded Fastener Hole*, 51[th] AIAA SDM Conference Proceedings, Orlando, April 12-15 2010.

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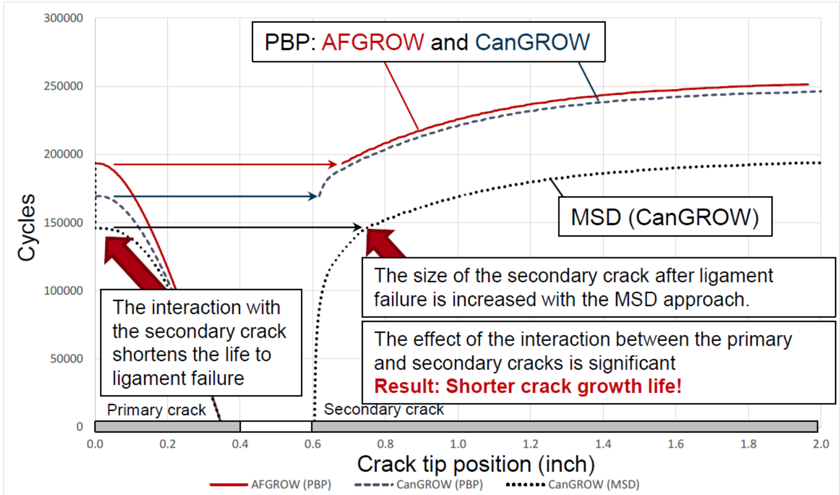
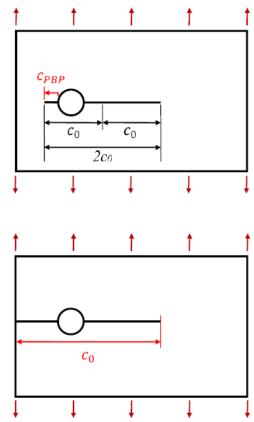
Simultaneous Crack Growth

Crack Growth Results – Crack Tip Positions vs. Cycles

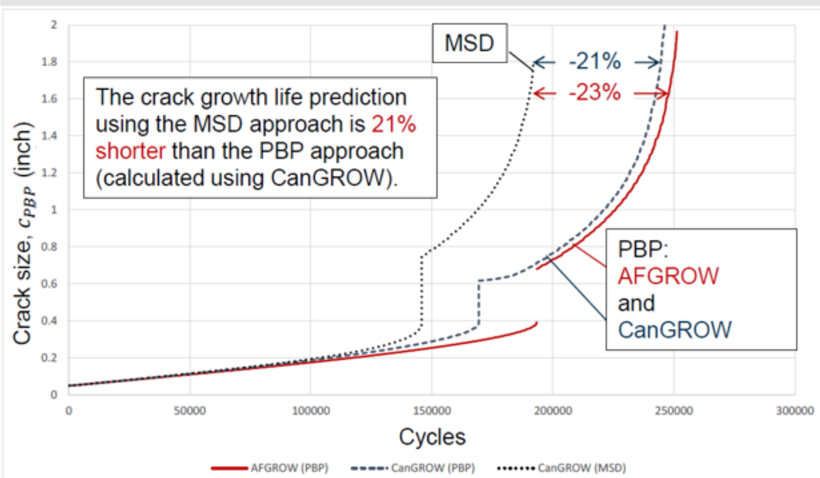




Canada 23

Simultaneous Crack Growth

Crack Growth Results – Lead Crack



Approach	Life (cycles)
PBP/AFGROW	251,279
PBP/CanGROW	246,357
MSD/CanGROW	193,797

Approach	Cont. Crack
PBP/AFGROW	0.681"
PBP/CanGROW	0.618"
MSD/CanGROW	0.746"

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WG member observation and comments on findings presented in [11]:

NOTE: Assuming an overall reduction in time to critical crack length of 20% to 24%, the following figures show theoretical threshold and recurring inspection limits for different detectable crack sizes and the variation of crack interaction is considered in setting inspection intervals for the following:

- Threshold and recurring without explicit consideration of crack interaction (CI)
- Threshold without crack explicit interaction, recurring with explicit interaction
- Threshold and recurring with explicit crack interaction

The following examples are intended to illustrate that accounting for crack interaction in establishing inspection thresholds is typically of minimal value as was stated in the 2018 TAMCSWG Report [14] in Section 3.5, Inspection Thresholds, “There is little safety benefit in performing an inspection to detect fatigue cracking earlier than it could reasonably be expected that a detectable defect has developed.” Yet, as cracking and fatigue are both progressive, recurring interval may be significantly reduced by the consideration of crack interaction.

Inspection highlighted in YELLOW are threshold inspection below the targeted detectable crack length, while those in RED indicate crack length beyond residual strength capability.

Inspection (0.15)	No Crack Int.	No CI/Rec. CI	CI/CI
Threshold	123,000 cycles	123,000 cycles	97,000 cycles
2nd Inspection	216,500 cycles	190,500 cycles	164,500 cycles
3rd Inspection		258,000 cycles	232,000 cycles

- NDI Inspection (0.15" detectable)
- Detectable at 59,0000 No CI and CI)
- Recurring/Threshold = 0.76, 0.55, 0.70
- Beyond 194,000 crack growth prediction for CI Crack Growth

Inspection (0.20)	No Crack Int.	No CI/Rec. CI	CI/CI
Threshold	123,000 cycles	123,000 cycles	97,000 cycles
2nd Inspection	191,500 cycles	168,500 cycles	142,500 cycles
3rd Inspection	260,000 cycles	214,000 cycles	188,000 cycles

- NDI Inspection (0.20" detectable)
- Detectable at 109,000 No CI and 103,000 CI)
- Recurring/Threshold = 0.56, 0.37, 0.46
- Beyond 194,000 crack growth prediction for Simultaneous Crack Growth

Inspection (0.6)*	No Crack Int.	No CI/Rec. CI	CI/CI
Threshold	123,000 cycles	123,000 cycles	97,000 cycles
2nd Inspection	160,700 cycles	146,500 cycles	120,500 cycles
3rd Inspection	198,400 cycles	170,000 cycles	144,000 cycles
4th Inspection		193,500 cycles	167,500 cycles
5th Inspection			191,000 cycles

- *Detectable– Failed Ligament (0.60)
- Detectable at 170,600 No CI and 147,000 CI)
- Recurring/Threshold = 0.31, 0.19, 0.24
- Beyond 194,000 crack growth prediction for CI Crack Growth

Appendix E Voting Summary

		AC 25.571-1X revision options									
WG Voting Members	3: No rule change	4.6.1.1: Add statement to "extent of damage"	4.6.1.2: Add a refer to 91-82A for crack interaction	4.6.2.1: Add definition to Appendix 1	4.6.2.2: Add examples to supplement definition	4.6.3: Distinguish WFD vs Unique Design Feat for CI	4.6.4: Use fatigue reliability to establish when	4.6.5.1: MoC – Four broad categories[1]	4.6.6.1: Add a new section for inspection intervals	4.6.6.2: refer to 91-82A for inspection intervals	4.6.7: SDO to develop MoC in a separate document
Airbus	Support	Support	No	Support	No	No	No	No	No	No	No
Boeing	Support	Support	No	Support	No	No	No	No	No	No	No
Bombardier	Support	Support	No	Support	No	No	No	No	No	No	No
British Airways	No	Support	Support (prefers 4.6.1.1)	Support	Support	Support (proposed alternative language)	Support	Support	Support	Support	Support
Dassault	Support	Support	No	Support	No	No	No	No	No	No	No
Delta Air Lines	Support	Support	Support	Support	Support	Support	Support	Support	Support	Support	Possible
Embraer	Support	Support	No	Support	No	No	No	No	No	No	No
FedEx	No	Support	Support	Support	Support	Support	Support	Support	Support	Support	Possible
Gulfstream	Support	Support	Support	Support	No	Support	Support	No	No	Support	No
Mitsubishi	Support	Support	Support	Support	No	Support	No	No	No	Support	No
Textron	Support	Support	Support	Support	No	Support	Support	No	No	Support	Possible
United Airlines	Support	Support	Support	Support	Support	Support	Support	Support	Support	Support	No
FAA	Abstain	Support	No – prefer 4.6.1.1	Support	Support	Support (with minor change)	Support (with minor change)	Support (with minor change)	Support	Support	Possible
WG NAA Participants											
CAA	No	Support	Support, prefer 4.6.1.1	Support	Support	Support	Support	Support	Support	Support	Possible
ANAC	No	Support	No	Support	Support	Support	Support	Support	Support	No	Possible
Transport Canada	Support	Support	Support	Support	Support (with clarification)	Support	Support	Support	Support	No	Possible
EASA	No	Support	Support, with some clarification – prefers 4.6.1.1	Support	Support (with clarification)	Support (note that EASA uses term "Design Detail Point")	Support	Support	Support	Support	Possible

[1] Voting members of WG positions for 4.6.5.2 are identical to 4.6.5.1

Appendix F Boeing Summary of Crack Interaction Consideration for DTE (Supplemental Discussion to Section 4.5)

Boeing's approach to considering crack interaction for local fatigue crack damage is discussed in Ulf Goranson's *Damage Tolerance Facts and Fiction* (1993) (later republished in [18]). Although this paper was written prior to § 25.571 Amdt 132, most of the concepts discussed are still used today – including the concept of MSD or multiple site damage.

Figure 11 from Ulf Goranson's paper (see below) is used to describe an assumed dependency of secondary crack sizes on the lead crack size for DTE analysis. Here, both the lead and secondary cracks are referred to as "Multiple Site Damage" (MSD). It can be inferred that the use of the term MSD in this paper is meant to refer to the simultaneous presence of cracks at the same detail or adjacent details common to the same structural element, which is consistent with AC 120-104 definition, and in adjacent structural elements. This dependent relationship can be useful for setting initial crack sizes in a complex cracking scenario. The progression of this scenario is then handled by SIF solutions or analytical assumptions that are designed with the interaction of these cracks in mind. The interaction accounts for the existence of cracks on the opposite side of a hole in the same structural element, proximity of adjacent tips in the same structural element and how effectively load can be redistributed to adjacent structural members that also contain secondary cracks. The progression of this scenario ends when the structure can no longer sustain residual strength loads and that is typically associated with a critical lead crack length. The residual strength analysis of the structure also considers the presence of these secondary cracks in addition to the lead crack. The generic structural detail shown is meant to refer to localized fatigue damage in fatigue critical structure. Some aspects of this dependency have been applied to analysis in WFD susceptible structure.

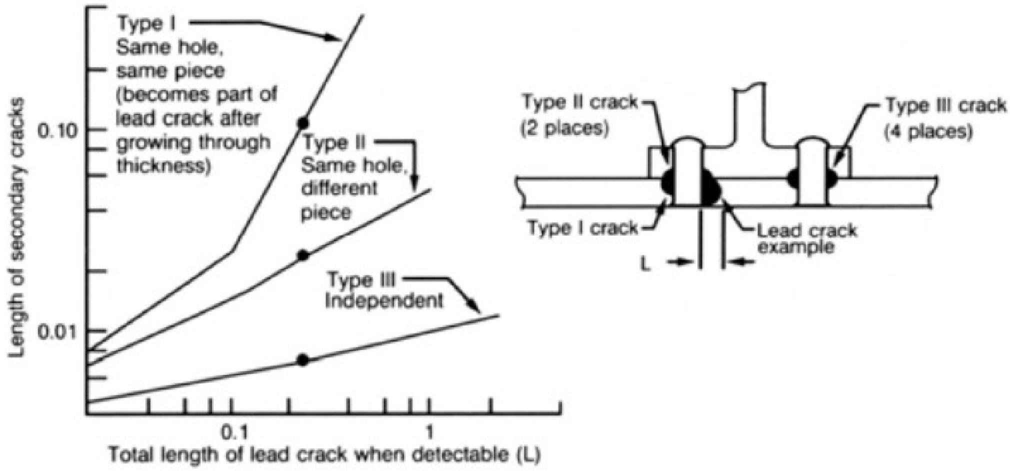


Figure 11. Multiple Site Damage (MSD) Size Analysis Guidelines

Advisory Circular 120-104 provides a similar definition (below), but one that focuses on the similar details common to the same structural element where WFD is a concern.

Multiple site damage (MSD)—A source of widespread fatigue damage characterized by the simultaneous presence of fatigue cracks in the same structural elements.

Boeing has used the term MSD when discussing both DTE (local) and WFD (global) analyses and acknowledges that most OEM's may not use the term MSD in context with DTE (local) analysis.

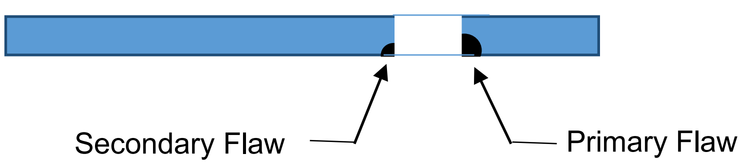
Appendix G Crack Interaction Examples (Supplemental Discussion to Section 4.6.2.2)

This appendix documents the examples of cracking scenarios warranting interaction considerations that were used in WG discussions and is related to proposal 4.6.2.2 (referenced section and Appendix E identifies those members supporting incorporation of these notional illustrations into guidance). Note, these examples are not comprehensive. This appendix also does not describe how an applicant should demonstrate the cracking configuration has been considered. These are examples of cracking configurations which industry has observed in certain structural details from both test and service experiences. Also, this appendix does not specify that all of these scenarios are equally critical for interaction effects. This is highly dependent on too many variables to be captured here, including (but not limited to): relative crack sizes, material properties, remote stresses, local stress state, other geometric qualities (hole diameter, spacing, etc.), and manufacturing quality.

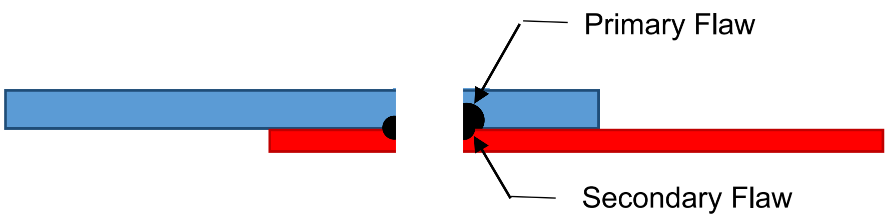
These two sets of examples were presented and discussed amongst the WG members throughout the tasking. The first set of examples, labeled (a) are primarily only illustrations. The second set of examples, labeled (b), show illustrations but also include brief statement of the type of interaction effect likely needing consideration for that detail.

Example Set (a)

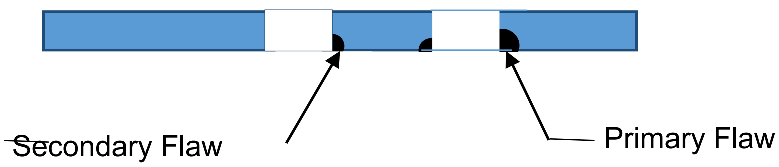
- Primary and Secondary flaws in one element at a single hole



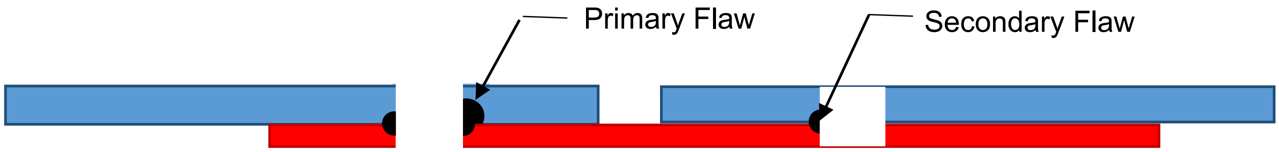
- Primary and Secondary flaw in adjacent elements at a single hole

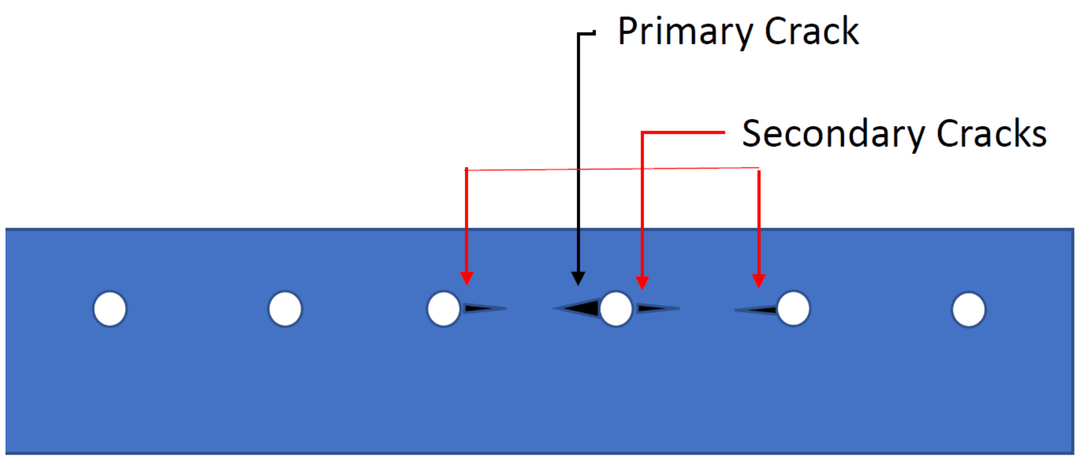


- Primary and Secondary flaw in one element at adjacent holes growing toward each other.

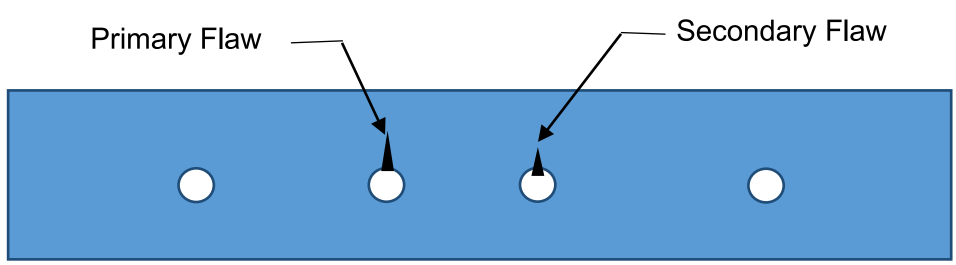


- Primary and Secondary flaw in 2 elements of an assembly growing toward each other.





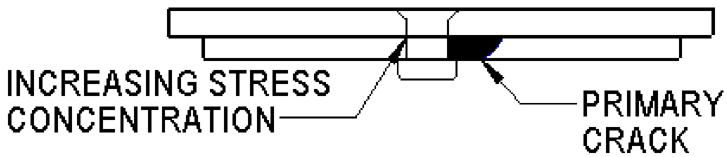
- Primary and Secondary cracks in one element at adjacent holes growing parallel



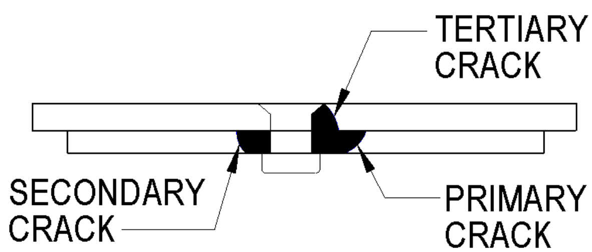
Example Set (b)

Crack interaction should always be considered. However, the use of crack interaction when establishing inspection intervals may or may not be necessary. Examples of when crack interaction may be necessary in an analysis include the following but are not limited by these examples.

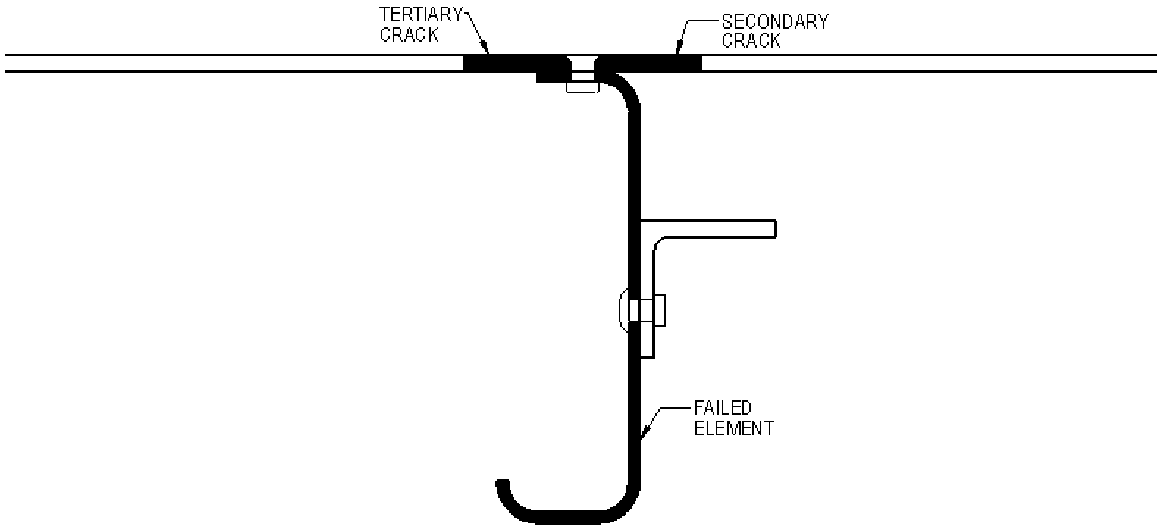
1. As a large primary crack on one side of a hole grows the stress concentration on the opposite side of the hole increases causing increased probability of a secondary crack initiation on the opposite side of the hole.



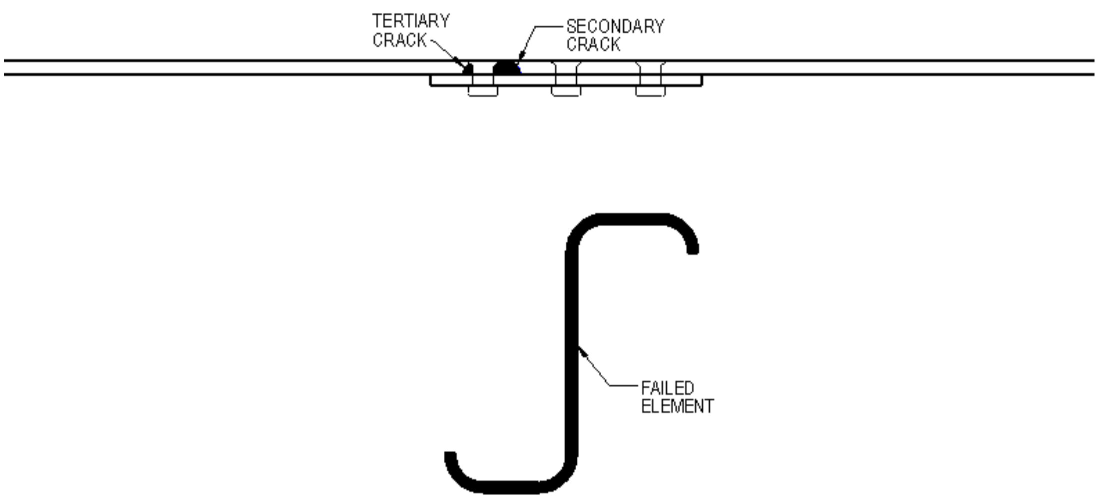
2. As primary and secondary cracks grow in one layer of a multi load path (MLP) structure the operating stresses in an attaching layer increase causing increased probability of crack initiation and accelerated crack growth in that attached layer. These types of interactions are usually weak and it is unlikely these cracks will interact to significantly alter the crack propagation rate until they become large or an element fails.



3. Failure of a hidden element of an MLP structure can cause the operating stresses to increase in the remaining elements causing increased probability of crack initiation and accelerated crack growth in the remaining elements. This may include elements which are directly attached, such as shown in view (a), or elements which are not directly attached, yet provide a common load path nonetheless, such as “floating” frames (frames which are not directly fastened to the fuselage skin via shear ties) shown in view (b).


TERTIARY
CRACK
SECONDARY
CRACK
FAILED
ELEMENT

(a)


TERTIARY
CRACK
SECONDARY
CRACK
FAILED
ELEMENT

(b)

Appendix H Supplemental Discussion to Section 4.6.5.2

This appendix contains content related to the potential proposal described in Section 4.6.5.2 (i.e., a method of compliance example), which did not receive enough member support to be proposed as a change to AC 25.571-1D to FAA. Rationale provided by members who supported and by those who opposed this recommendation are provided in the main report. The inclusion of this material in this appendix is not intended to convey endorsement by the WG. Rather, it is to document the proposal considered and ultimately opposed by majority of WG.

Analytical methods to establish repeat inspection intervals

The assumption of cracking scenarios is one of the key elements to maintain integrity of structure when setting up for any damage-tolerance based inspection calculation. A cracking scenario that is not representative can invalidate any analysis results.

The WG recognizes the physics of multiple cracks in proximity, either in the same metallic element or attaching elements, results in an increase in damage-growth (crack propagation) rate and a reduction of critical primary crack size relative to a scenario for same structural detail(s) with only a single crack. Such increase in damage-growth rate and/or smaller critical crack size has the expected effect of smaller period of detectable life of the largest flaw (as demonstrated in Appendix D). When compared to a more representative cracking scenario, damage tolerance analyses that do not consider the effect of multiple cracks in proximity when there is a potential for their simultaneous existence may lead to an unconservative inspection program for the PSE being evaluated.

FAA AC 91-82A, Parag. 10.b.(1) states that an applicant's damage tolerance evaluation "should *consider* the actual sites, cracking scenarios, and crack propagation … and at some point, should include crack interaction." (italics added for emphasis). The WG members recognize that the term "consider" provides applicants with flexibility in the method by which the effect is addressed as part of their analysis. Sub paragraph (b) of the same paragraph in the AC warns applicants that oversimplification in an analysis may result in an ineffective inspection program if the solutions (and presumably associated assumptions) are not representative. However, it is also recognized that a simplified evaluation may be acceptable provided it is conservative, with qualification that all simplifying assumptions be explained and justified.

The WG members all agree with the basic premise that the presence of multiple cracks within a single element or within adjacent/attached elements results in an increase in damage-growth rate and/or reduction of critical crack size(s) relative to a scenario with a single crack, and this effect has been witnessed both in test and service experience. The WG members also recognize there are many different ways in which this effect may be considered within a damage tolerance analysis. The WG members do not believe that any single method is superior to another method with respect to achieving safety objectives, provided the methods are demonstrated to be validated as reliable and/or conservative.

It is understood there is a spectrum of complexity for engineering approaches employed by applicants (with agreement by regulators) to address similar damage scenarios when establishing the structural maintenance programs (including inspections or other procedures). As deemed acceptable in the AC, it is expected that the equalizer between solutions of different complexity will be the degree of conservatism and potential validation via specific testing or service experience. On one end of this spectrum of engineering approach complexity may be a particular structural detail which is uniquely modeled using a finite element model to determine local SIF, strain energy release rate, etc. under a complex fatigue spectrum in the presence of many adjacent cracks of various sizes based on testing or in-service findings. Such complex modeling may be validated through strain gages on a test article and crack growth rates validated through marker bands added as part of a fatigue test spectrum while loads are verified through measurements obtained from flight test and potential residual strength tests with the specific cracking array. On the other end of the spectrum an analysis may use superposition of published SIF solutions which are representative of similar structural details where additional conservative assumptions relative to the actual expected operation are added on top of the basic solution. The latter approach is expected to result in more frequent inspections relative to the more complex and specifically studied scenario. This is the typical benefit of investment in extensive testing and analytical complexity when safety objectives are similarly achieved. One objective of using a simplified analytical approach is to ensure that assumptions used are indeed sufficiently conservative.

There is no single recommended means of remediating accomplishment of the most complex analysis approach because there are degrees of freedom available to applicants to address similar damage scenarios. The WG has looked at some of the potential factors an applicant may employ as a means to mitigate the complexity of their analyses which incorporates consideration of crack interaction effects. Note, this is not comprehensive, but is based on good faith effort by WG members to identify expected common factors based on experience of these members. Furthermore, the end result of the evaluation can still result in un-conservatism if particular assumptions are unconservative or unrealistic. In other words, the end result of the analysis will be sensitive, to varying degrees, to the combination of all assumptions, so applying conservatism in one assumption may not yield the desired effect if other assumptions are unrealistic or unconservative.

Potential Conservative Assumptions for Simplified Analysis Methods

There are four major parameters to consider when establishing the extent of damage as part of the calculation of an inspection interval. These are the detectability with the inspection techniques to be used, the associated initially detectable crack size, the residual-strength capabilities of the structure, and the likely damage-extension rate. All of these parameters could be affected by oversimplification of the analysis method except for the detectability.

A simplified analysis that does not explicitly account for crack interaction may result in the following:

- A detectable crack length that is larger relative to the secondary cracking. This could be unconservative if the inspection area is obscured or the effects of larger secondary cracks result in a primary critical crack length that is smaller than is detectable.
- Damage-extension rates that are slower resulting in longer inspection intervals. This could be unconservative and result in an inspection interval that will not find a crack prior to reaching a size that exceeds the residual-strength capabilities of the structure.

To capture the deleterious effects of potential crack interaction and to avoid extensive complexity in the analysis, applicants may need to include one or more of the following assumptions or factors in the damage tolerance analysis:

1. **Conservative initial flaw size distributions**. The use of conservative initial secondary crack sizes can compensate for large relative primary crack lengths and shorten the detectable period. Large initial flaw sizes that include large linked up cracks may not be affected by multiple initiation sites contained within the large crack.
2. **Conservative patching assumptions**. Patching is a process to describe how adjacent smaller cracks link-up to create a single larger crack. Patching assumptions that assume larger damage as the lead crack reaches a certain length or criteria may compensate for slower damage extension rates by shortening the time between detectable and critical crack lengths.
3. **A lower typical operating fatigue stresses** (versus industry typical for the same aircraft life) or a **conservatively assessed Limit of Validity (LOV)**. Test evidence and/or service experience may indicate that fatigue cracking influenced by crack interaction maybe unlikely to occur during the operational life of an aircraft with these factors applied.
4. **A conservative load or stress spectrum.** Conservative factors applied in a load spectrum utilized in crack growth may compensate for slower damage extension rates by causing more damage accumulation for each flight cycle than a more representative spectrum.
5. **Higher-fidelity Non-Destructive Inspections (NDI)**; or *assuming* larger detectable crack length (i.e., lower detection capability) for a given inspection method or a higher POD for the detectable crack length. Larger than industry “typical” detectable crack lengths may compensate for slower damage extension rates by lowering the difference between detectable and critical crack lengths.
6. **Conservative critical crack length** (in the context of residual strength capabilities). Using higher residual strength factors or not taking credit for multiple load path construction will shorten the critical crack length and

may compensate for slower damage extension rates by lowering the difference between detectable and critical crack lengths.

7. **Not claiming all the applicable "credits" in the fatigue crack growth assessment.** Slower damage extension rates may be compensated for by limiting or excluding the effects of crack retardation, beneficial residual stresses, fastener hole filling, effects of multiple load paths, etc.
8. **Higher than industry "typical" probabilities of detection**. Slower damage extension rates may be compensated for by the utilization of greater factors (shorter inspection interval and/or higher POD) applied to the length of time for the crack to grow from the detectable crack size to the critical crack size when calculating an inspection interval.
9. **Conservative material property values** (in public domain) vs. more refined proprietary (and company-specific) data sets. Slower damage extension rates may be compensated for by the utilization of more conservative plain stress fracture toughness values and lower ultimate allowables which result in shorter critical crack lengths or the direct use of conservative (faster) crack growth rates.
10. **Conservatism associated with the implementation of a company's full scale fatigue testing with follow-up evaluation** (e.g., from initial setup to residual strength determination, including teardown). Test evidence from a conservatively implemented full scale fatigue test (e.g., more than three lifetimes factor, conservative residual strength requirements, extensive tear down procedures, etc.) may indicate that fatigue cracking influenced by crack interaction is un-likely to occur during the operational life of an aircraft.

Acronyms

AAWG	Airworthiness Assurance Working Group
AC	Advisory Circular
AD	Accidental Damage
AD	Airworthiness Directive
AMC	Acceptable Means of Compliance
ANAC	Brazilian National Civil Aviation Agency
ARAC	Aviation Rulemaking Advisory Committee
CFR	Code of Federal Regulations
CI	Crack Interaction
CRI	Certification Review Items
CS	Certification Specifications
DAH	Design Approval Holders
DSG	Design Service Goal
DT	Damage Tolerance
DTE	Damage Tolerance Evaluation
IP	Issue Paper
ISP	Inspection Start Point
EASA	European Aviation Safety Agency
ED	Environmental Damage
FCS	Fatigue Critical Structure
FMP	Fatigue Management Program
FAA	Federal Aviation Administration
FEM	Finite Element Model
FSFT	Full-scale fatigue test
GSHWG	General Structures Harmonization Working Group
IP	Issue Paper(s)
LEFM	Linear Elastic Fracture Mechanics
LOV	Limit of Validity
MED	Multiple Element Damage
MLP	Multiple Load Path
MOC	Means of Compliance

MSD	Multiple Site Damage
NAA	National Aviation Authorities
OEM	Original Equipment Manufacturer
POD	Probability of Detection
PS	Policy Statement
PSE	Principal Structural Element
SDO	Standards Development Organization
SDR	Service Difficulty Report
SIF	Stress Intensity Factor
SLP	Single Load Path
SMP	Structural Modification Point
SSD	Significant Standards Differences
TAE	Transport Aircraft and Engine
TAMCSWG	Transport Airplane Metallic and Composite Structures Working Group
TCCA	Transport Canada Civil Aviation
UK CAA	United Kingdom Civil Aviation Authority
USAF	United States Air Force
WFD	Widespread Fatigue Damage
WG	Working Group

Revision Record

Release/Revision	**NEW**
Contract Number (if required)	
Limitations	
Description of Change	
Authorization for Release	

AUTHOR:

Name

Organization Number | Date

APPROVER:

Name

Organization Number | Date

DOCUMENT RELEASE:

Name

Organization Number | Date