Suggested Cracking Scenarios and Stages to Establish N_{th}, N_{rep} and N_{WFD}

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Cracking Scenarios for N_{th}, N_{rep} and N_{WFD}

- This presentation provides an acceptable means for establishing inspection threshold, repeat intervals for damage tolerance evaluations (DTE) and widespread fatigue damage (WFD) assessment-based inspections.
- Assumption of cracking scenario is the key step toward performing a proper damage tolerance evaluation and widespread fatigue damage assessment.
  - Incorrect cracking scenario invalidates the analysis results and yields an ineffective maintenance program, which can jeopardize the safety of the airplane.

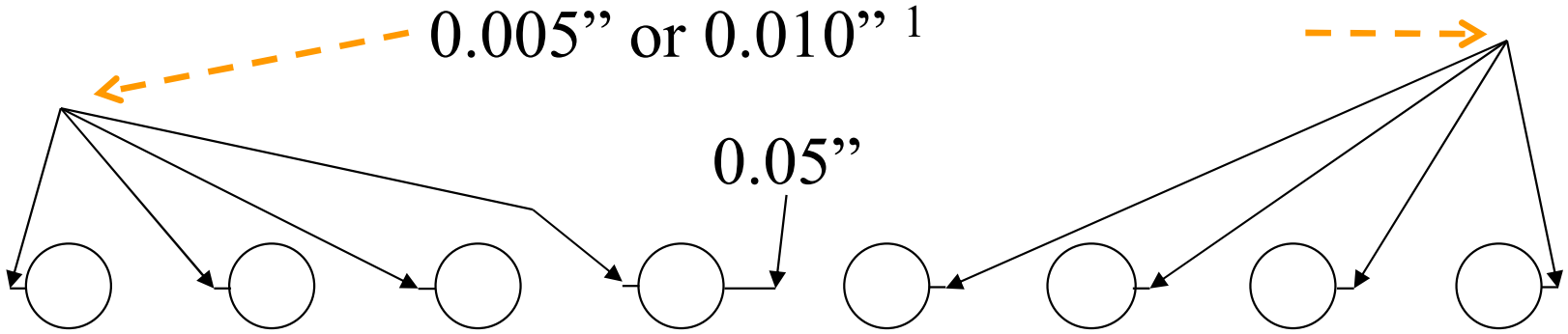
Cracking Scenarios for N_{th}, N_{rep} and N_{WFD}

- DTE is performed to set:
  - Inspection threshold (N_{th}) with an assumed initial flaw
    - Manufacturing flaw- § 25.571 amend. 25-96 & higher
  - Repeat intervals (N_{rep}) with an assumed damage scenario after N_{th}
    - Fatigue crack growth
  - Repeat intervals (N_{WFD}) with an assumed damage scenario after ISP
    - Multiple Site Damage (MSD) and Multiple Element Damage (MED) for Widespread Fatigue Damage assessment

Cracking Scenarios and Stages to Establish N_{th}

Setting Inspection Threshold for a Row of Holes

Initial (Rogue) Flaw Assumptions

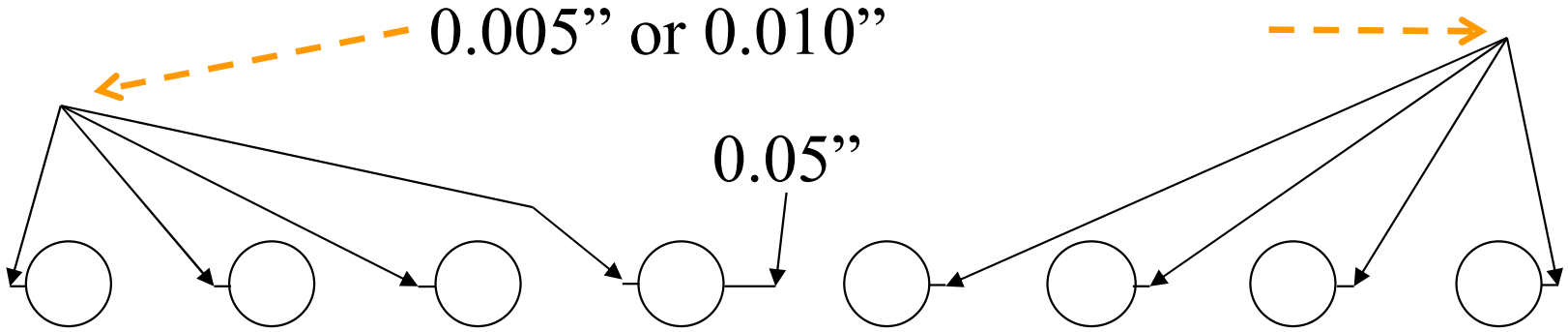


- Perform a crack growth analysis of a single 0.05” crack at a hole in a row of holes to failure, which is considered as a link-up to adjacent hole- *End of Stage 1.*
  - Growth of the 0.05” crack is done without interactions with the 0.01” crack
- Perform a similar crack growth analysis of a single 0.010” crack with the same scenario as above.
- The size of Δa_1 at the end of stage 1 is the growth of 0.010” crack during the cycles that it took the 0.05” crack to grow to the adjacent hole.

<1> USAF Structures Bulleting EN-SB-08-002

Setting Inspection Threshold for a Row of Holes

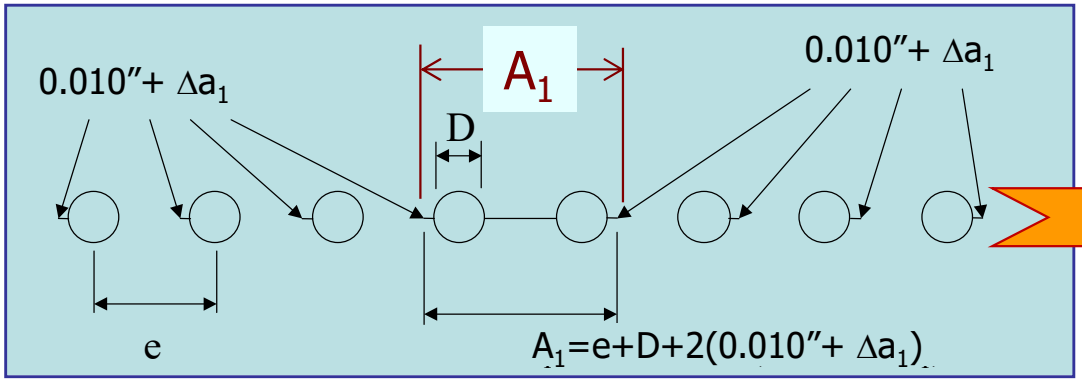
Initial (Rogue) Flaw Assumptions



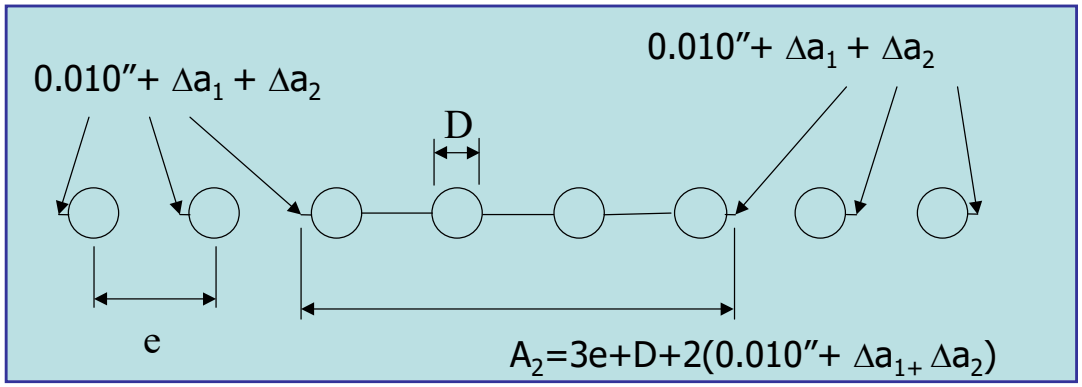
- The linked up holes plus 2*(0.010+Δa_1) grow to the adjacent holes- *End of Stage 2.*
- The Δa_2 is defined similar to Δa_1 as growth of 0.010+ Δa_1 at the end of stage 2.

Setting Inspection Threshold for a Row of Holes

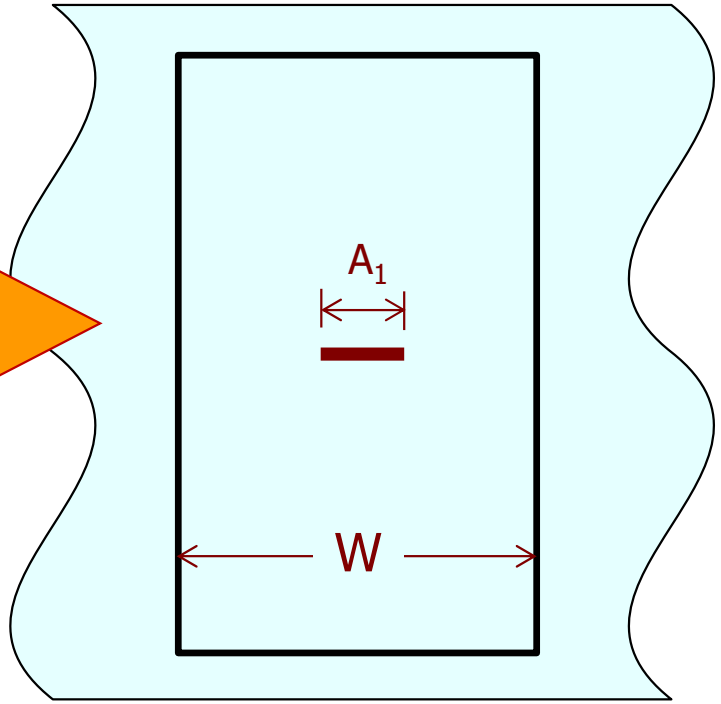
Continuing Damage



End of Stage 1



End of Stage 2



Grow the
$A_1 = 2\times(0.01+\Delta a_1) + e + D$
crack in a center crack panel to the critical crack length (a_{crit}) to obtain N_{cr}

Setting Inspection Threshold for a Row of Holes

Continuing Damage, cont.

- To simplify the analysis, at the end of Stage 1, consider the crack tips have formed a tip-to-tip crack (A_1) that can be considered as a crack in a finite width panel (center crack panel) and run it to the critical length.
  - In a collinear hole scenario, consider the panel width to be equal to 3 stiffener bays.
- The above scenario looks optimistic, however the growth period of this last stage is a small percentage of the total crack growth life and it is not impacted too much by the panel width size.

Rogue Flaw and Continuing Damage for a Built-Up Structure

Issue: Dependent and Independent Structures

Primary element

Remaining structure

1 Initial Flaw on the Primary Element (a_{PE})

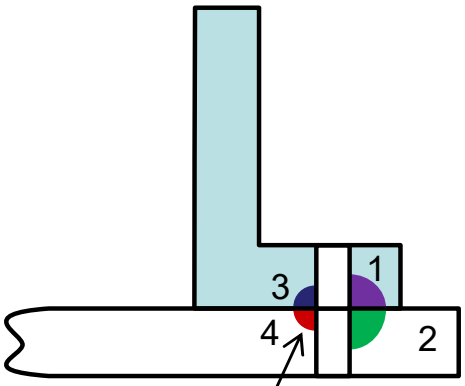
2 Initial Flaw on the Adjacent Element (a_{AE})

3 Continuing damage (a_{CD})

4 Continuing damage (a_{CD})

Dependent Structures

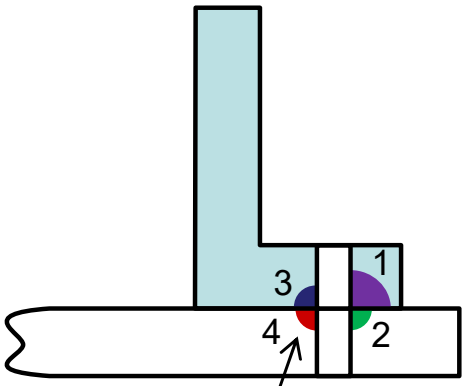
1) a_{PE} = 0.050”
2) a_{AE} = 0.050
3 & 4) a_{CD} = 0.005” or 0.010”



a_{CD} = 0.010” (structures with no crack arrest)
a_{CD} = 0.005” (structures with crack arrest)

Independent Structures

1) a_{PE} = 0.050”
2) a_{AE} = 0.010”
3 & 4) a_{CD} = 0.005”



a_{CD} = 0.005”

These cracks grow <u>simultaneously</u> but <u>without</u> interactions

Rogue Flaw and Continuing Damage for a Built-Up Structure

Issue: Dependent and Independent Structures

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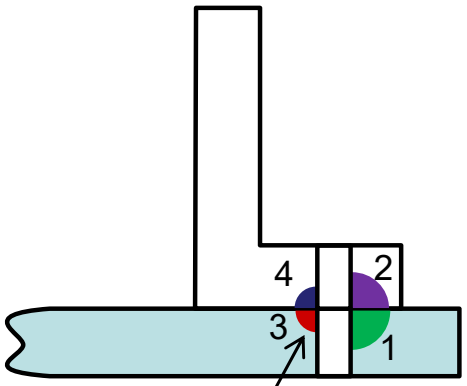

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Independent Structures

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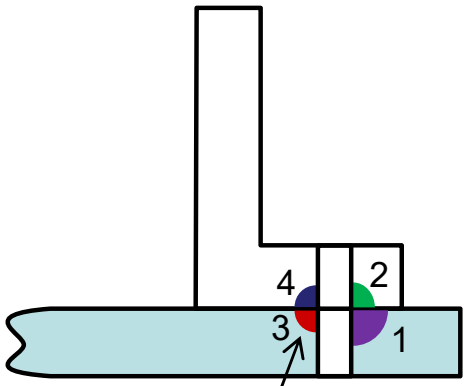
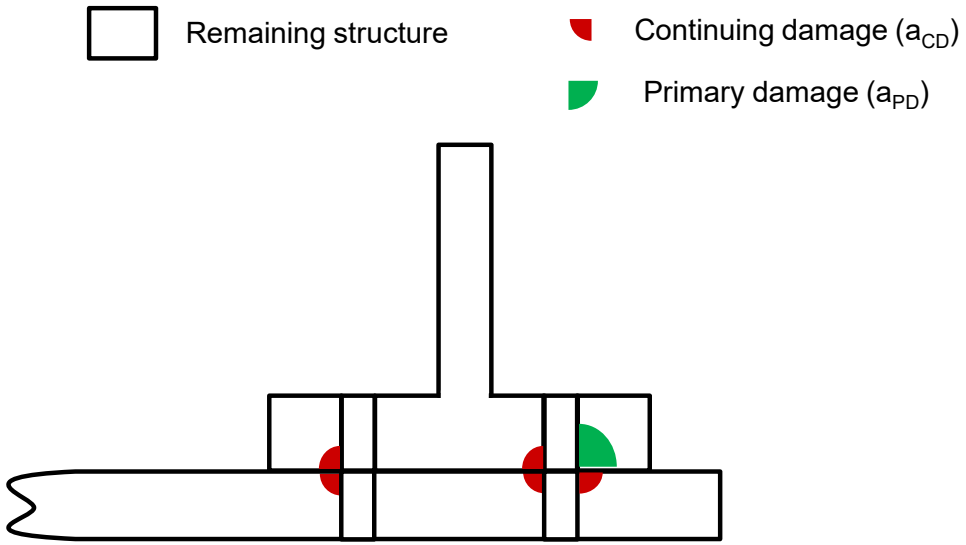


Proposal a_{CD} = 0.005”

These cracks grow <u>simultaneously</u> but <u>without</u> interactions

Rogue Flaw and Continuing Damage for a Built-Up Structure

Issue: Multiple Holes Structure

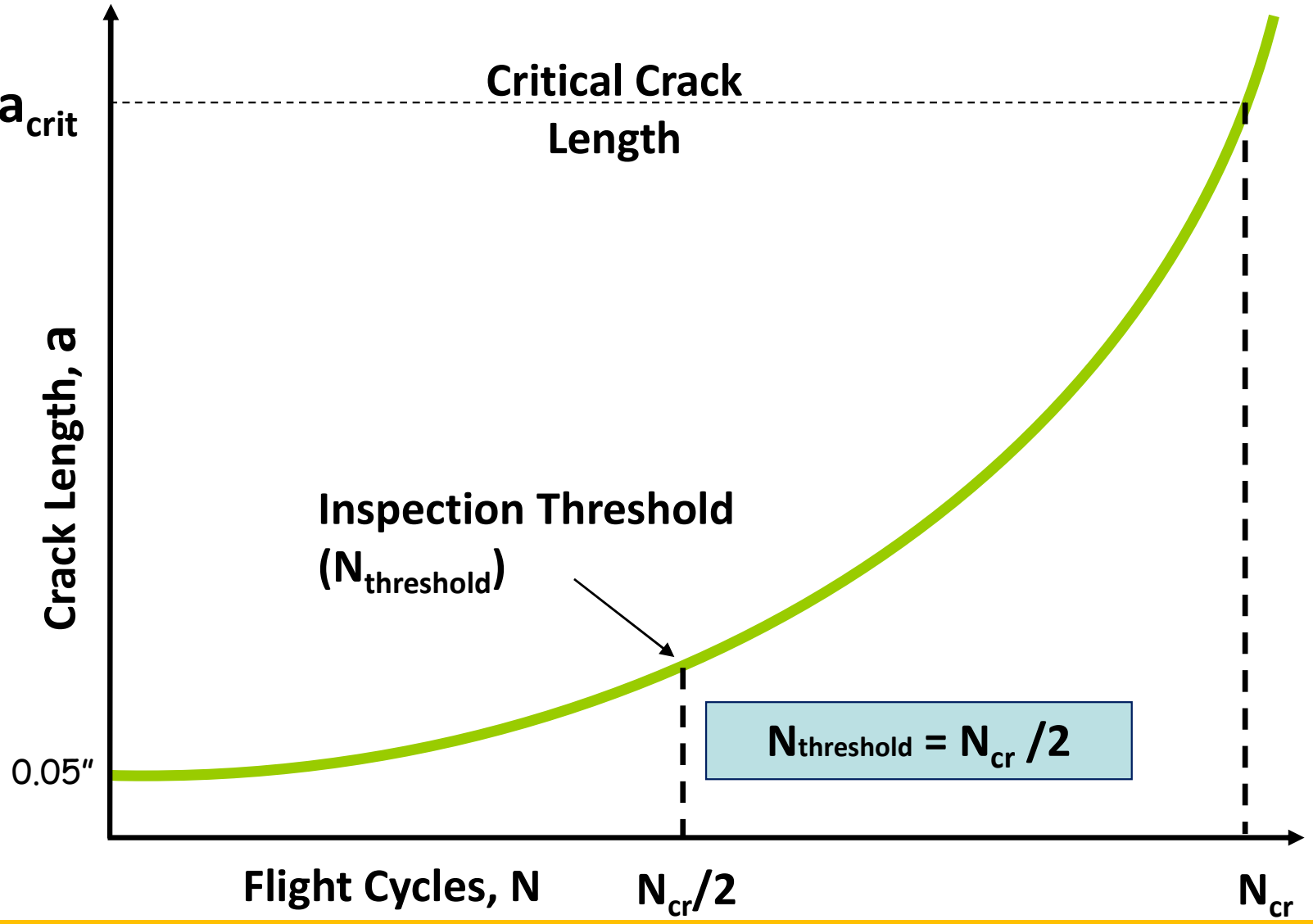


Note that the this figure is not intended to show the cracking scenario of the primary element. The cracking scenario for the primary structure should be consistent with the figure in the previous slide.

These cracks grow <u>simultaneously</u> but <u>without</u> interactions

Setting Inspection Threshold

Determination of inspection threshold ($N_{threshold}$)



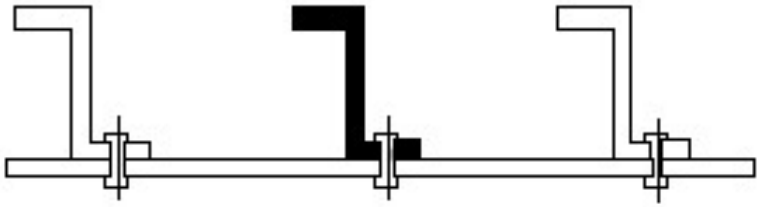
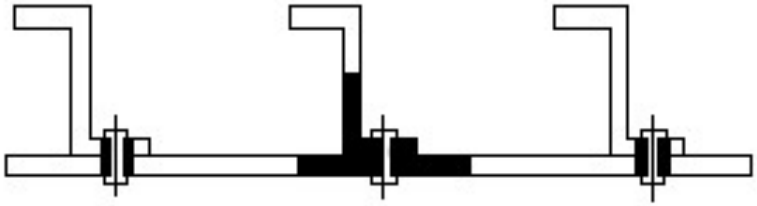
N_{th} = Lesser of ¾ DSG, fraction of unfactored fatigue life, $N_{cr}/2$

Cracking Scenarios and Stages to Establish N_{rep}

Crack Growth Cracking Scenario Establishing Repeat Intervals

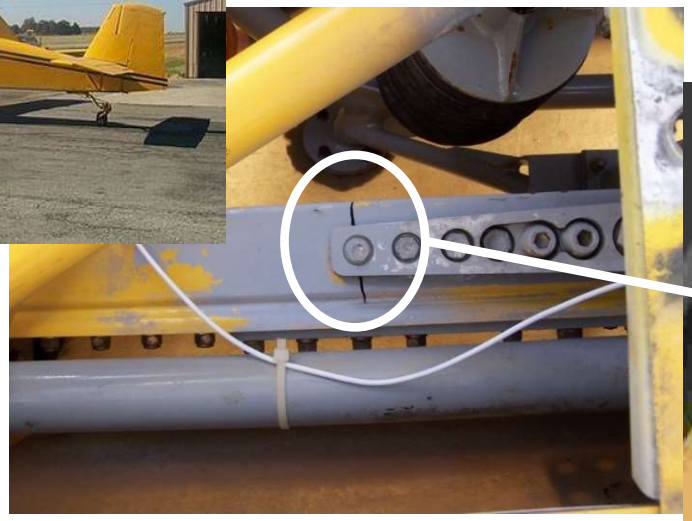
Evolution of Cracking Scenarios

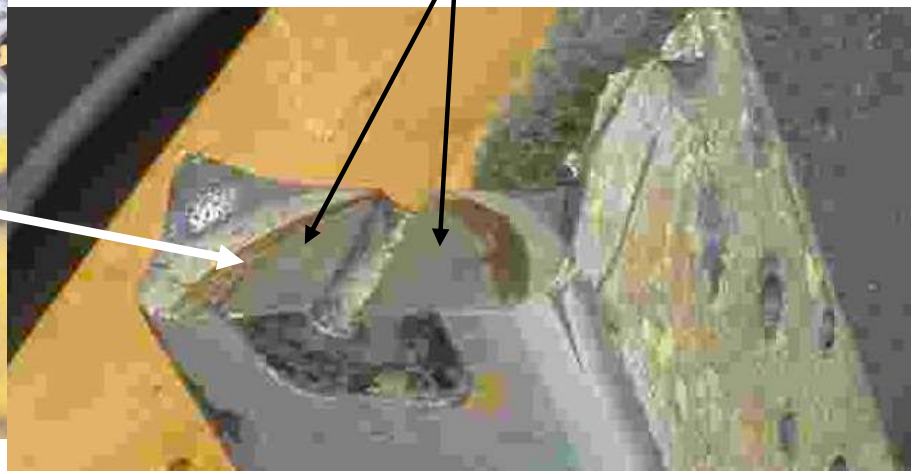
Cracking scenarios have gone through an evolution in the past several decades. This table demonstrates the damage tolerant requirements per § 25.571

Pre 1978- Fail-Safe	**Post 1978- Damage Tolerance**
Residual strength- Net Area	Residual strength- Fracture Mechanics
	
No crack growth required	Extensive crack growth required
No inspection required	Inspection required

Failure of a Spar due to Cracks at a Hole

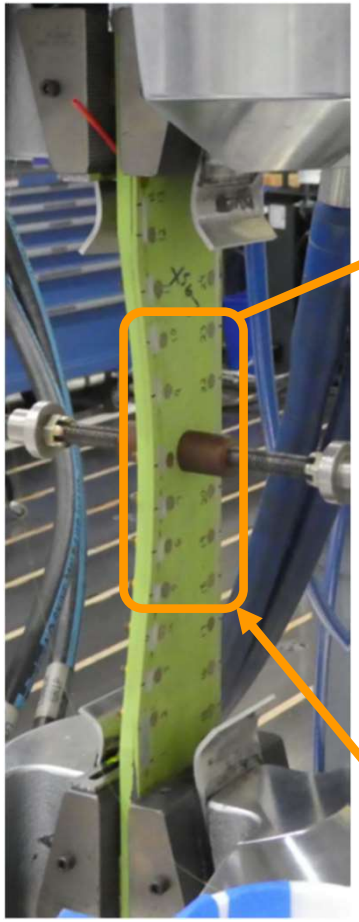
- Thrush Aircraft, Inc. Model 600 S2D/S2R
  - This example and many others indicate that at details such as hole, cracks nucleation and propagation is expected to be around the same time and interaction between the cracks must be accounted in damage tolerance evaluations.
  - This important observation is the result of fractographic evaluations and striation counts of failed members

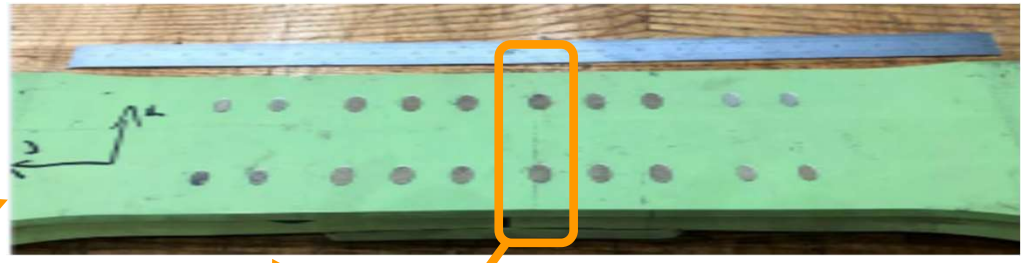


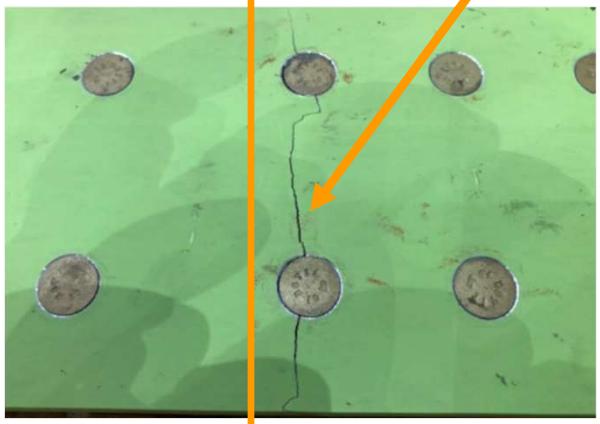


Multiple Cracks in Wing Rear Spar Notch Detail

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





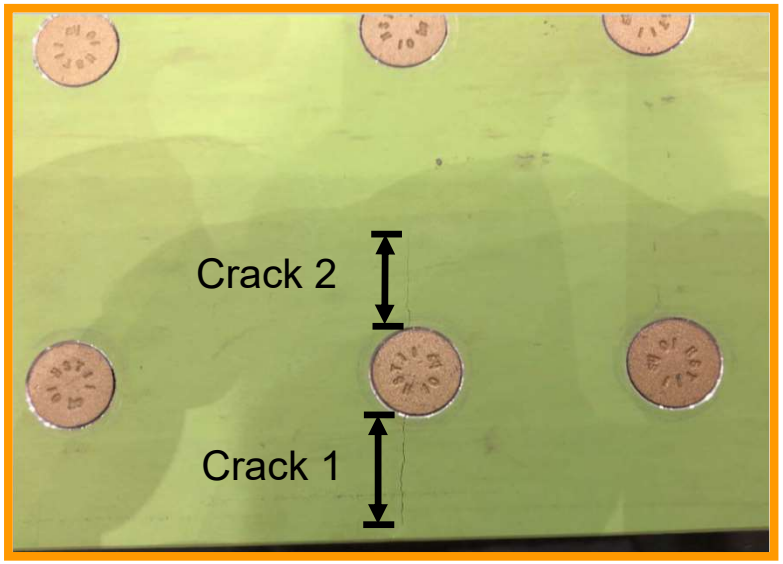


Critical Fasteners

Fracture Face A-A
(Highlighted areas indicate cracks at every detail)

Cracked Center Line Mid Spar Splice

There are 2 cracks at one of the fastener locations in the splice. 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. Crack 1 was not visually detectable 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.



Lessons Learned from 45 Years of History

- Fleet history and fatigue tests indicate that, after a period of usage, likelihood of existence of simultaneous cracks in structural components increases with time. This is called Natural Fatigue[1].
- Excluding simultaneous presence of fatigue cracks in detail design points in a principle structural element for crack growth analysis and ignoring interaction effects may result in an unrealistically long damage tolerance based inspections.
- Not accounting for simultaneous presence of cracks and ignoring the interaction effects has at least two major problems:
  1. Lives calculated by crack growth analysis may be unrealistically high, resulting in longer repeat intervals.
  2. Expected crack length at the time of inspection may be smaller than analysis indicates, which makes visual inspections unreliable.

<1> Normal Fatigue is a nominal condition, an inherent characteristic, expected, inevitable, predictable, where probability increases steadily with time

Lessons Learned from 45 Years of History

A consistent cracking scenario for natural fatigue is presented here[1]:

- In any Principal Structural Element with multiple Detail Design Points, lead crack plus secondary cracks should be considered based on data from test results or fleet history. This is consistent with dame tolerance evaluations principles required by §25.571.
- The following graph provides test-based data for secondary crack sizes associated with a lead crack in a given structural detail

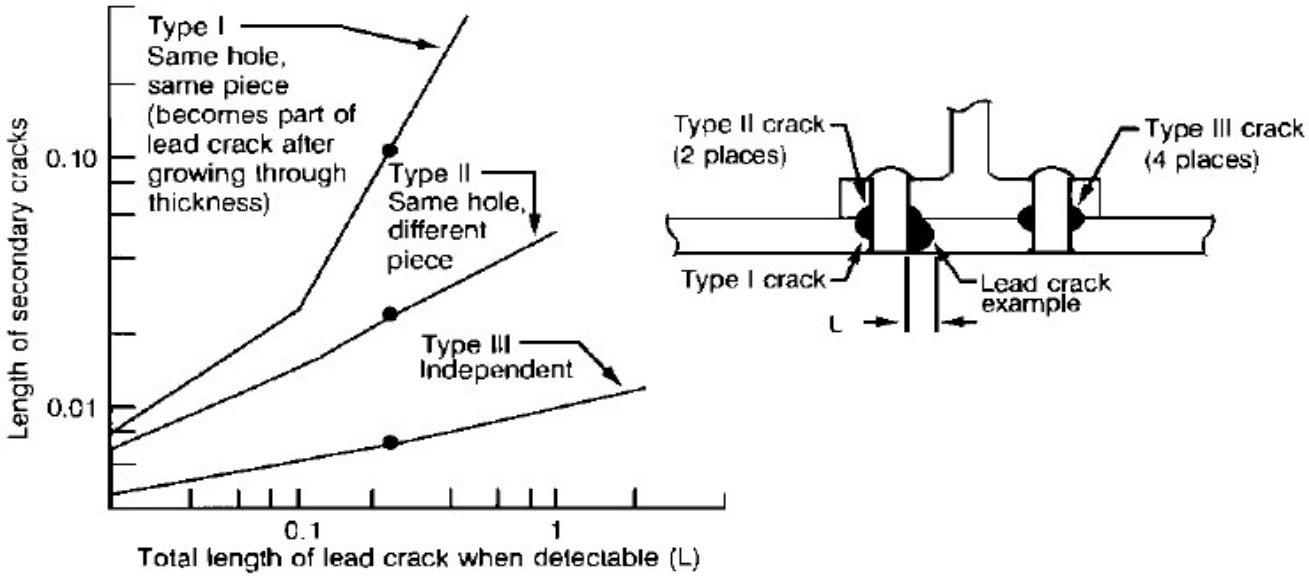
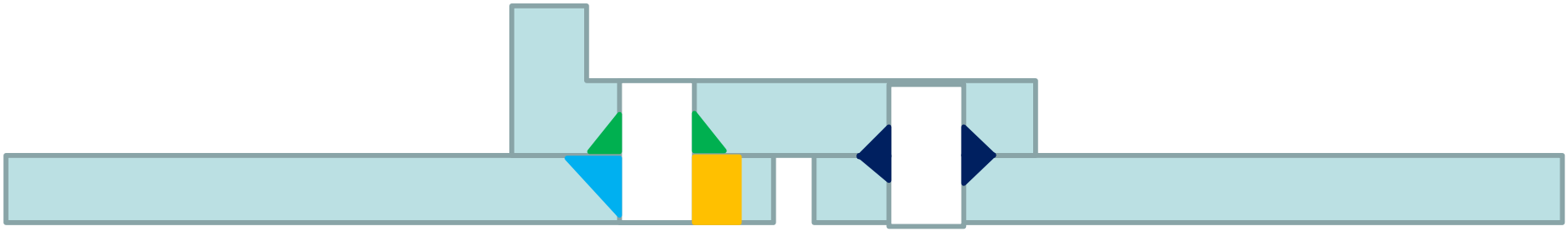


Figure 11. Multiple Site Damage (MSD) size Analysis Guidelines

<1> Ref. Damage Tolerance Facts and Fiction by Dr. Ulf Goranson, Fig 11

Crack Growth Scenario For Local MSD

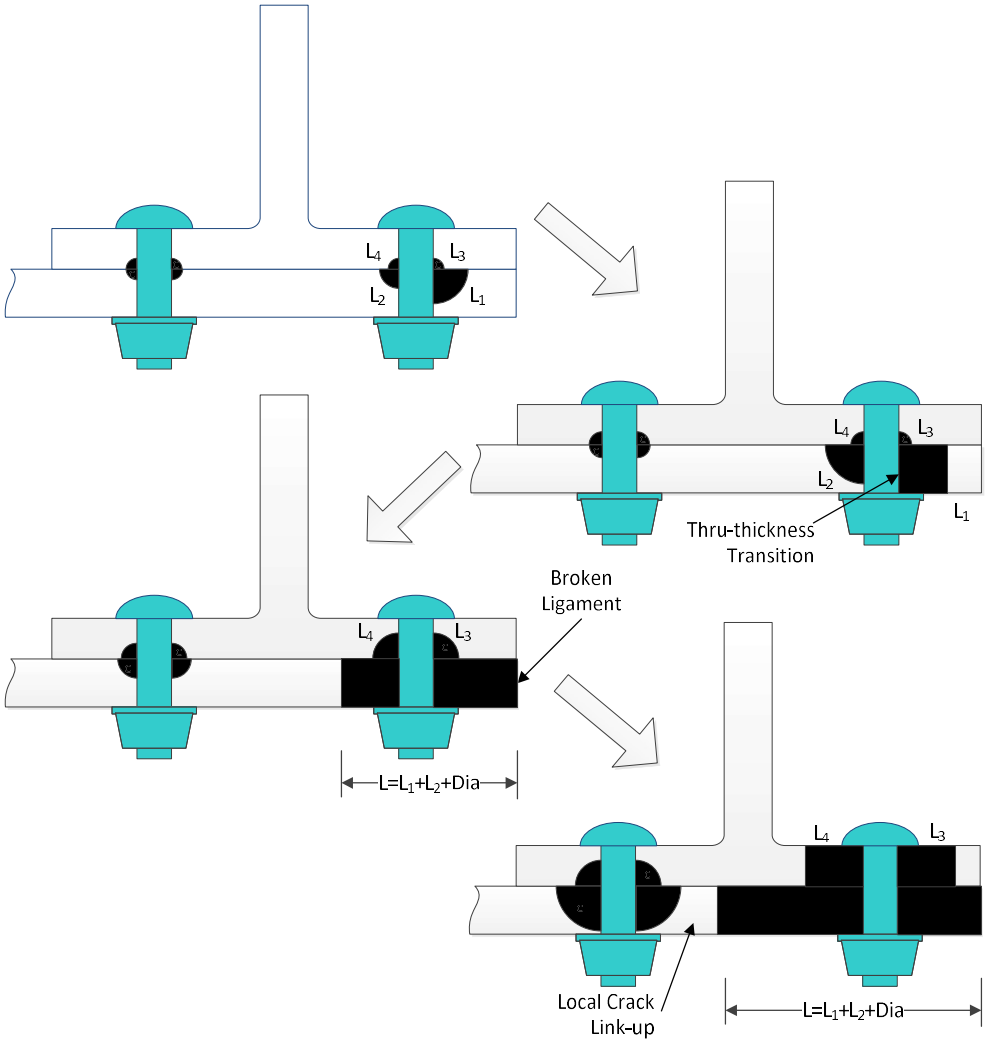
- Based on this graph, the cracking scenario consistent with § 25.571 post-amendment 25-45 for normal fatigue crack growth should be as follows[1]:
  - Assumed Lead Crack: 0.05”
  - Corresponding Secondary Cracks:
    - Same hole/same part (Type I): 0.015”
    - Same hole/different part (Type II): 0.010”
    - Different holes (Type III): 0.005”



  - All cracks should grow with interaction effects

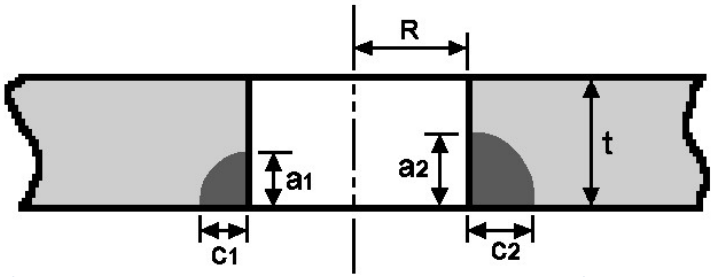
<1> Ref. *Damage Tolerance Facts and Fiction* by Dr. Ulf Goranson

Crack Growth Stages for Local MSD in a Stiffener



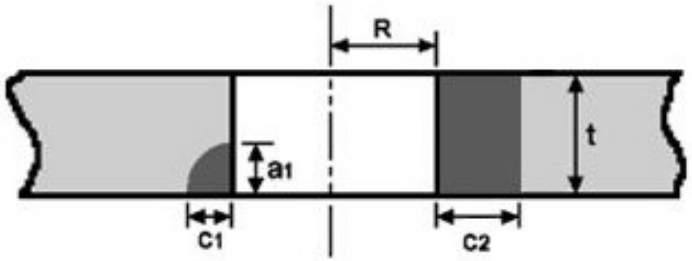
Crack Growth Stages For Local MSD Using Afgrow Software

Stage 1:



Double, Non-Symmetric Corner Cracks at a Straight Shank Hole

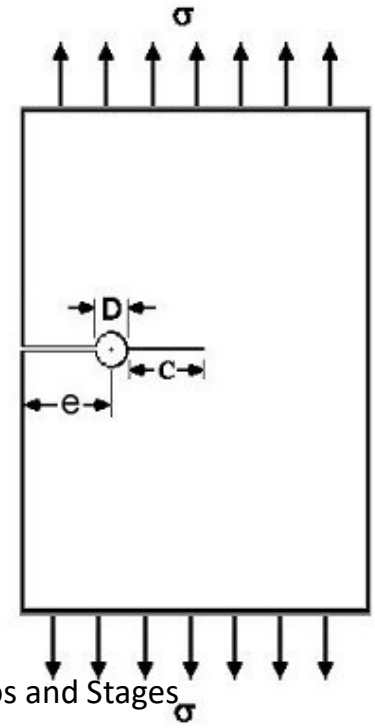
Stage 2:



Combinations of Corner and Straight Through Cracks at a Hole

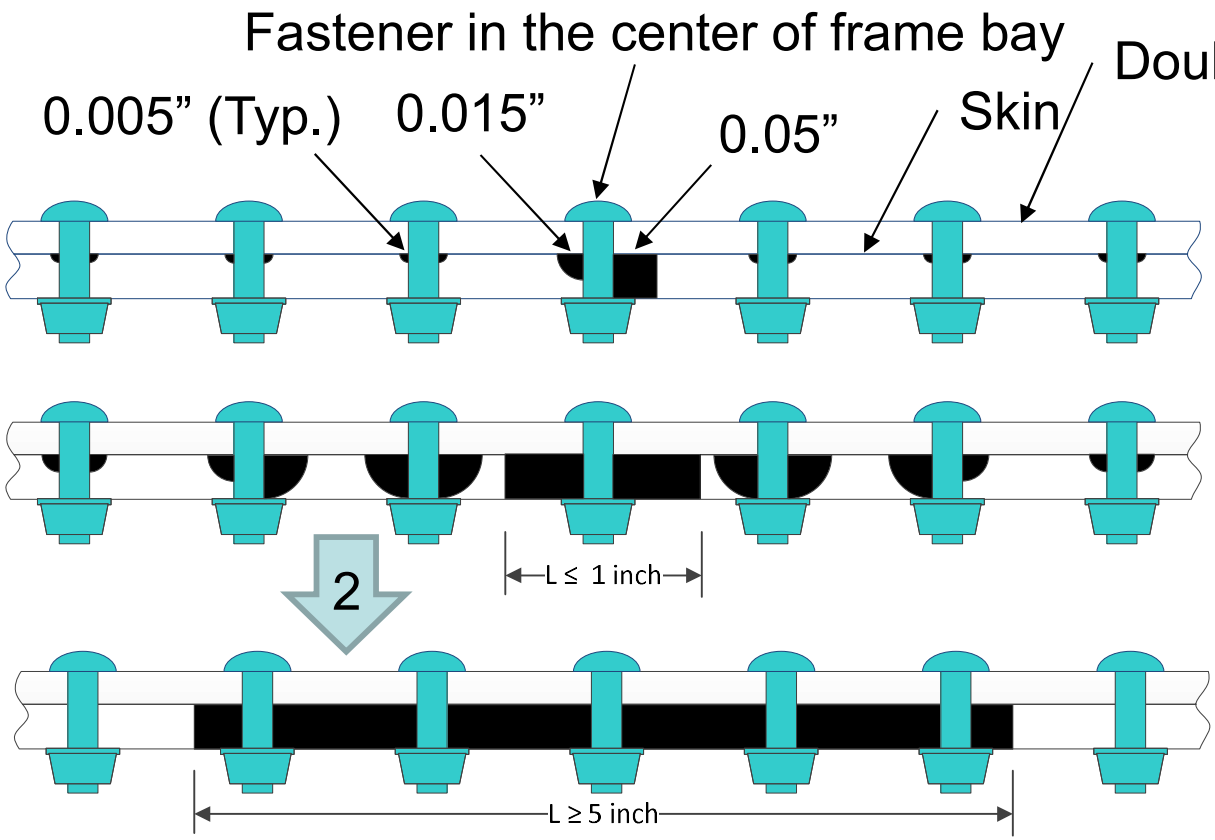
Stage 3:

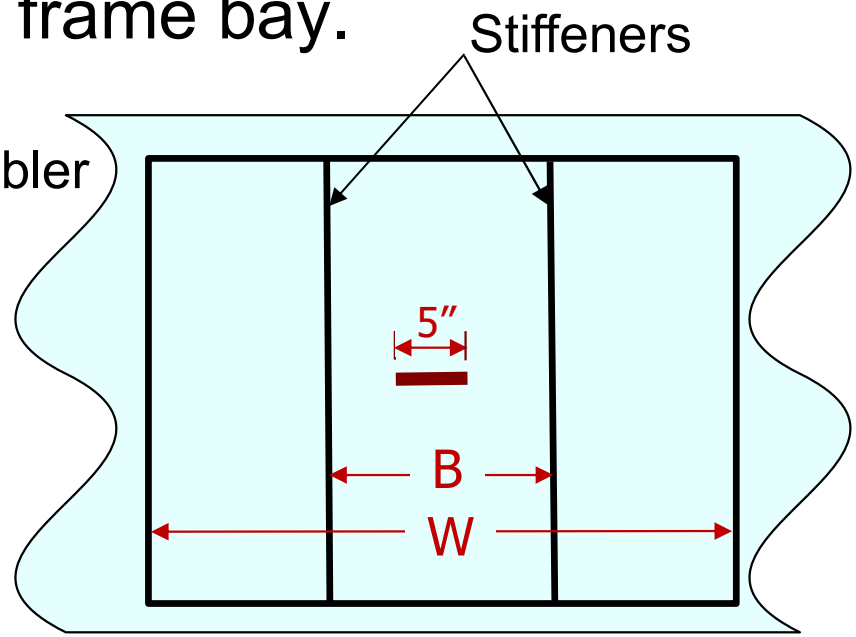
Continuing Damage



Crack Growth Stages for Local MSD in a Row of Holes

Crack growth stages for setting repeat intervals to prevent catastrophic failures from local fatigue damage[1] that can be caused by lower bound cracking in one frame bay.





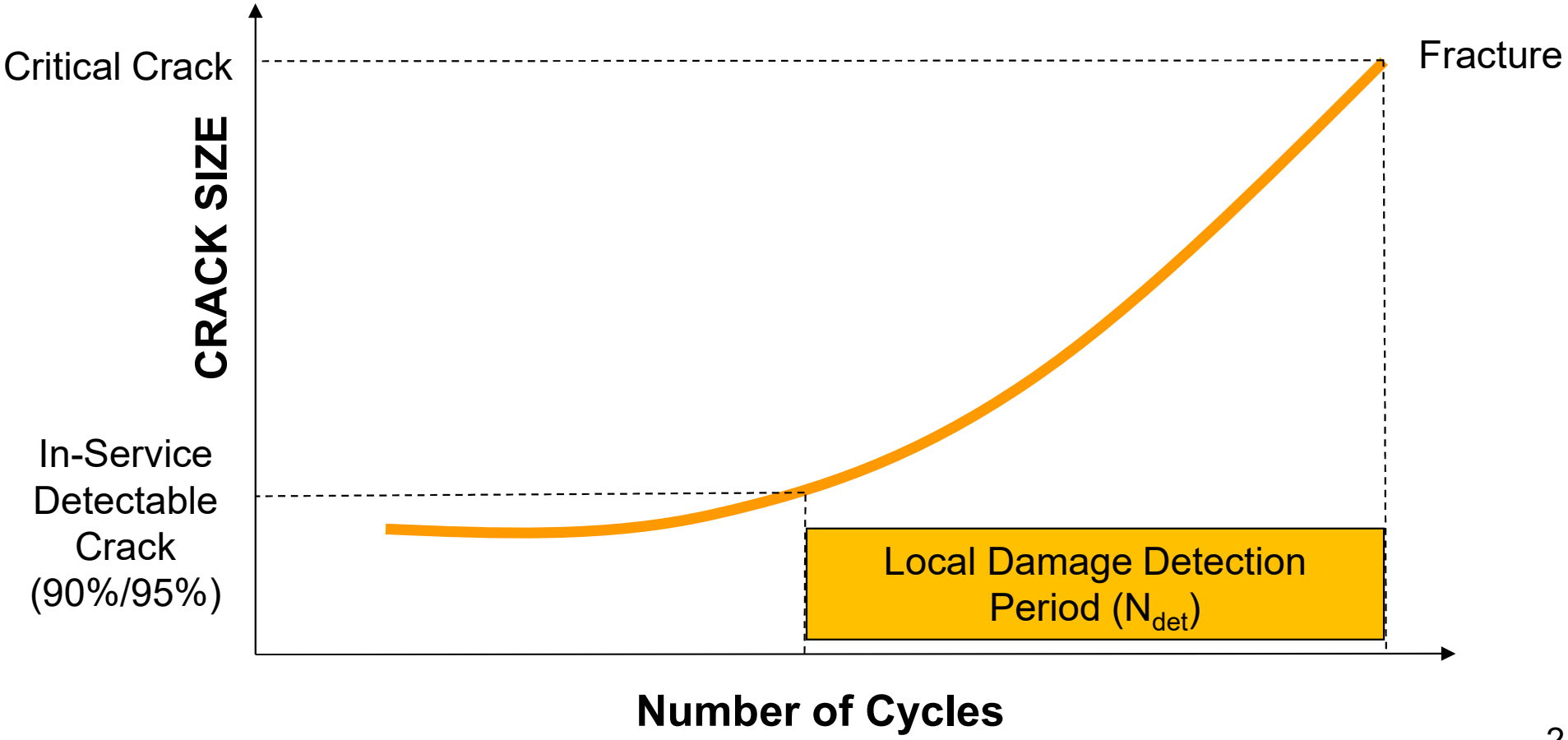
Grow a 5" crack in a center crack panel to the critical crack length (a_{crit}) to obtain N_{det} (Assume W=3xB)

<1> This cracking scenario and stages should be used to establish repeat intervals for skin with 1) small doublers and 2) joints up to WFD Inspection Starting Points

<2> Ref. Damage Tolerance Facts and Fiction by Dr. Ulf Goranson, Fig 16

Establishing N_{rep} from N_{det}

To establish repeat intervals for damage tolerance based inspection that is consistent with a high degree of detectability, the local damage detection period (N_{det}) should be divided by 3[1]: $N_{rep} = N_{det} / 3$

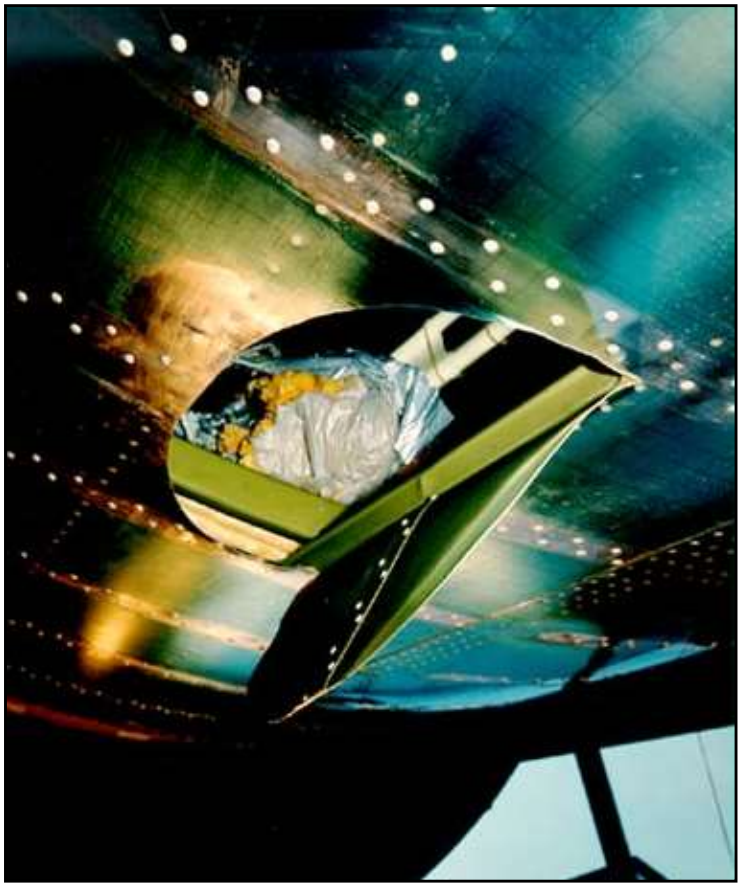


<1> Factor of 3 corresponds to POD=99.9%

Cracking Scenarios from MSD and MED to Establish N_{WFD}

Local MSD Link-Up versus WFD Condition

Local MSD link-up
(confined to one stiffener bay)

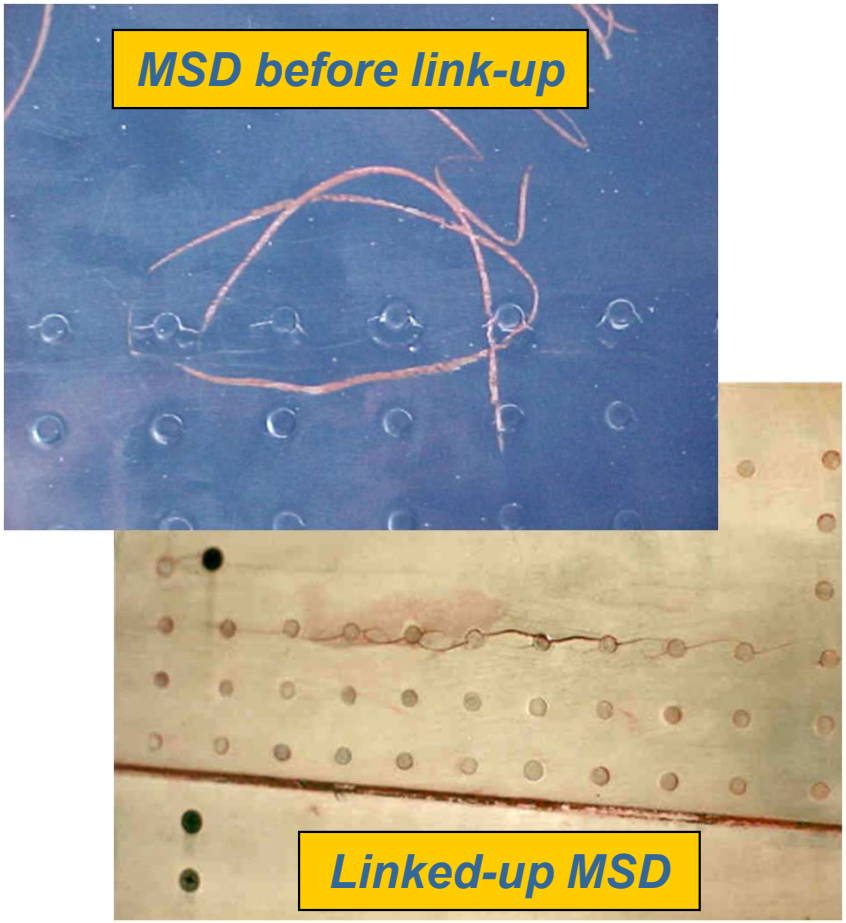


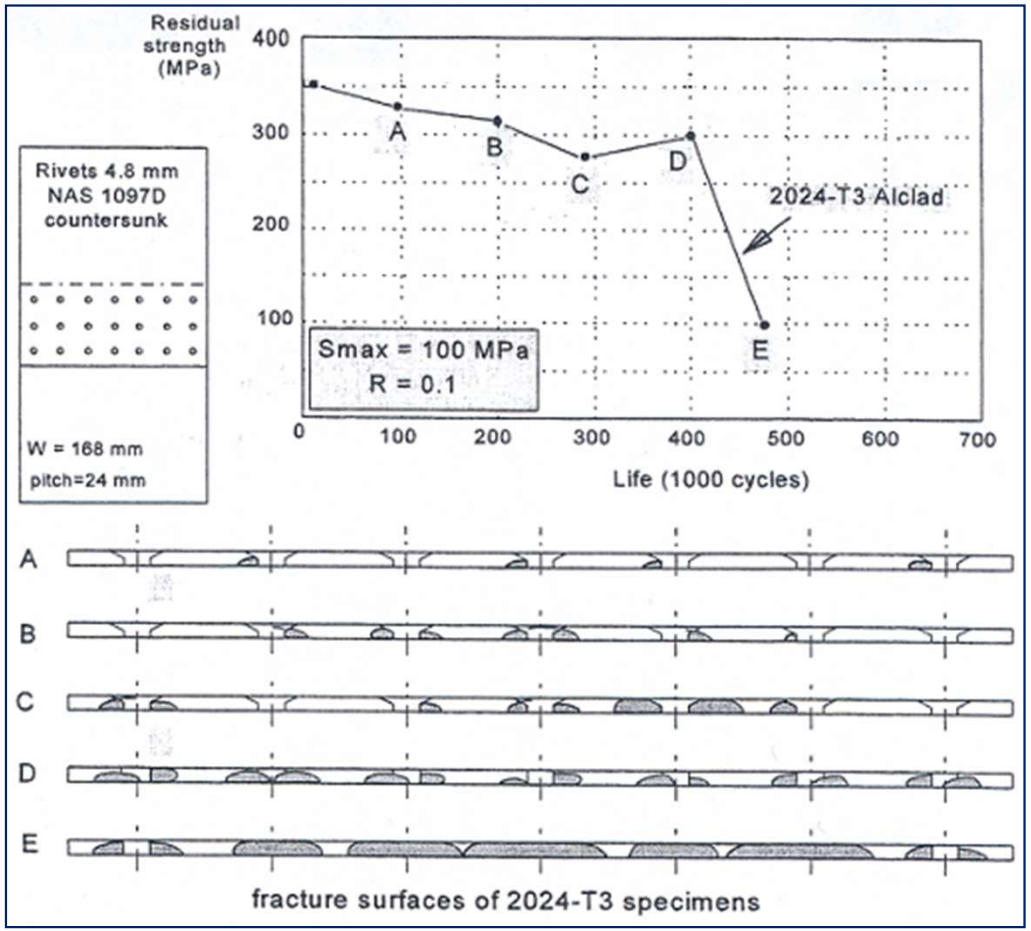
Fuselage skin with intermediate tear strap

MSD leading WFD condition

Examples of MSD Leading to WFD

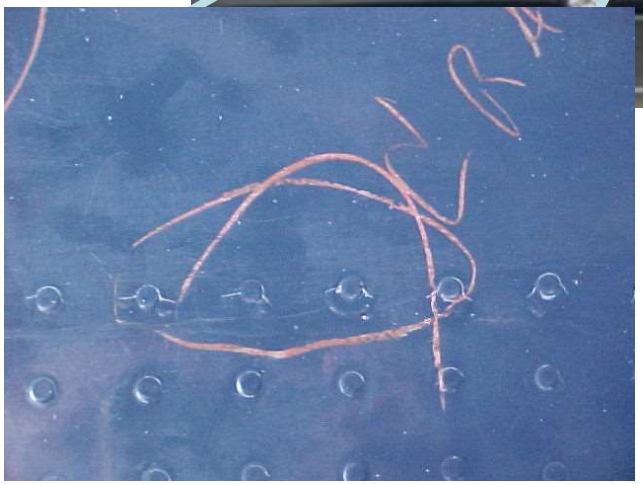
- Service history and fatigue test results indicate that normal fatigue leads to multiple cracks at the holes with similar stress levels and geometry.
- This type of cracking is known as *MSD that leads to WFD*.

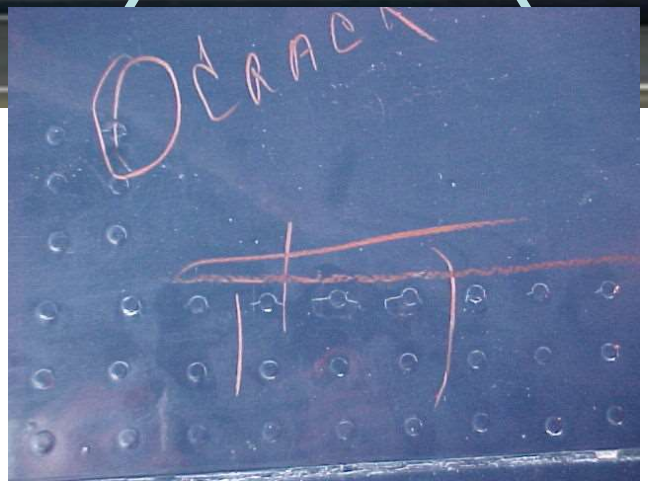


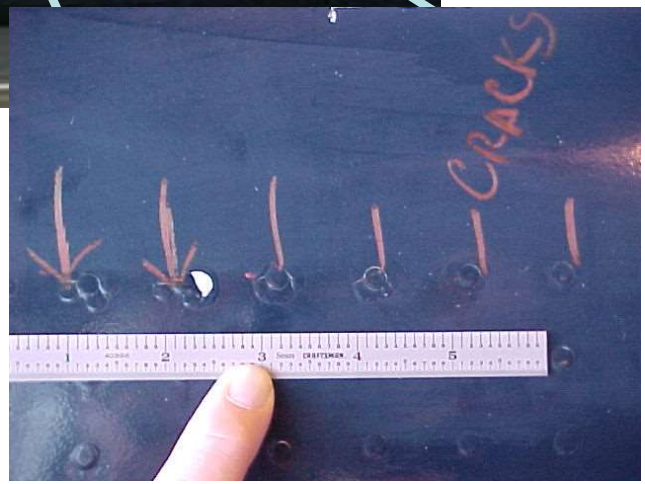


Example of MSD That Leads to WFD

17 year old 737-300 with approximately 36,000 flight cycles after completion of a C-check inspection

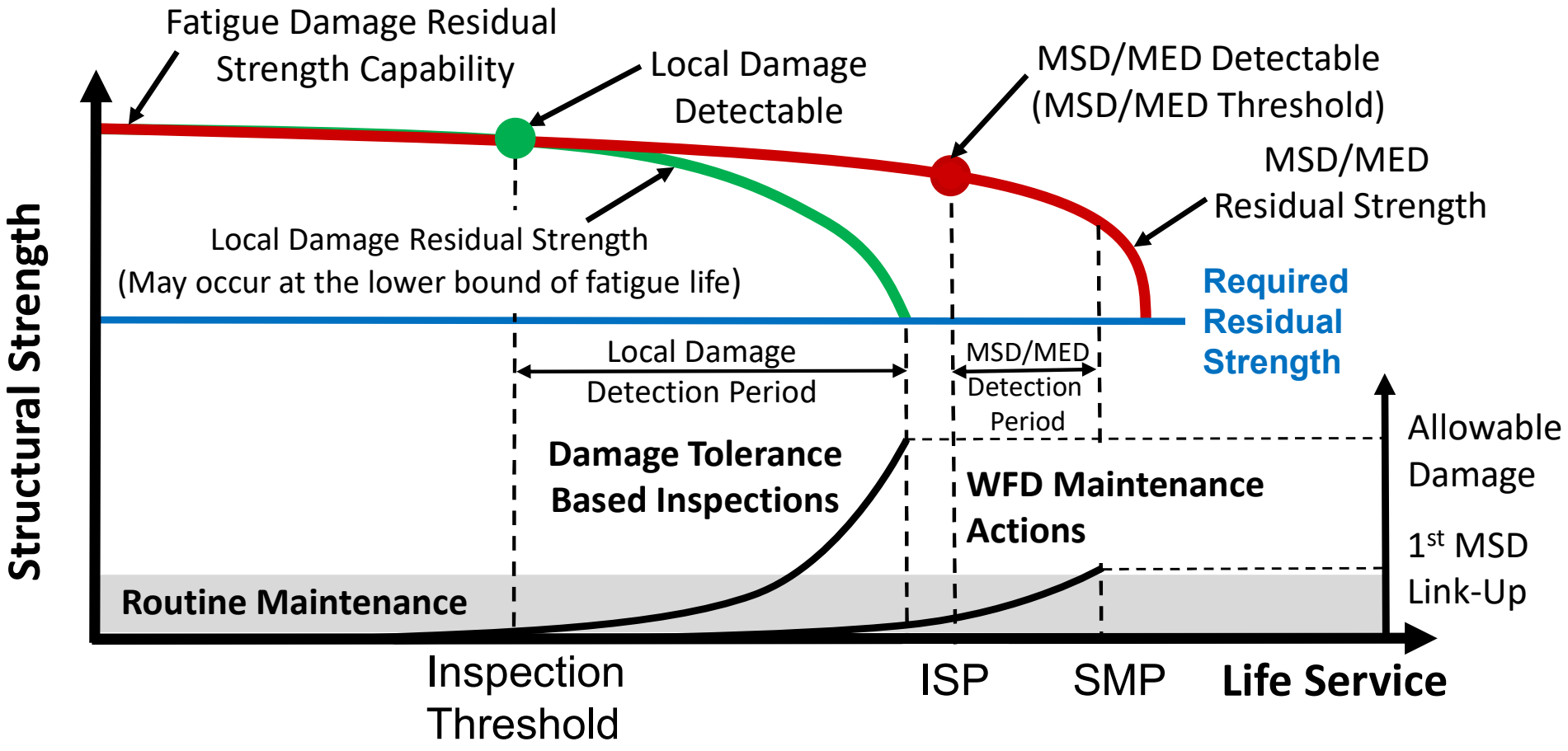






Structural Strength vs. Service Life

Relationship of *Routine* maintenance program, *Damage Tolerance* based inspections, and *WFD* maintenance program[1]



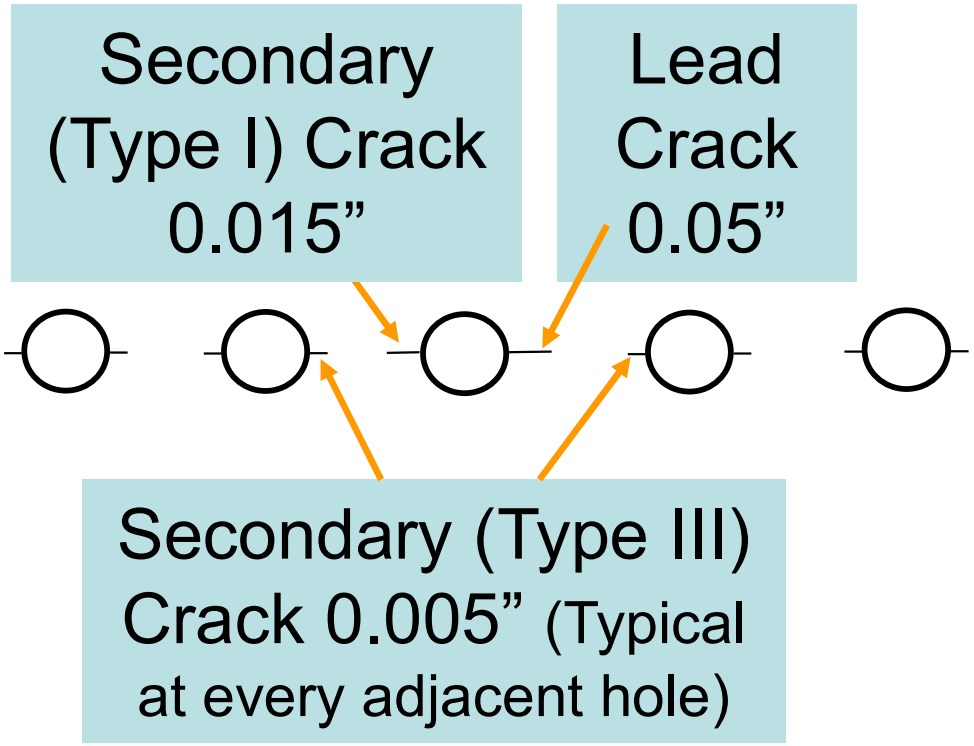
ISP- Inspection staring point, SMP- Structural modification point

1) Reference: Widespread Fatigue Damage Evaluation Method by Patrick Safarian, ICAF 2013 Jerusalem, Israel

Crack Scenario for MSD in a Row of Holes

Normal fatigue leads to cracks at multiple locations

- Assumption for cracking scenario for a damage tolerance analysis must consider a lead crack and secondary cracks in all detail design points



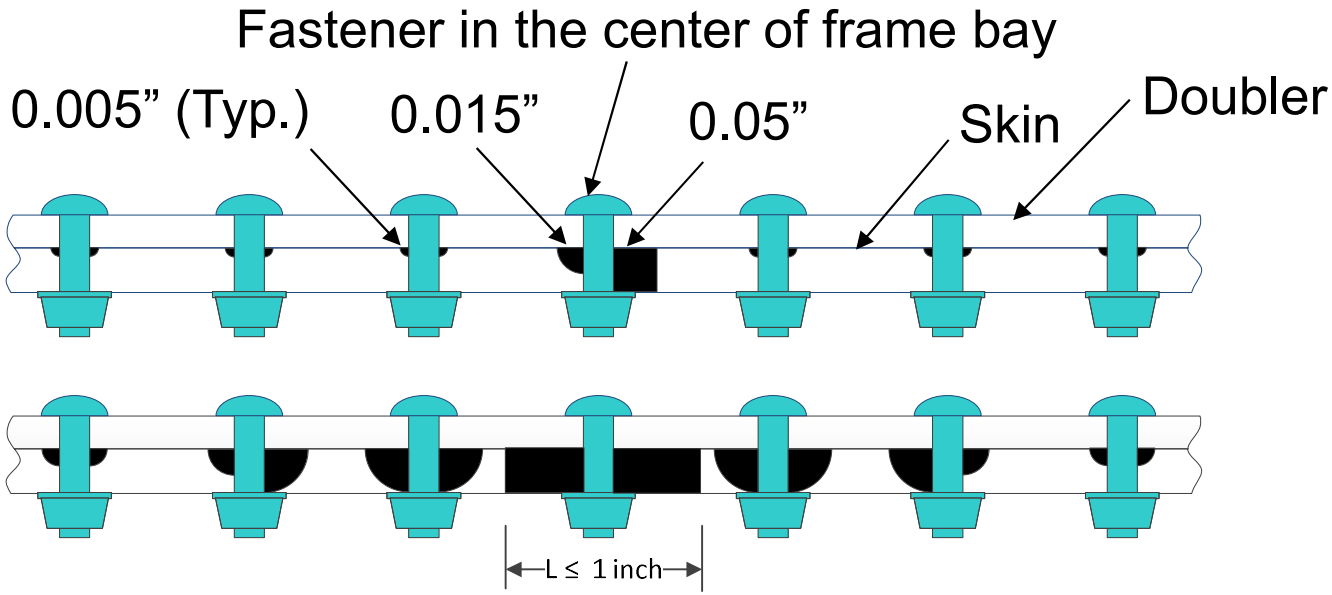
These holes represent the holes in the middle of a stiffening bay

- All cracks should grow <u>with</u> interactions

Crack Growth Stages For **MSD** Leading to WFD

Crack growth stages for setting repeat intervals to prevent catastrophic failures from MSD that leads to WFD[1]

- According to AC 25.571-1D, to establish repeat intervals from ISP to SMP the crack growth analysis should be limited to the first link-up.
- To establish repeat intervals as part of WFD maintenance actions, at ISP set N_{WFD}= MSD/MED Detection Period / 4 [2]



<1> This cracking scenario and stages should be used to establish repeat intervals for the time between ISP and SMP, if inspection is practical for the structure
<2> If inspection is not practical, then set SMP= ISP

Setting Repeat Intervals for **MED** Leading to WFD

- Determine the detectable crack size at each element based on the inspection technique (consult NDT Manual).
- To set repeat intervals for DT-based inspection program, a lead crack in the critical element plus secondary cracks in other details including in the adjacent elements should be assumed.
  - Growth of the lead crack could be accomplished with load redistribution to adjacent elements.
- To set repeat intervals to prevent WFD, starting at ISP a lead crack should be assumed at every similar element.
  - An example of adjacency of elements for MED that leads to WFD is having 3 fuselage frames within 5 adjacent ones that operate at similar stresses, 10%; i.e. have similar fatigue characteristics.
  - Crack growth in each element should not be done with the assumption that the load redistributes to the adjacent elements.
  - Use the same approach to establish N_{WFD} as for MSD

Crack Growth Scenarios Summary

- Choice of cracking scenario is the **key** aspect of realistic DTE
- Crack growth analysis is used to set inspection threshold (N_{th}) and repeat intervals (N_{rep} and N_{WFD})
  - Choice of cracking scenarios must be consistent with the application of the fracture mechanics to set $\mathbf{N_{th}}$, $\mathbf{N_{rep}}$ and $\mathbf{N_{WFD}}$
  - The assumption of the initial crack to determine the inspection threshold is a manufacturing induced damage, thus it is acceptable to select a single crack at a critical location plus continuing damages, growing without interactions.
  - The assumption of the initial crack to set repeat intervals must consider accumulation of fatigue damage, thus a lead crack at the critical location must be accompanied by secondary cracks at other locations due to normal fatigue.
    - Effect of crack growth interaction should be included in DTE