ENTE NAZIONALE PER L'AVIAZIONE CIVILE

STC Structural Substantiation Workshop

Antenna Installation Damage Tolerance & Cabin Interior issues

ANTENNA DT
the ENAC EXPERIENCE

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SCOPE

To present some conservatism and criticality in Antenna DT from ENAC experience

One **Part 23 STC** example

has been selected

SUMMARY

- ENAC activity in Antenna DT
- Part 23 case – the background
- Pressurization and bending loads
- The fatigue inertia load factor for crack propagation – Spectrum considerations
- Crack growth path and doubler load transfer
- Threshold and inspection interval
- Material characteristics
- Summary of conservative assumptions
- Some critical issues
- Conclusions and reference material

ENAC activity in Antenna DT 2007 – 2014

Enac Activity in Antenna DT

- Certification activity carried out as a Qualified Entity
  [Art. 20 Reg. (EC) 216/2008]
- Period 2007 – 2014 → 10 STCs
- **4 STCs for Part 23 aircafts**
  - Beechcraft Baron 58P
  - Piper PA 31-T Ceyenne II
- **6 STCs for Part 25 aircrafts**
  - DC 8-72
  - DC 9 (MD 80)
  - Cessna 500 Citation
  - Cessna 650 Citation II
- Applicants from: **Italy, France, Spain, UK**

Part 23 case
The background

Part 23 Case – background

- The DOA needed to extend its Terms of Approval in DT Antenna Installation (both for Part 23 & 25)

- 3 STCs applications were in place for the **Piper PA 31T Ceyenne II** [CAR 3/FAR 23]

- The Applicant elected to use **CS 23.573(b)** in order to estabish a conservative DT methodology for Antenna Installation in pressurized cabins

- The antenna was installed on the a/c under a previous FAA approval and the a/c was flying under the competent NAA responsibility before the EASA STC approval

Part 25 Case – background

CS 23.573 Damage tolerance and fatigue evaluation of structure

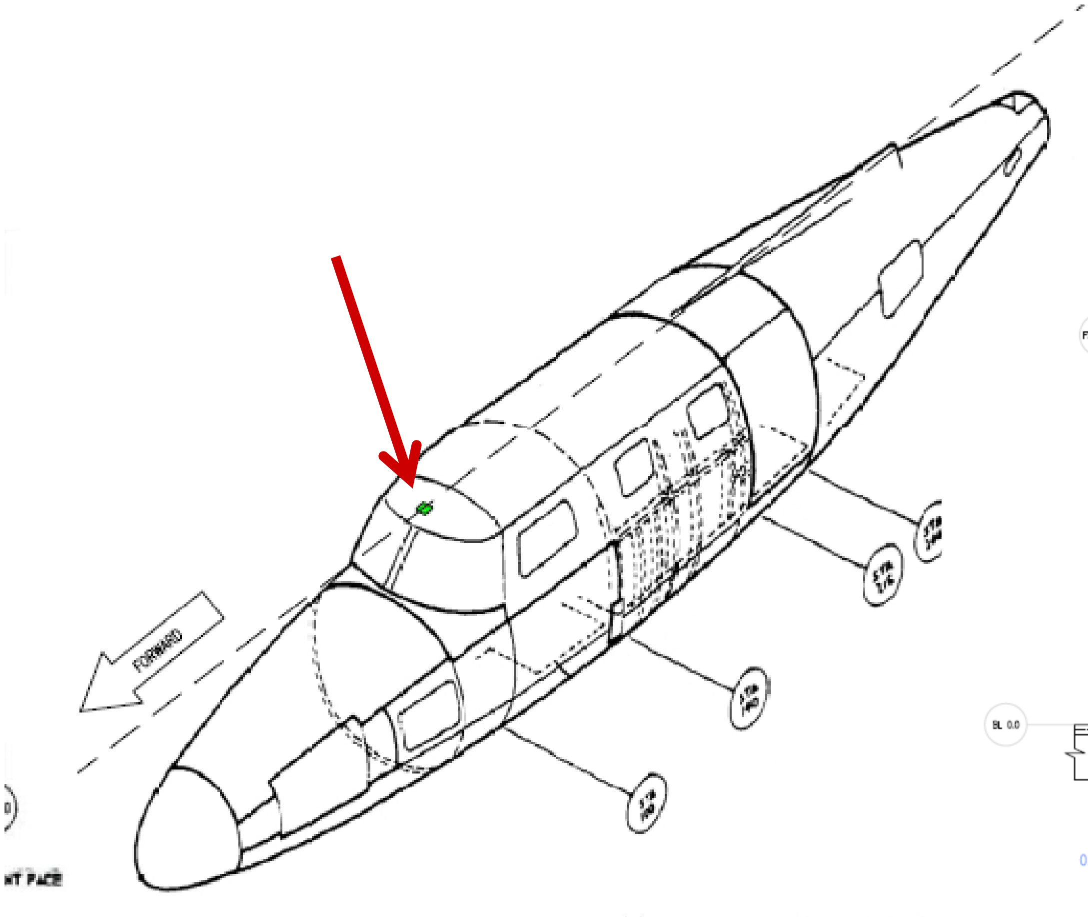
(b) *Metallic airframe structure.* If the applicant elects to use CS 23.571(c) or CS 23.572(a)(3), then the damage tolerance evaluation must include a determination of the probable locations and modes of damage due to fatigue, corrosion, or accidental damage. The determination must be by analysis supported by test evidence and, if available, service experience. Damage at multiple sites due to fatigue must be included where the design is such that this type of damage can be expected to occur. The evaluation must incorporate repeated load and static analyses supported by test evidence. The extent of damage for residual strength evaluation at any time within the operational life of the aeroplane must be consistent with the initial detectability and subsequent growth under repeated loads. The residual strength evaluation must show that the remaining structure is able to withstand critical limit flight loads, considered as ultimate, with the extent of detectable damage consistent with the results of the damage tolerance evaluations. For pressurised cabins, the following load must be withstood:

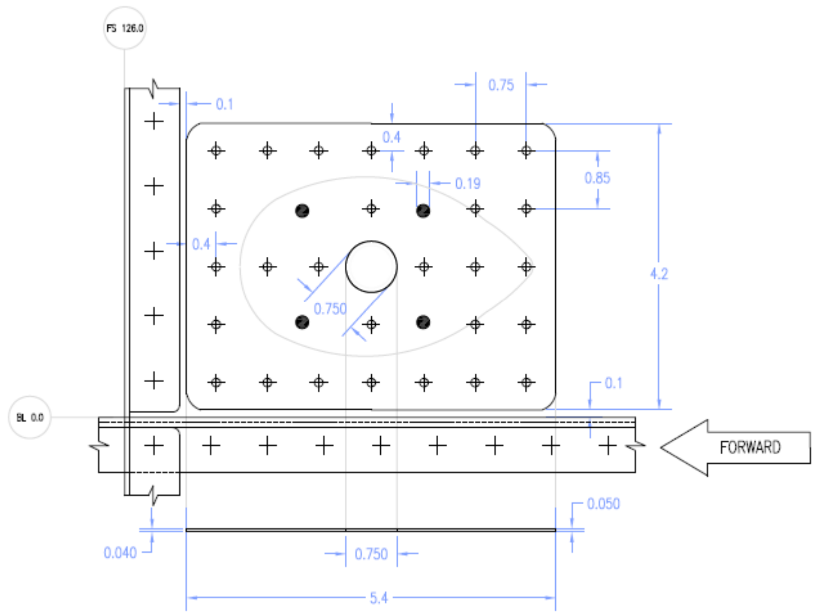
(1) The normal operating differential pressure combined with the expected external aerodynamic pressures applied simultaneously with the flight loading conditions specified in this subpart, and

(2) The expected external aerodynamic pressures in 1g flight combined with a cabin differential pressure equal to 1.1 times the normal operating differential pressure without any other load.

Part 23 Case – background

- The STC deals with GPS Antenna installation





ONLY SKIN AFFECTED

Part 23 Case – background

- DT approach

Chicago ACO (adapted) + Conservatisms

DAMAGE TOLERANCE ANALYSIS
FOR
ANTENNA INSTALLATIONS
ON
PRESSURIZED TRANSPORT
AIRPLANES

Chicago Aircraft Certification Office

+

ADAPTATION
- Fatigue facor (1.8 vs 1.3)
- 1-g beam stress
- Initial crack scenario
- Inspection Factor of Safety

CONSERVATIVE ASSUMPTIONS

Pressurization and Bending Loads

Pressurization and Bending Loads

- Differential pressure

  1.1 * (nominal differential pressure p)

  [Note: 1.1 is the same factor prescribed for residual strenght]

  p = 5.75 psi

- External aerodinamic pressure (p_a)
  - Chicago paper recommends: **p_a = 0.5 psi**
  - The Applciant assumed: **p_a = 0.6 psi**
  - (Other Part 25 STCH assumed p_a = 1 psi)

Recomended value : 0.5 – 1 psi

Pressurization and Bending Loads

- Total differential pressure was used both for crack propagation (conservative) and residual strenght

$$p_{tot} = 1.1\,p + p_a = 6.9\ \text{psi}$$

- Circumferential pressure stress

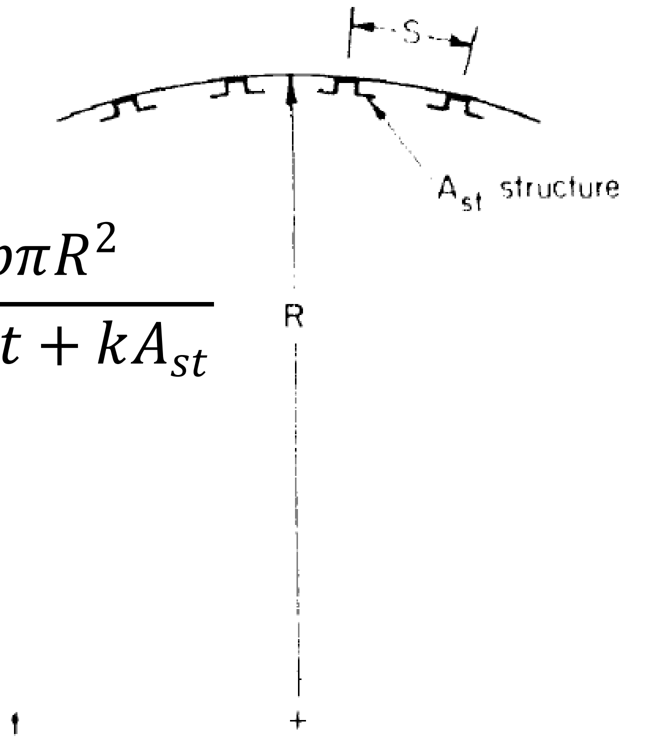
$$\sigma_{pc} = (1.1p + p_a)\frac{R}{t}$$

- Longitudinal pressure stress

$$\sigma_{pl} = (1.1p + p_a)\frac{R}{2t}$$

Pressurization and Bending Loads

- **Stringers sectional area neglected**
  for deriving longitudinal pressurization loads



$$p\pi R^2 = (2\pi Rt + kA_{st})\sigma_{pl} \Rightarrow \sigma_{pl} = \frac{p\pi R^2}{2\pi Rt + kA_{st}}$$

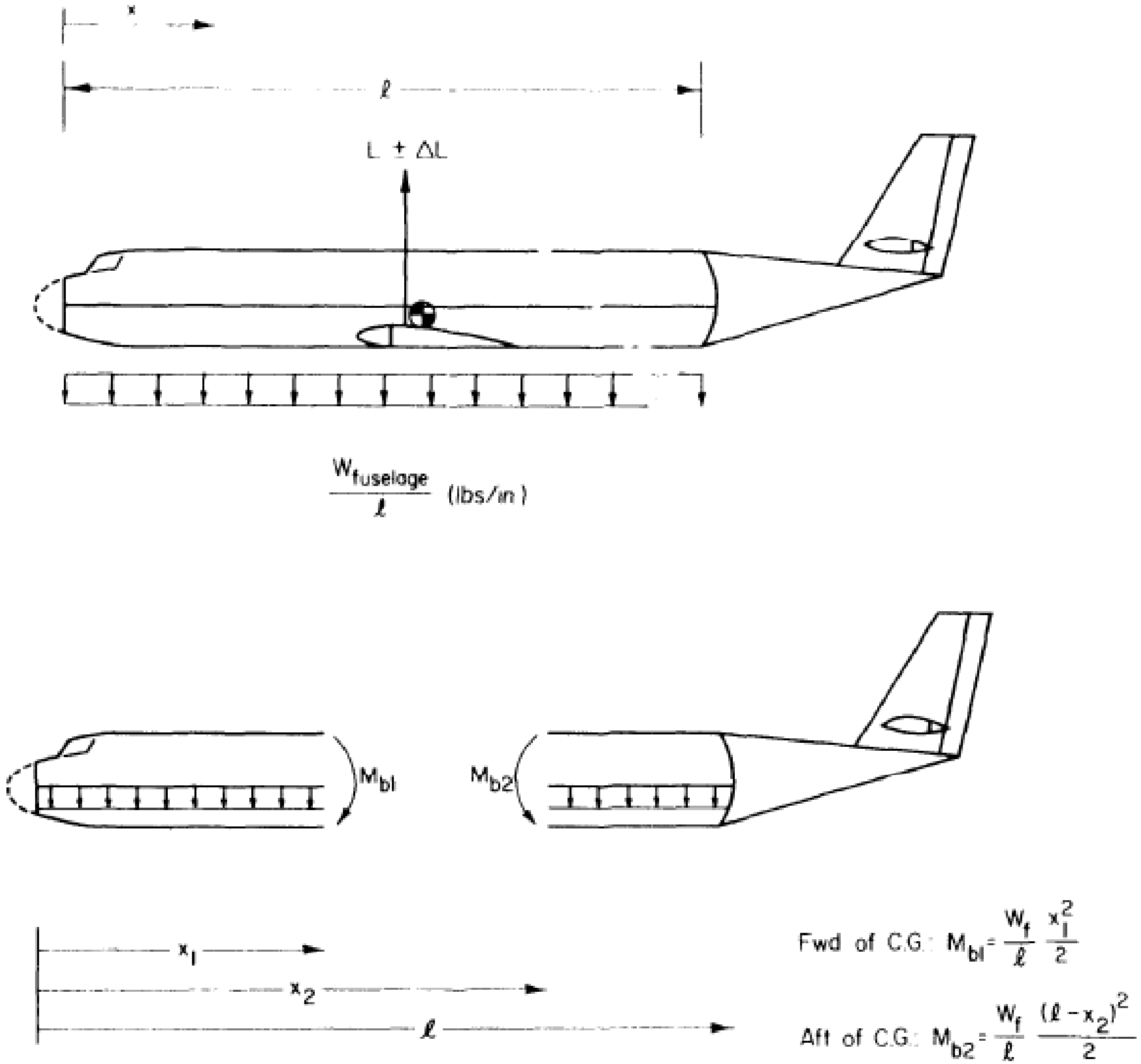
$$\boxed{A_{st} = 0 \Rightarrow \sigma_{pl} = \frac{pR}{2t}}$$

k = number of stringers

A_{st} = striger sectional area **assumed = 0**

Pressurization and Bending Loads

- Fuselage bending stress – **beam model for 1-g stress**



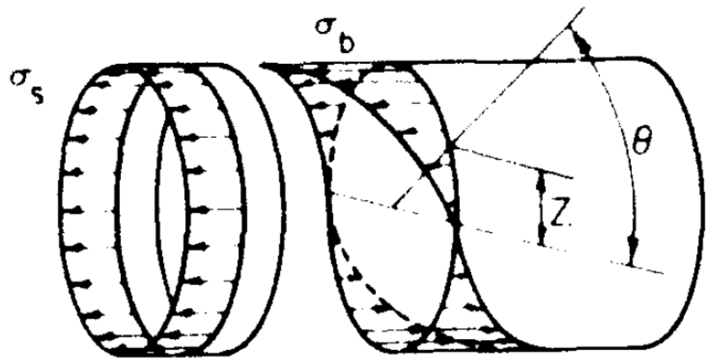
Tail Loads neglected

- It can be compensated by increasing the fuselage weight
- Conservative if the Tail Lift Lt is UP

Pressurization and Bending Loads

- **Stringers inertia neglected**

  for deriving longitudinal bending stress (**1-g stress**)



$$M_{b,FWD\_CG} = \frac{W_f x^2}{2l}$$

$$M_{b,AFT\_CG} = \frac{W_f (l-x)^2}{2l}$$

$$Z = R \sin \vartheta$$

$$\sigma_{bl} = \frac{M_b Z}{\pi R^3 t + k \frac{1}{2} A_{st} R^2}$$

$$\boxed{A_{st} = 0 \Rightarrow \sigma_{bl} = \frac{M_b}{\pi R^2 t} = \sigma_{1-g}}$$

W_f = Fuselage Weight **assumed = MTOW**

for large transport a/c the following formula is often used (from weight breakdown): **W_f = MZFW - 0.2*MTOW**

Z = Vertical distance from fuselage center **assumed = R**

A_{st} = Stringer sectional area **assumed = 0**

Pressure and Bending Loads

- In the longitudinal stress formula the total bending stress is assumed proportional to 1-g bending stress via the inertial load factor n_z

$$\sigma_l = \sigma_{pl} + \sigma_b = \sigma_{pl} + n_z \sigma_{1-g}$$

- The Chicago paper derives the 1-g stress loads using a "zero-margin-at-ultimate-load" methodology, i.e.

$$\mathbf{1.5\ (\ pR/2t + n_{z,max}\,\sigma_{1\text{-}g}\ ) = F_{tu}}$$

- not used here (beam model used) -

- For transport aircrafts **n_z=1.3** is deemed adequate **for crack propagation** (see considerations about TWIST)

Pressurization and Bending Loads

- Circumferential and longitudinal loads act at the same time

- In principle it could not be excluded the crack could propagate at angles

- To cover this the Applicant agreed to apply the **combined circumferential and longitudinal stress** both to longitudinal and circumferential crack propagation

$$\sigma_{l,crack} = \sigma_{c,crack} = \sqrt{\sigma_{circ}^2 + \sigma_{long}^2}$$

The fatigue inertia load factor for crack propagation Spectrum considerations

Spectrum considerations

- How to adapt the 1.3 factor for Part 23 aircrafts?

- Fuselage stresses are due to inertia loads which in turn are due to wing loads

  → Fuselage spectrum for bending loads can be obtained from the wing spectrum

- **Maneuvering and gust spectra** of **AC 23-13A** were used to estimate an **equivalent inertia load factor** for fatigue starting from the evaluation of the **mean load factors**

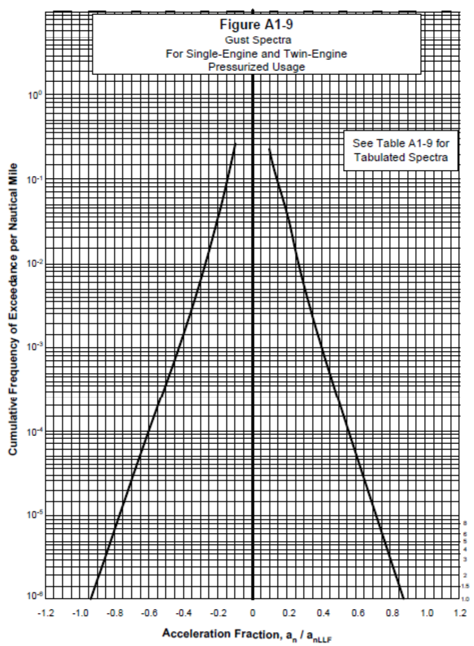
Spectrum considerations

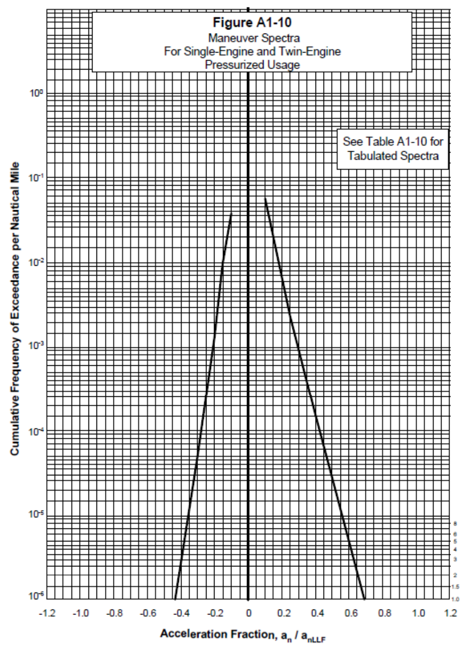
- AC 23-13A Charts A1-9 and A1-10 for Single engine press. a/c

Exceedances vs Acceleration Fraction a_n / a_{nLLF} ($n_z = 1 + a_n$)

$$\frac{a_n}{a_{nLLF}} = \frac{Incremental\,Maneuver\,Load\,Factor\,at\,Operating\,Weight}{Incremental\,Design\,Limit\,Maneuver\,Load\,Factor\,at\,Maximum\,Gross\,Weight}$$

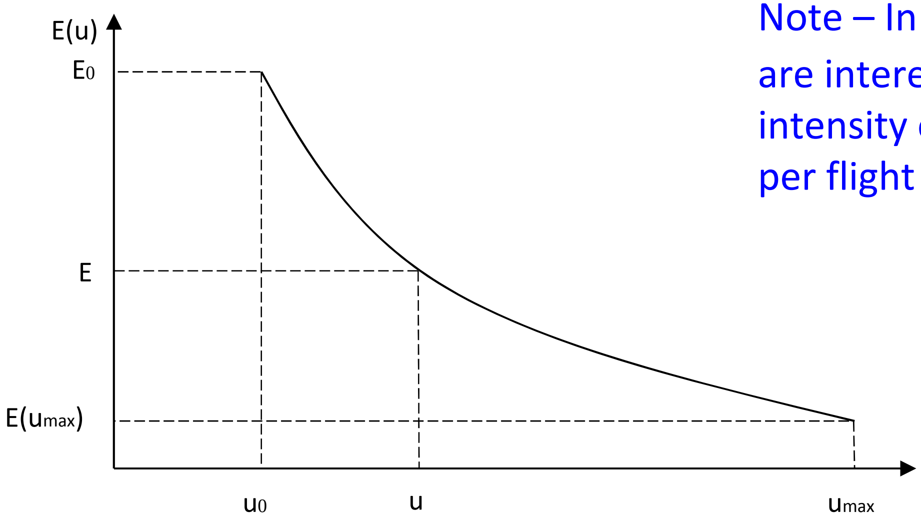
$$\frac{a_n}{a_{nLLF}} = \frac{Incremental\,Gust\,Load\,Factor\,at\,Operating\,Weight}{Incremental\,Design\,Limit\,Gust\,Load\,Factor\,at\,Maximum\,Gross\,Weight}$$



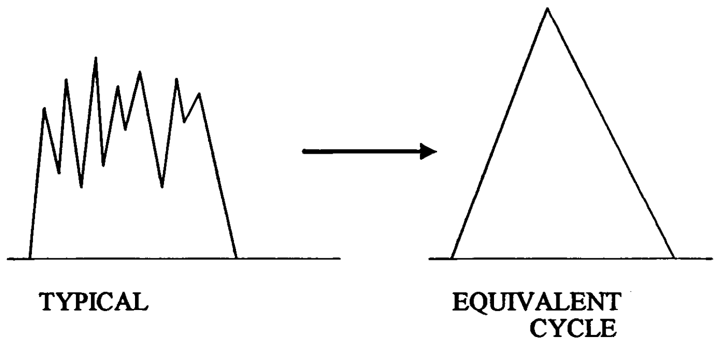


Spectrum considerations

- The method of calculating the mean was based upon **probability considerations**
- Consider an **exceedances gust velocity diagram** (1 nm range)



Note – In the Chicago scheme (1 cycle per flight) we are interesting in finding a “fatigue equivalent” intensity of the gust and not how many occurrencies per flight this intensity occurs



u = gust velocity

u_0 = minimum (damaging) gust velocity

$E(u)$ = number of exceedances with respect the velocity u

E_0 = $E(u_0)$ = total number of excedances

Spectrum considerations

- To derive the **mean gust velocity** u_e from the exceedance diagram E(u) let us assume

  U = gust velocity as a **random variable**

- The probability of encountering (in 1 nm) a gust whose intensity U is greater than u is

$$P(U > u) = \frac{E(u)}{E_0}$$

- The probability of encountering (in 1 nm) a gust whose intensity U is less than or equal to u is

$$P(U \leq u) = F(u) = 1 - P(U > u) = 1 - \frac{E(u)}{E_0}$$

F(u) = Repartition function of U

Spectrum considerations

- Probability density of U

$$f(u) = \frac{dF(u)}{du} = \frac{d}{du}\left[1 - \frac{E(u)}{E_0}\right] = -\frac{dE(u)/du}{E_0}$$

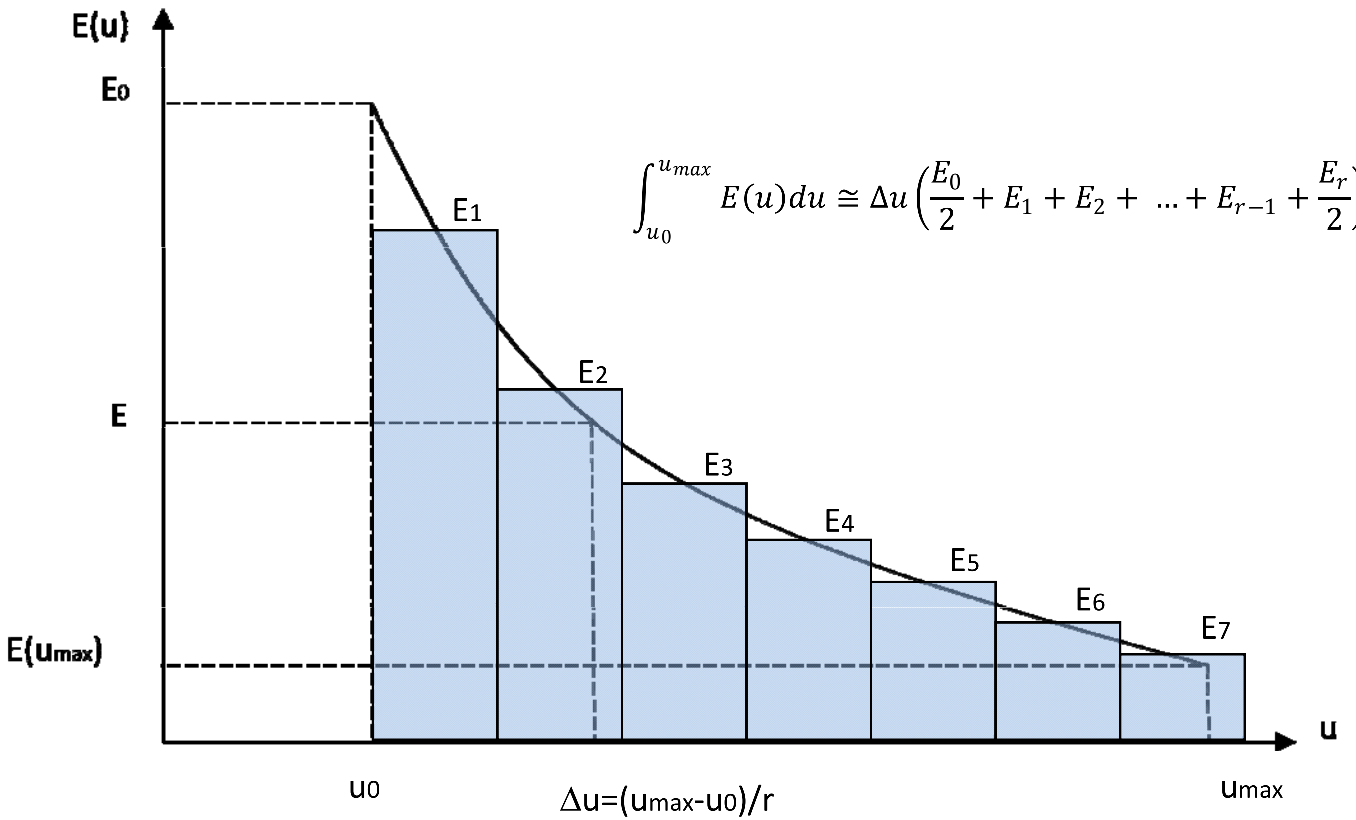
- Mean value of U – **50% probability** (integrating by parts)

$$u_e = \int_{u_0}^{u_{max}} uf(u)du = \frac{1}{E_0}\left[u_0 E(u_0) - u_{max} E(u_{max}) + \int_{u_0}^{u_{max}} E(u)du\right]$$

- By using the probability density function any quantile of U can be calculated (e.g. 1-sigma, etc.)

Spectrum considerations

- Integral discretization
  - r = number of exceedance discrete levels, $u_r = u_{max}$, $E_r = E(u_{max})$
  - $\Delta u = (u_r - u_0) / r$ = gust velocity integration step



$$\int_{u_0}^{u_{max}} E(u)du \cong \Delta u \left(\frac{E_0}{2} + E_1 + E_2 + \ldots + E_{r-1} + \frac{E_r}{2}\right)$$

(r = 7)

Spectrum considerations

- The integral can be easily solved **numerically** starting form the available **tabulated exceedance values**

$$u_e = \frac{1}{E_0}\left[u_0 E_0 - u_r E_r + \Delta u \left(\frac{E_0}{2} + E_1 + E_2 + \ldots + E_{r-1} + \frac{E_r}{2}\right)\right]$$

- Once u_e is obtained the corrisponding gust load factor follows directly from known (regulatory) formula

- The results are
  - **Mean Nz_gust** (A1-9 spectrum) = **1.46**
  - **Mean Nz_maneuvers** (A1-10 spectrum) = **1,36**

- **Considering the calculated mean values the Applicant applied Nz = 1.8**

Spectrum considerations

- In order to find out the mean value directly on the exceedance diagram it is possible to set

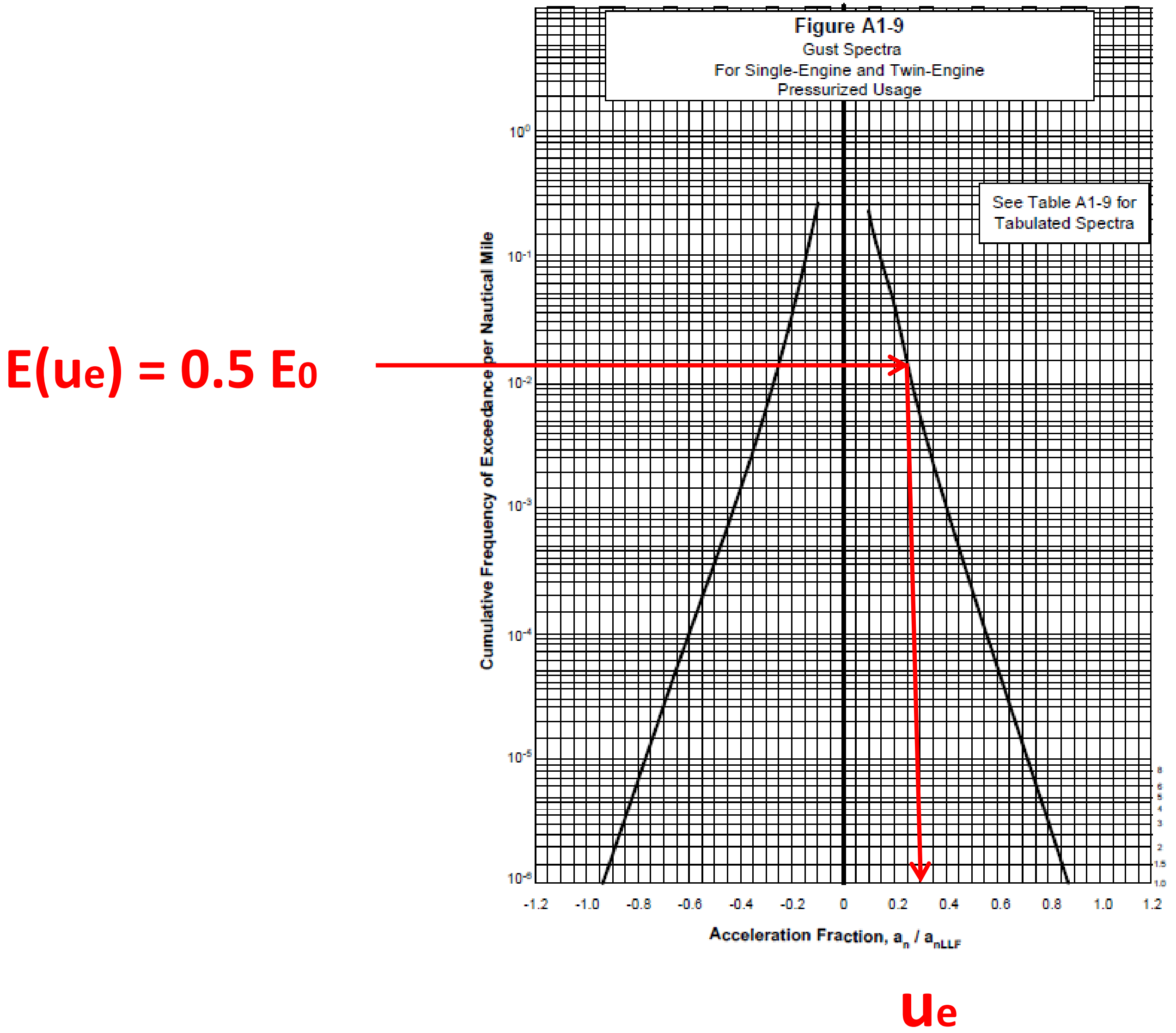
$$P(U > u_e) = \frac{E(u_e)}{E_0} = 0.5 \Rightarrow E(u_e) = 0.5E_0$$

and enter the exceedance diagram with this value

- Similarly any **p-quantile u_p** of U (random variable) could be obtained simply by imposing

$$P(U > u_p) = \frac{E(u_p)}{E_0} = p$$

Spectrum considerations



$E_0 = 0.223784$

$u = a_n / a_{nLLF}$

Spectrum considerations

Let us now derive the **10th quatiles (90% prob. of having a lesser value) of gust and manuvering load factor from AC23-13A spectra**

- **Gust** (A1-9)

  E_0 = 0.224

  E = $0.1*E_0$=(0.1)(0.224)= = 2.24*10^-2

  a_n/a_{nLLF} = 0.25

  [graphically estimated]

  a_{nLLF} = 2.92

  [from AC 23-13A]

  a_n=(0.25)(2.92)=0.73

  n_z=1+a_n = **1.73**

- **Maneuver** (A1-10)

  E_0 = 0.05617

  E = $0.1*E_0$=(0.1)(0.05617)= = 5.62*10^-3

  a_n/a_{nLLF} = 0.25

  [graphically estimated]

  a_{nLLF} = 3.36 (= $N_{z,max}$)

  [conservative]

  a_n = (0.25)(3.36) = 0.84

  n_z=1+a_n = **1.84**

  [n_z = **1.57** with a_{nLLF} = 2.36 = $\Delta N_{z,max}$]

→ **Conclusion: the factor 1.8 could be considered adequate**

Spectrum considerations

- Now how about the **1.3 fatigue factor** accepted by the Chicago paper for transport aircraft?

- Using the **TWIST** spectrum it is possible to estimate the 1.3 factor as the **90th percentile (10th quantile)** s_1 **of the relative stress ratio** $S = \sigma / \sigma_m$ (random variable)

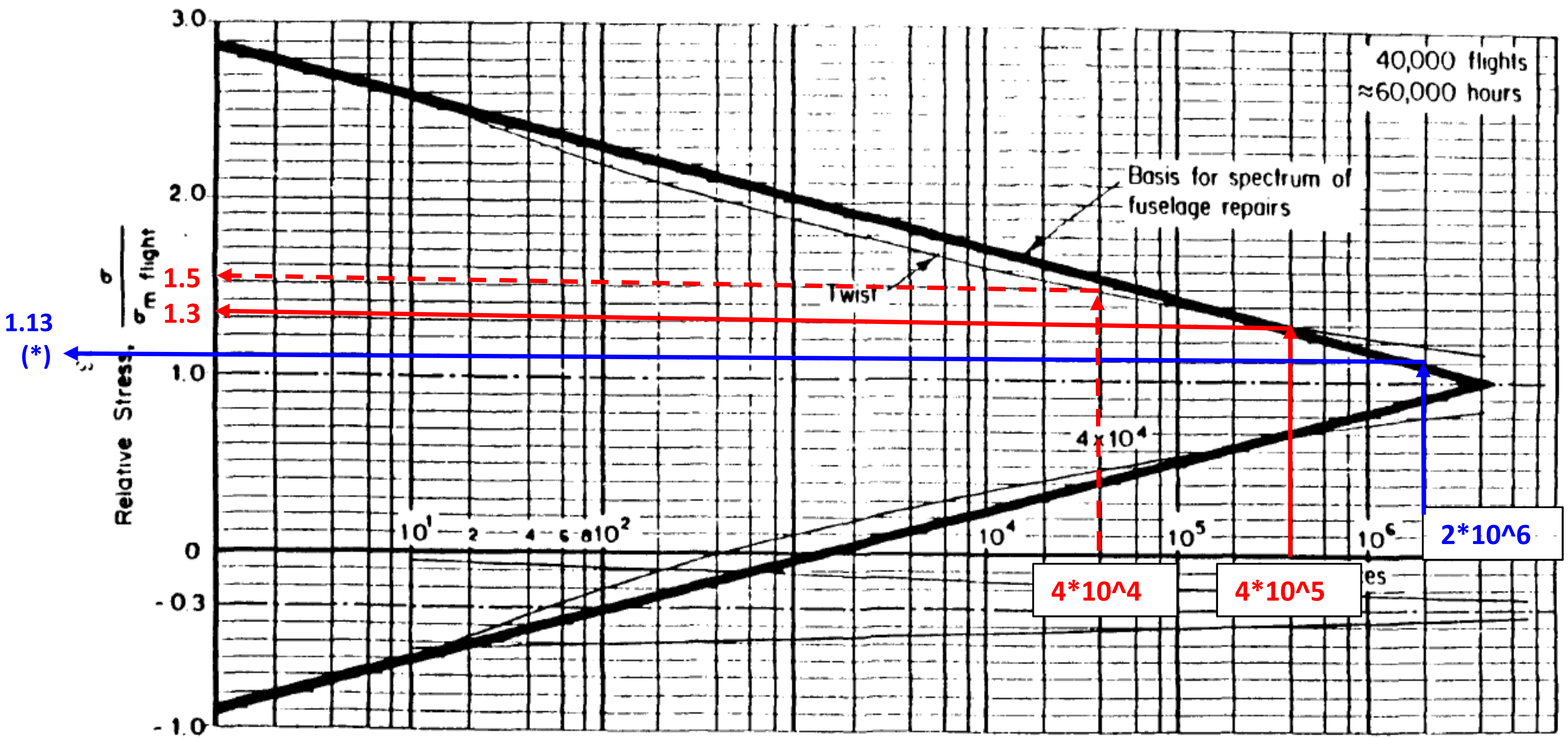
  - $E_0 =$ **4*10^6** = total exceedances ($S=1$)
  - s_1 = 10th quantile → 10% Prob $S > s_1$ (90% Prob $S \leq s_1$)
  - $P(S > s_1) = E(s_1) / E_0 = 0.1$ → $E(s_1) = 0.1 * E_0$ **= 4*10^5**

$E(s_1)$ = 4*10^5 → (TWIST) → s_1 = 1.3

Spectrum considerations

- **TWIST quantiles**

$\sigma/\sigma_m = 1.3$	10-th quantile	–	$P(\sigma/\sigma_m > 1.3) = 0.1$
$\sigma/\sigma_m = 1.5$	1-th quantile	–	$P(\sigma/\sigma_m > 1.5) = 0.01$
$\sigma/\sigma_m = 1.13$	50-th quantile	–	$P(\sigma/\sigma_m > 1.13) = 0.5$



(*) Derived by numerical integration – not graphically

Load transfer
Crack growth path

Load transfer and Crack growth

- **AFGROW** used for doubler and skin trough thickness crack growth
- No retardation
- No crack interaction
- Crack growth form connector hole
  - **Far field stress reduction due to doubler neglected**
    (Total stress applied on the skin and on the doubler)
- Crack growth along the first rivet line
  - **Load sharing between skin and doubler : 50% - 50 %**
  - **Pin load at the first and second rivet line : 60% - 40%**
- The crack was supposed to propagate on a portion of skin having the size of the **doubler footprint**

Load transfer and Crack growth

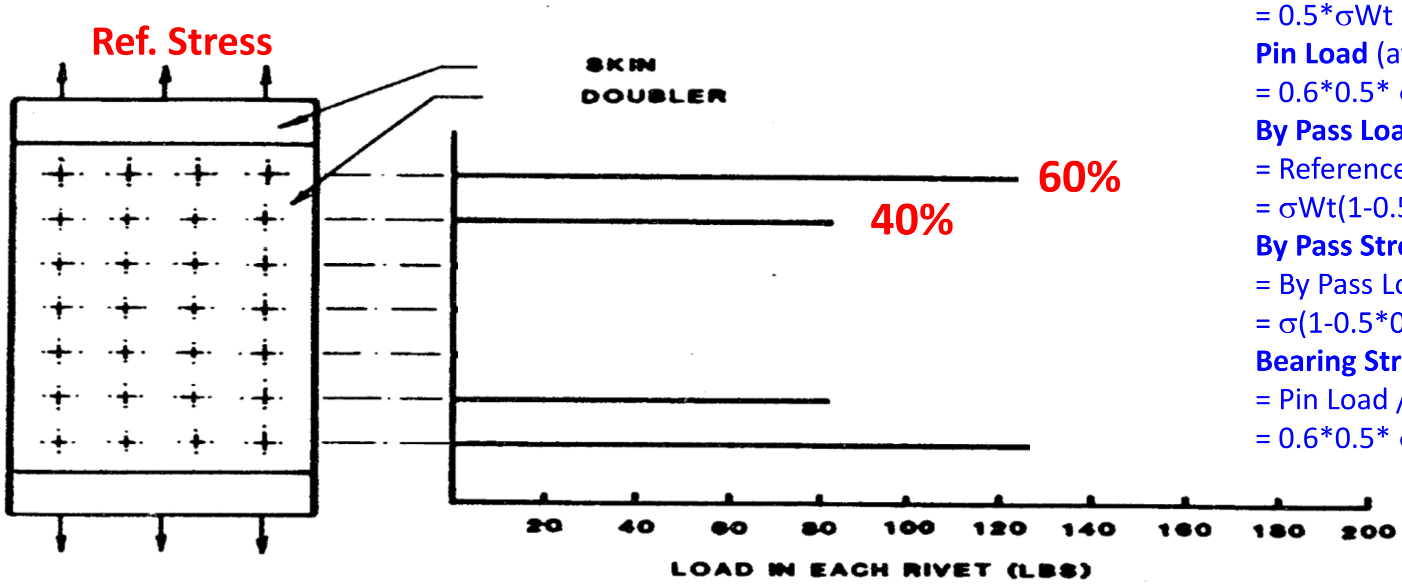
- The critical crack length was determined based on the following criteria
  - **K=Kc (Allowable Residual Strenght)** $$\sigma_{RS} = \frac{K_C}{\beta(a)\sqrt{\pi a}}$$
  - **Net Section Residual Strenght**
- a = a_{cr} when

Min {Allowable RS, Net Section RS}

= Regulatory RS

Load transfer

- **Load Transfer – TCAA approximation**



Reference stress
$= \sigma$
Reference Load
$= \sigma Wt$
Doubler Load
$= 0.5*\sigma Wt$
Pin Load (at First Rivet Line)
$= 0.6*0.5*\ \sigma Wt$
By Pass Load
= Reference Load - Pin Load
$= \sigma Wt(1-0.5*0.6)$
By Pass Stress
= By Pass Load / Wt
$= \sigma(1-0.5*0.6)$
Bearing Stress
= Pin Load / Dt
$= 0.6*0.5*\ \sigma\ (W/D)$

Stress on skin (at First Rivet Line) = Function of By Pass Stress and Bearing Stress

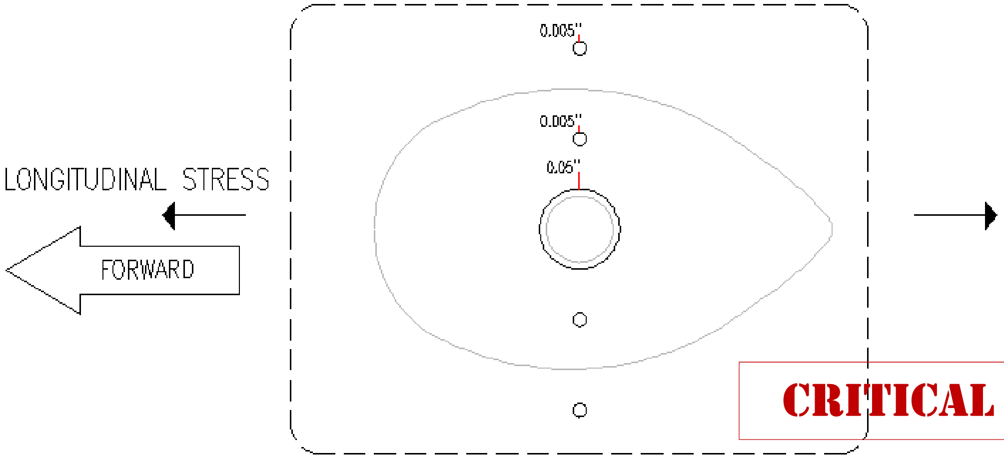
Tension Ratio = By-Pass Stress/Reference Stress = **1 – (0.5)(0.6) = 0.7**

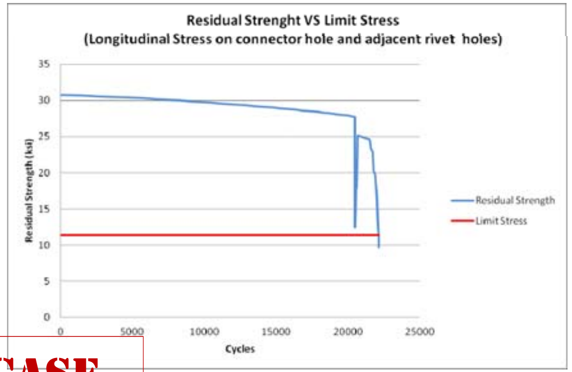
Bearing Ratio = Bearing Stress / Reference Stress = **(W/D)(0.5)(0.6)**

- **Tension Ratio** assumed **= 1 → By-Pass Stress = Ref. Stress**

Crack growth path

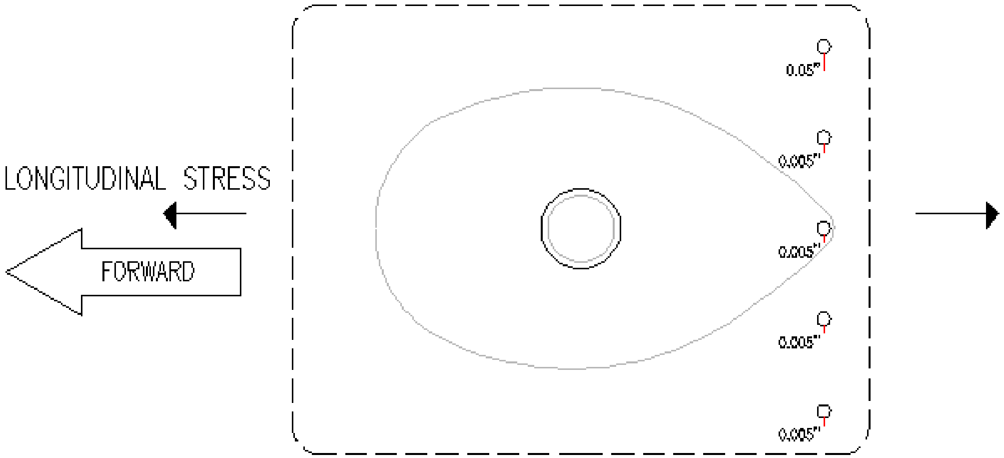
- **Circircumferential crack growth on skin from connector hole**

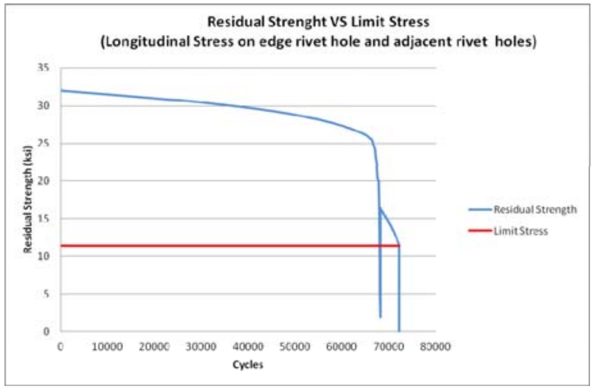




CRITICAL CASE

- **Circircumferential crack growth on skin along first rivet row**





Threshold and Inspection Interval

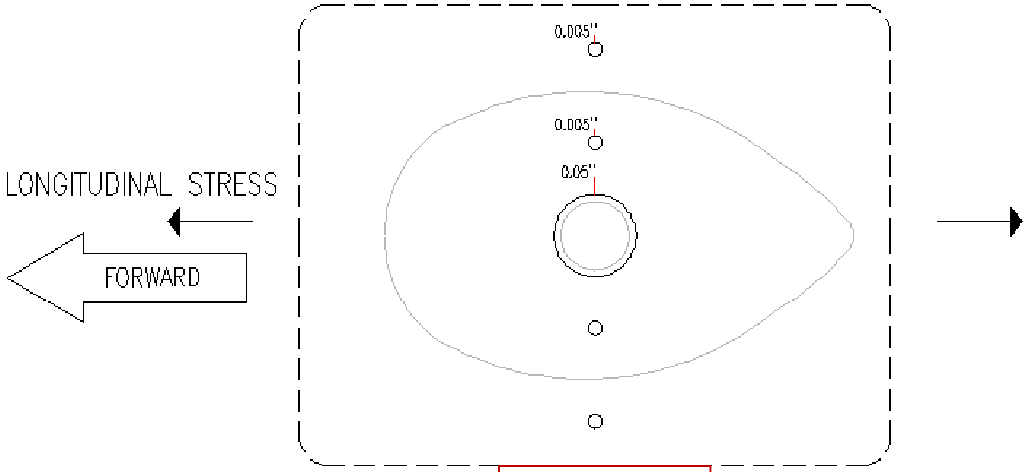
Threshold and Inspection Interval

- **Threshold**
  - **N_0 = N(a_{CR})/2 or N(a_{DET}) whichever is the less**
  - **The threshold was set to 0** because the antenna was installed prior the EASA STC approval (**history unknown**)
  - First inspection carried out immediately after the STC approval

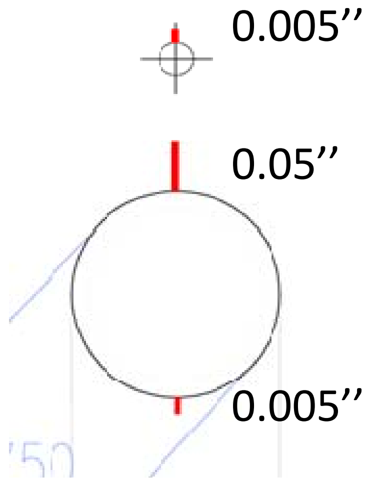
- **Inspection Interval – Safety Factor**
  - **Inspection Interval = [N (a_{CR}) – N (a_{DET})] / K**
  - Chicago paper : K=2
  - **Recommended: K=3**
  - Chosen: K=3*2=**6** (to cover unknowns)

Threshold and Inspection Interval

- For the crack growth initial scenario the Chicago policy requests a secondary crack emanating from connector hole



chosen

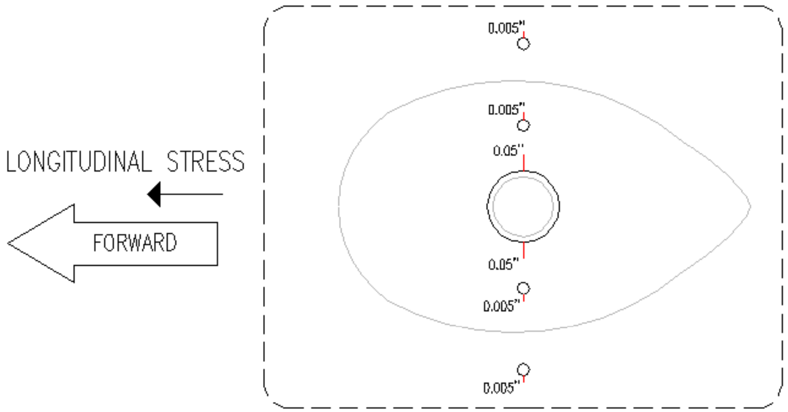


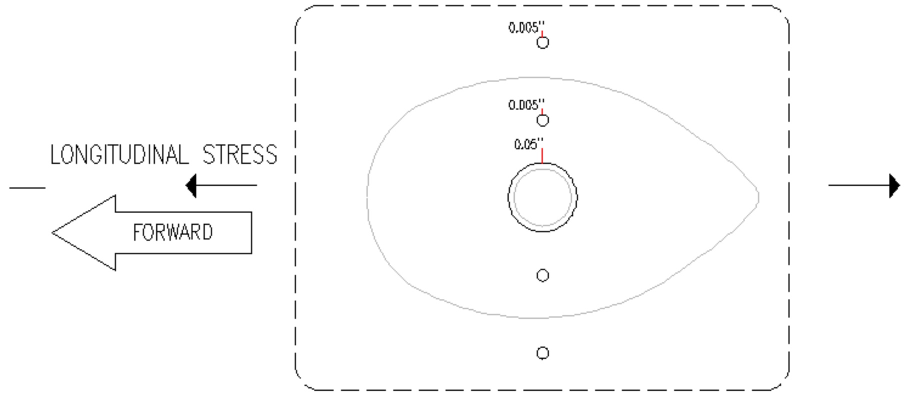
Chicago

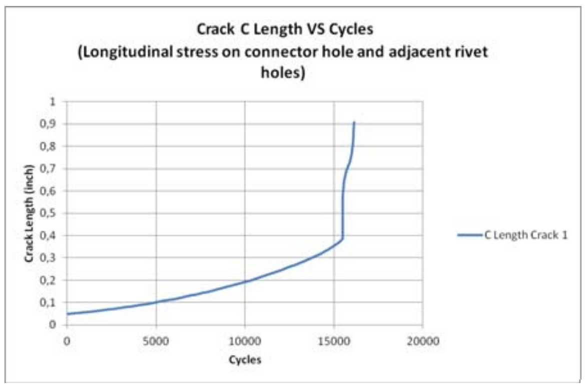
- The Applicant considered only a 0.05’’ initial crack emanating from the connector hole
- Nevertheless the safety factor of 6 covered this point

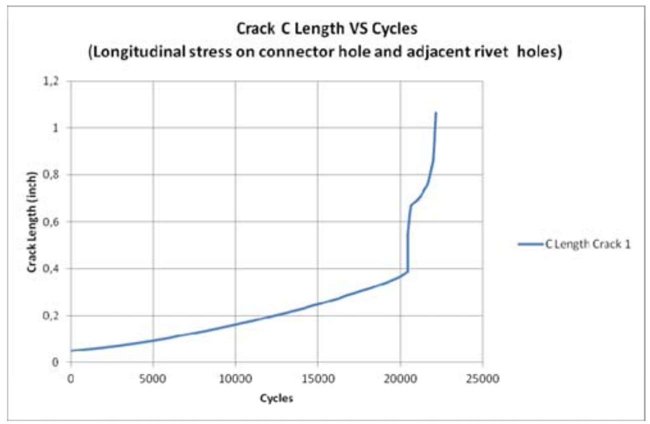
Threshold and Inspection Interval

- Comparison between two crack initial scenarios
- Critical case – Circum. crack on skin from connector hole









Threshold and Inspection Interval

a_{cr} = 0,55''

a_{det} = 0,125'' (Ultrasonic NDI)

Inspection Interval = $(N_{cr} - N_{det}) / K$

- **Case 1 – only primary crack from hole**

N_{cr} = 20500 cycles

N_{det} = 8300 cycles

K = 6

Interval = **2033 cycles**

- **Case 2 – primary and secondary crack from hole**

N_{cr} = 15500 cycles

N_{det} = 6600 cycles

K = 3

Interval = **2966 cycles**

Threshold and Inspection Interval

ALS

- No threshold published – First inspection requested immediately after STC approval
- Ultrasonic Inspection
- Antenna removal
- Inspection for cracks both on doubler and skin from inside and outside

Material characteristics

Material characteristics

- Conservative values were selected with respect to grain direction for crack propagation mechanical characteristics
- Walker equation coefficients for 2024-T3/T42 (T-L) from Chicago paper

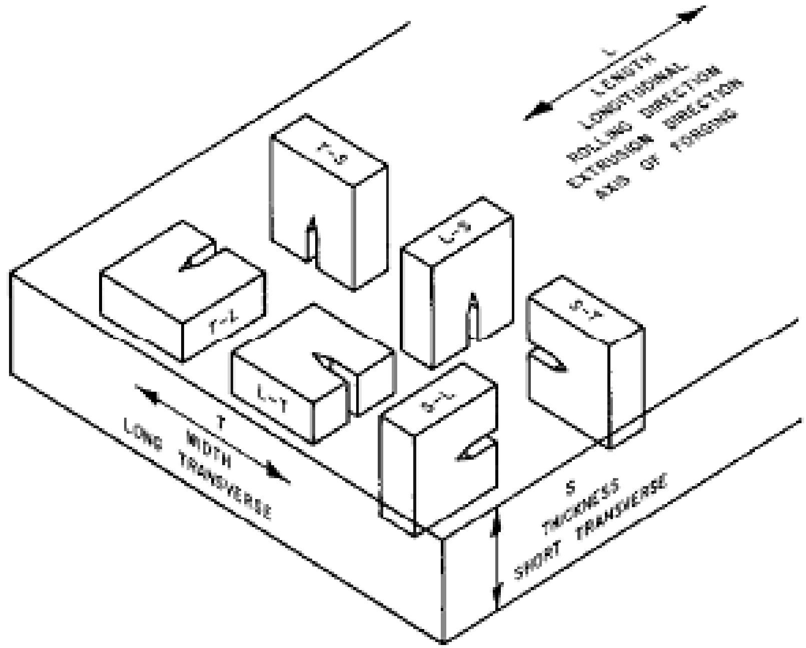


Figure 1.4.12.3(a). Typical principal fracture path directions.

Summary of Conservative Assumptions

Conservative Assumptions

- 1.1 factor on the differential pressure for crack propagation
- Stress reduction effect due to the stringers on longitudinal pressurization and beam stress neglected
- By-Pass Stress = Reference Stress
- Fuselage Weight = MTOW for beam stress calculation
- Circumferential and longitudinal stresses combined together
- Fatigue inertia load factor for crack propagation = 1.8
- Far field stress reduction due to the doubler neglected for skin crack propagation from connector hole
- No retardation effect
- Safety factor K=6 for the inspection interval
- Threshold zeroed (first inspection immediately after STC approval)
- Most severe material characteristics (grain direction)

Some criticality

Mandatory vs Sheduled Inspections

- Even if **crack life is greater than the a/c design (remaining) life** an adequate inspection program should be established

- **Long periods with residual strength under ultimate load capability should be avoided**

  in particular when accidental damages and/or corrosion are possible

- To be covered by **appropriate safety factors**

DOA Considerations

- STCs involving Antenna installation are usually originated by electro-avionic modifications
- DOAs (STCH) with no (or limited) experience in DTA is not unusual
- Designers and CVEs can have a “non-structural” background

… Nevetheless they need to perform and check DTA

DOA Considerations

How the DOA should demonstrate its capability?

- **Courses** on structural repair and DT for people involved
- **S/W** tutorial
- 2 – 3 STCs should be reviewed by the Certification Team in order for the DOA **to define, discuss an agree a conservative DT methodology**
- The level of conservativism should be **adequate for the DOA** and could be reduced over time as enough experience is gained
- The methodology should be frozen in a **design manual** in order for the DOA to exercise its privileges

Conclusions
and Reference Material

Conclusions

- STC antenna installation can be addressed by **simplified methodologies** based on a constant aplitude crack propagation models
- A number of conservative assumptions can be established taking account of **DOA experience**
- Particular attention should be paid – among others to:
  - **Load spectrum**
  - **Doubler load transfer model**
  - **Crack propagation model and S/W used**
  - **Effectivness of NDI and maintenance tasks**

Reference Material

- **FAA Chicago Aircraft Certification Office**, *Damage Tolerance Analysis for Installations on Pressurized Transport Airplanes*, J. H. McGarvey, FAA, 2002.

- **TCAA SI 513-001**, *Approval Procedure s for Modifications and Repairs to Damage Tolerant Aircraft Structures*

- **DOT-VNTSC-FAA-91-16**, *Generation of Spectra and Stress Histories for Fatigue and Damage Tolerance Analysis of Fuselage Repairs,* FAA,1991

- **FAA-AIR-90-01**, *Repairs to Damage Tolerant Aircraft,* T. Swift, FAA, 1990

Thank you for attention!

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