Cessna Twin Wing Spar Theory and Practice

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- Founder, CIHOLAS Enterprises (electronics research and development)
- Pilot, PP-ASEL-IA, 2000 hours
- Owner, Cessna T210L
- Potential owner: 421C
- Objective: examine basis and provide alternative approaches

Outline

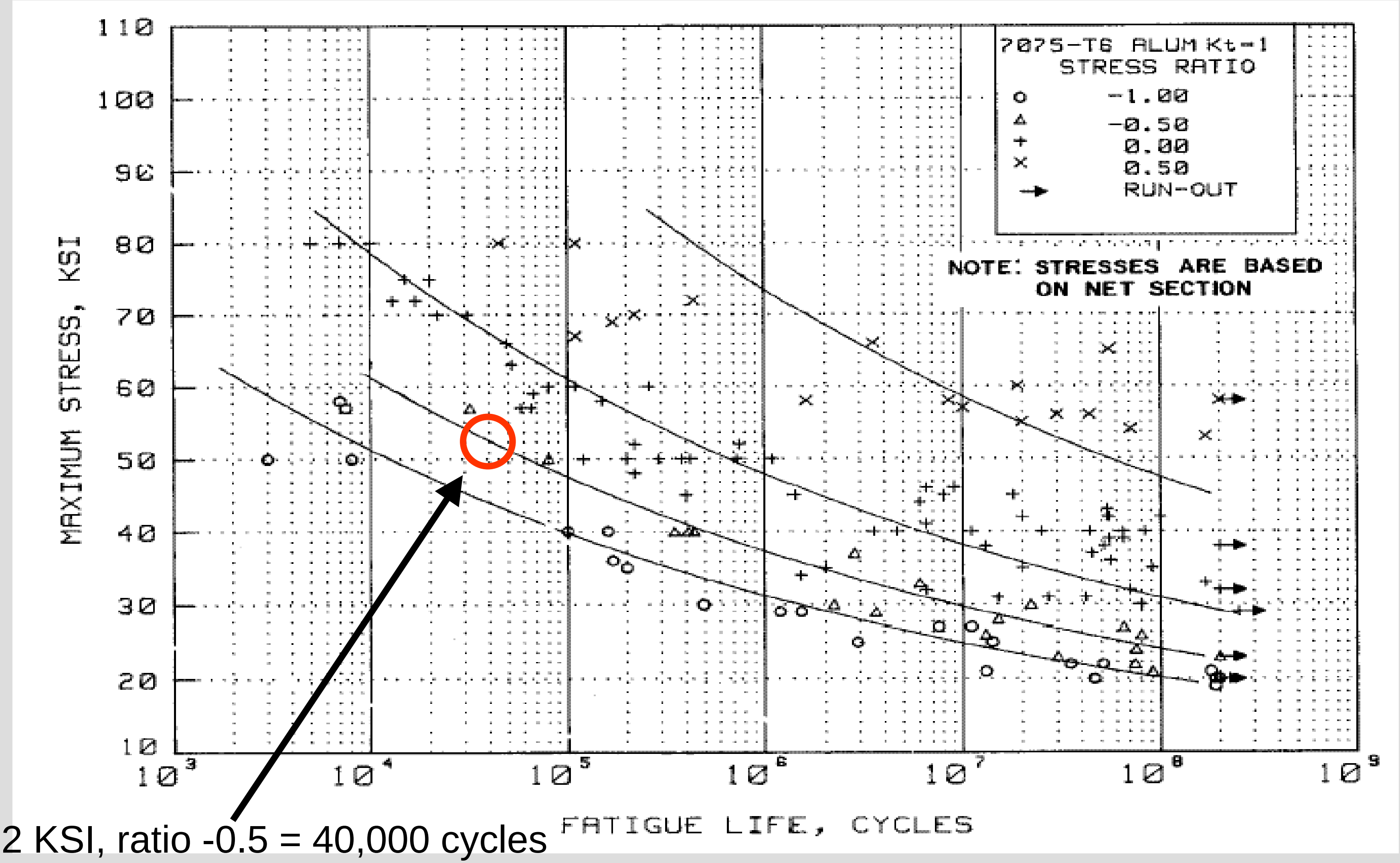
- Compliance Times:
  - How sensitive is fatigue life?
  - Stress computation
  - Crack computation
  - Setting fatigue life
- Field Data
- Conclusions
- Suggestions

How Sensitive is Fatigue?

Fatigue: How Sensitive?

- 7075 yields at ~75 KSI
- +3.8G is 100% limit load
- Yield is at 150% of limit load, ~5.7G
- Assume a gust of +/- 3G (-2G to +4G)
- Spar stress -26 KSI to +52 KSI in gust
- Stress ratio is -0.5 (-26 KSI / +52 KSI)
- So, how many cycles is that?

SN Curves



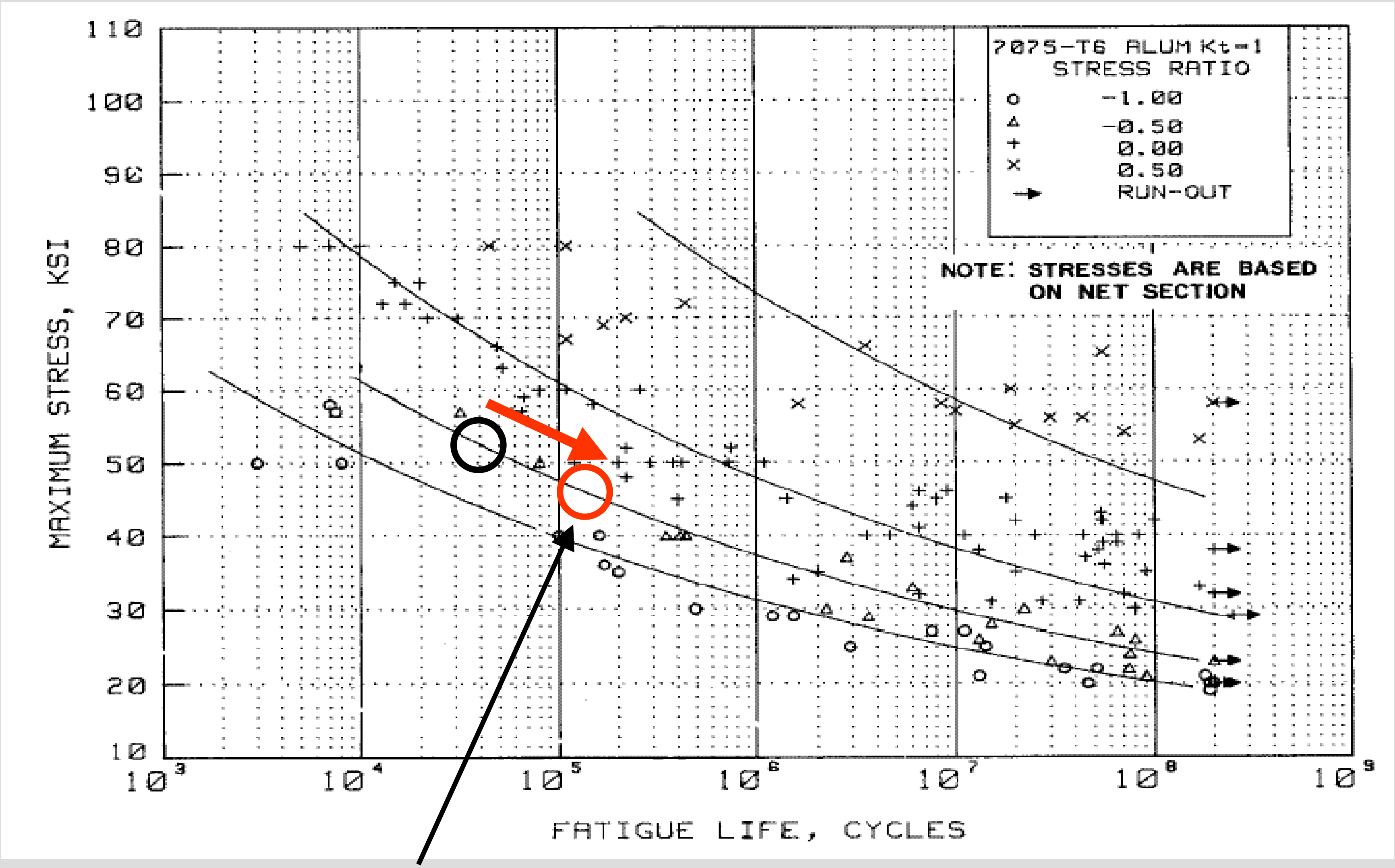
52 KSI, ratio -0.5 = 40,000 cycles

Source: MIL-HDBK-5J Figure 3.7.6.1.8(a)

Make Small Adjustment

- Suppose spar has 10% margin above CAR 3.173 requirements
- Spar then can hold 165% limit load, 6.3G
- Stresses reduced by 10% during gust
- Same gust applied
- Spar cycles -23 KSI to +47 KSI
- Stress ratio still -0.5
- How many cycles now?

SN Curves

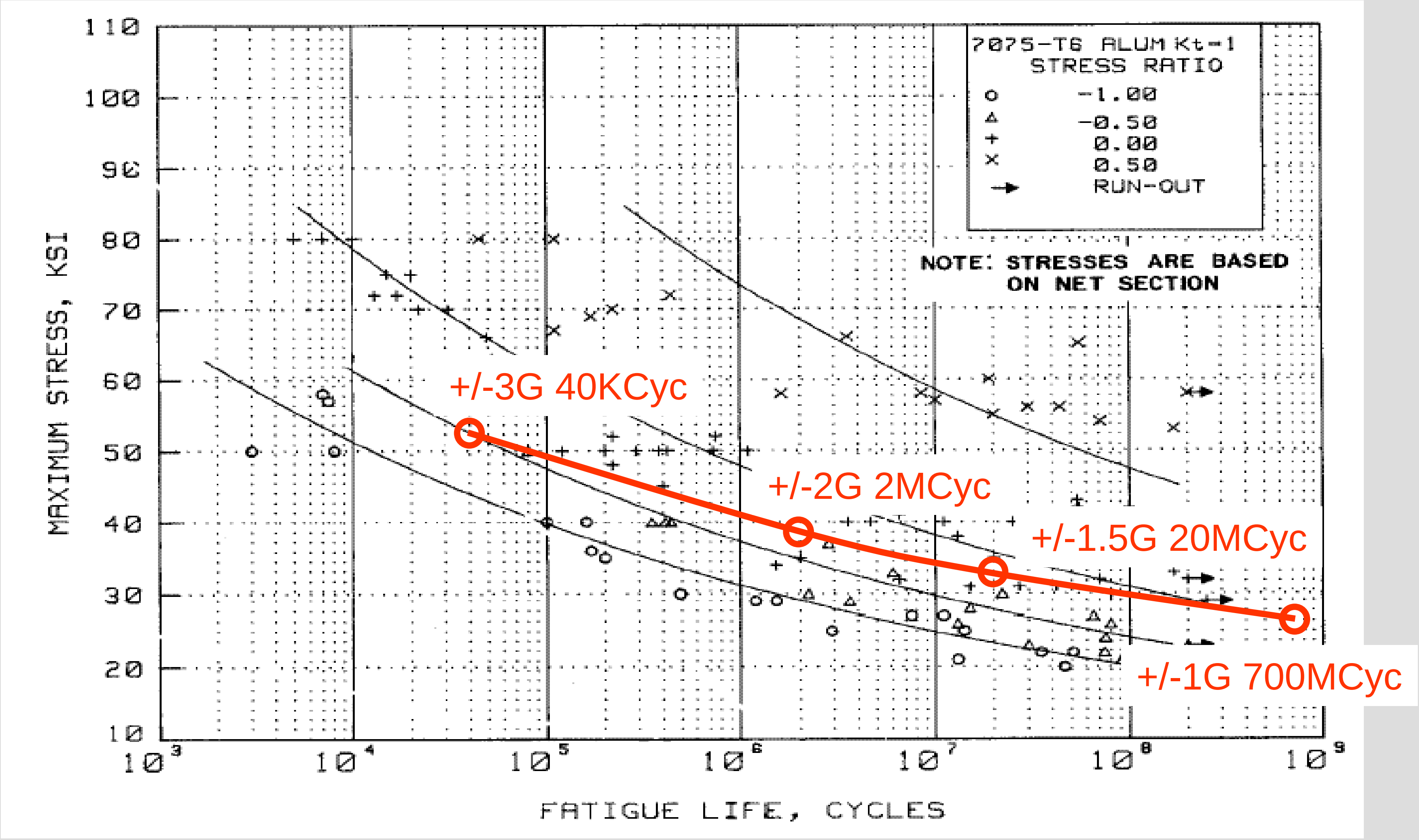


47 KSI, ratio -0.5 = 130,000 cycles

Stress “Profile”

- As gust loads go down:
  - Max stress level reached decreases
  - Stress ratio increases (stress amplitude smaller)
- We can draw the stress “profile” on the SN curve as an airplane experiences various gust loads
  - +/- 3G: 52 KSI, ratio -0.50
  - +/- 2G: 39 KSI, ratio -0.33
  - +/- 1.5G: 33 KSI, ratio -0.20
  - +/- 1G: 26 KSI, ratio 0.00

Stress “Profile”



Source: MIL-HDBK-5J Figure 3.7.6.1.8(a)

SN Curves: Meaning

- At very high G loadings, 10% reduction in stress is 3 times the life, 20% reduction is 10 times the life.
- At lower G loadings, life improvement is even greater.
  - Stress is lower (curve gets flatter)
  - Stress ratio increases (smaller stress amplitude relative to static stress)
- Error “gain” is at least 30, could be much higher

Computing Stress

Computing Fatigue Life

- Stress equation
  - Determine how lift, load, gusts create stress
- Load profile
  - Determine load distribution
- Fatigue damage
  - Apply load/gust spectra to create stress
  - Measure crack formation and growth
- Set fatigue life
  - Set reasonable lifetime for desired probability

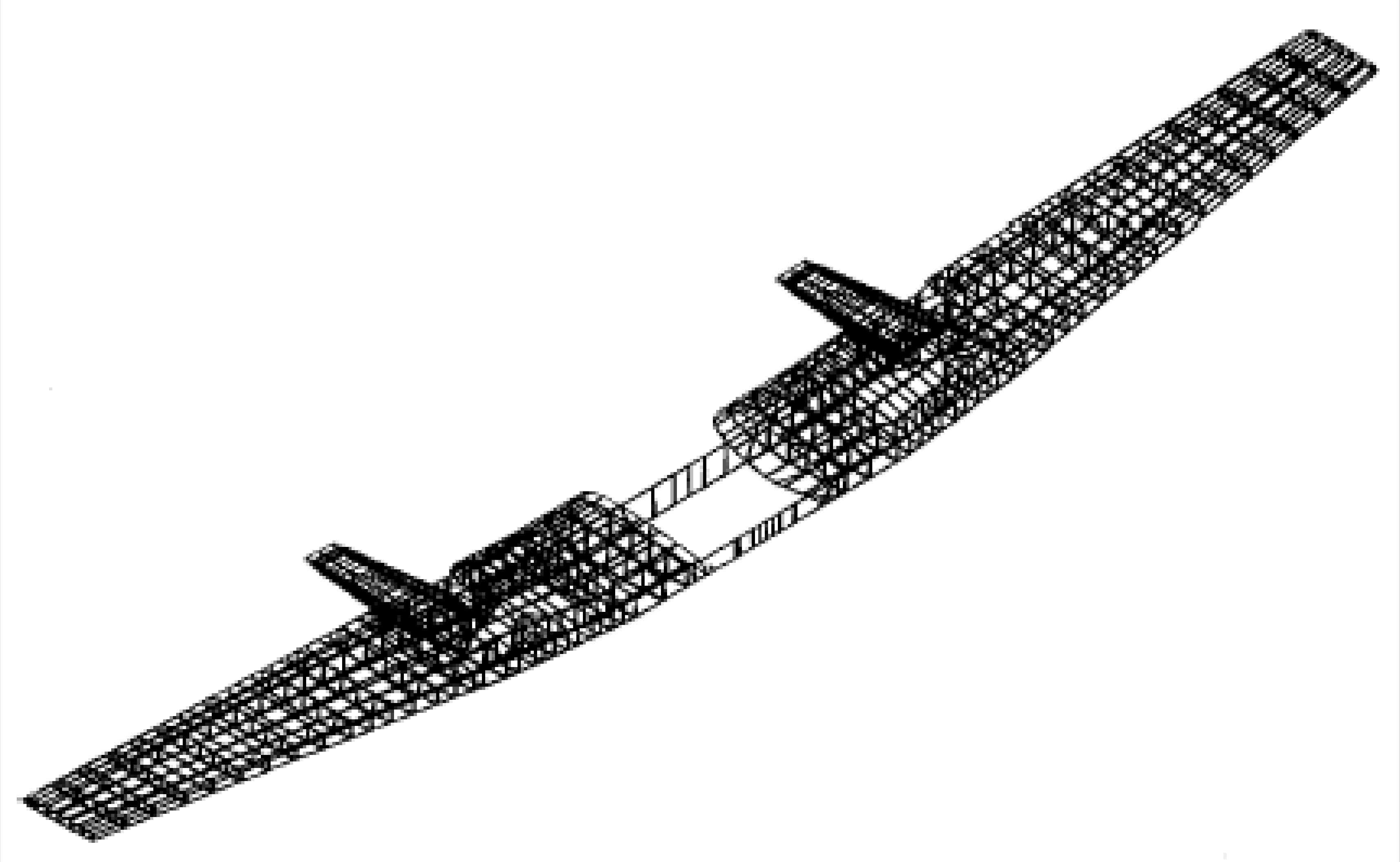
Cessna: Stress Equations

- Cessna uses Finite Element Analysis (FEA) to generate computer model
- Stresses in spar are derived from loading this model
- FEA model has significant potential for error
- Errors can be buried deep inside subtle assumptions and are not easily detected

FEA Model

- Constructed of primitives: CBEAM (spar caps), CQUAD (flat rectangular plates), and CTRIA (flat triangular plates).
- Simplistic primitives fail to account for real world effects of:
  - Lightening holes
  - Rivet bond lines
  - Stiffening flanges

FEA Model



Source: Cessna SID report 98/66 Figure 3

Reality

Source: Cape Air Slide 18

FEA: Simplistic

- To make FEA model computationally reasonable, must simplify
- Simplifications deviate from actual structure in significant ways
- Deviations not easily detected or measured

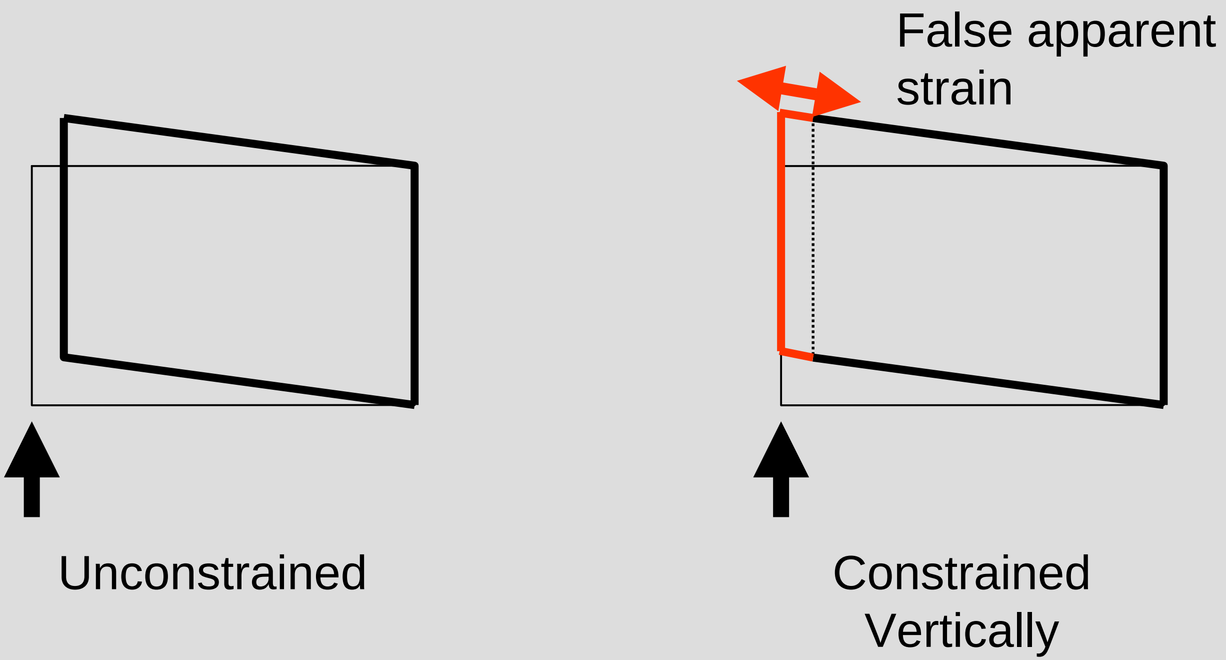
Convergence

- FEA computation requires “convergence”
- Stress causes dimensional change
- Changing dimension of one part affects all neighboring parts
- Changing neighboring parts affects the first part
- Solution is iterative, it “converges”
- Complex FEA models take a long time

NASTRAN Constraints

- Convergence speed can be dramatically improved by adding “constraints”
- Constraints reduce freedom of movement
  - Example: constrain point to vertical movement
- But, constraints can inject false stress if model “fights” it
- Here is one example…

Shear Web



Vertical constraint induces false strain in model
Error on each web is small, but accumulates

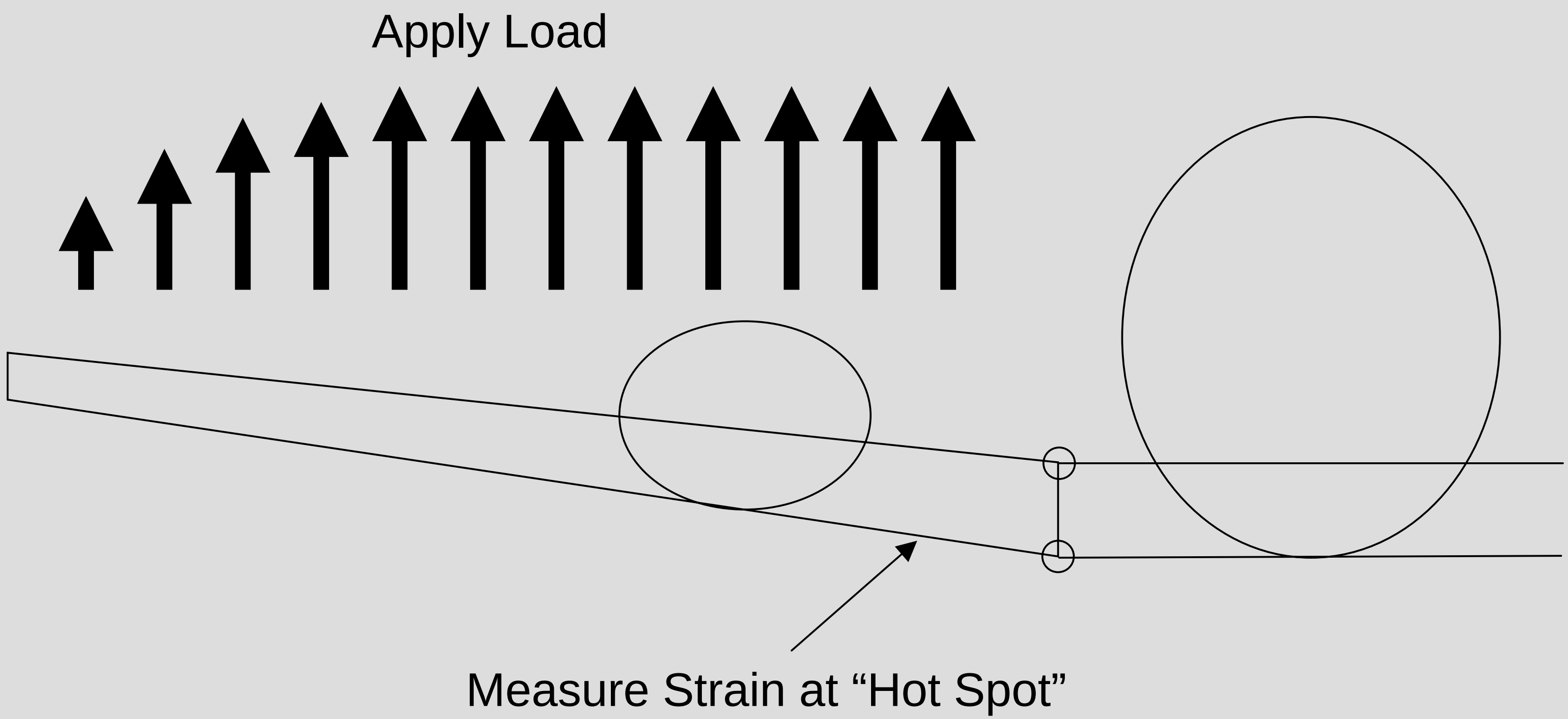
Constraints

- Public has no visibility into FEA model
- Constraints can be so subtle that model creators don’t realize it
- Data from FEA model should be carefully evaluated

FEA Verification

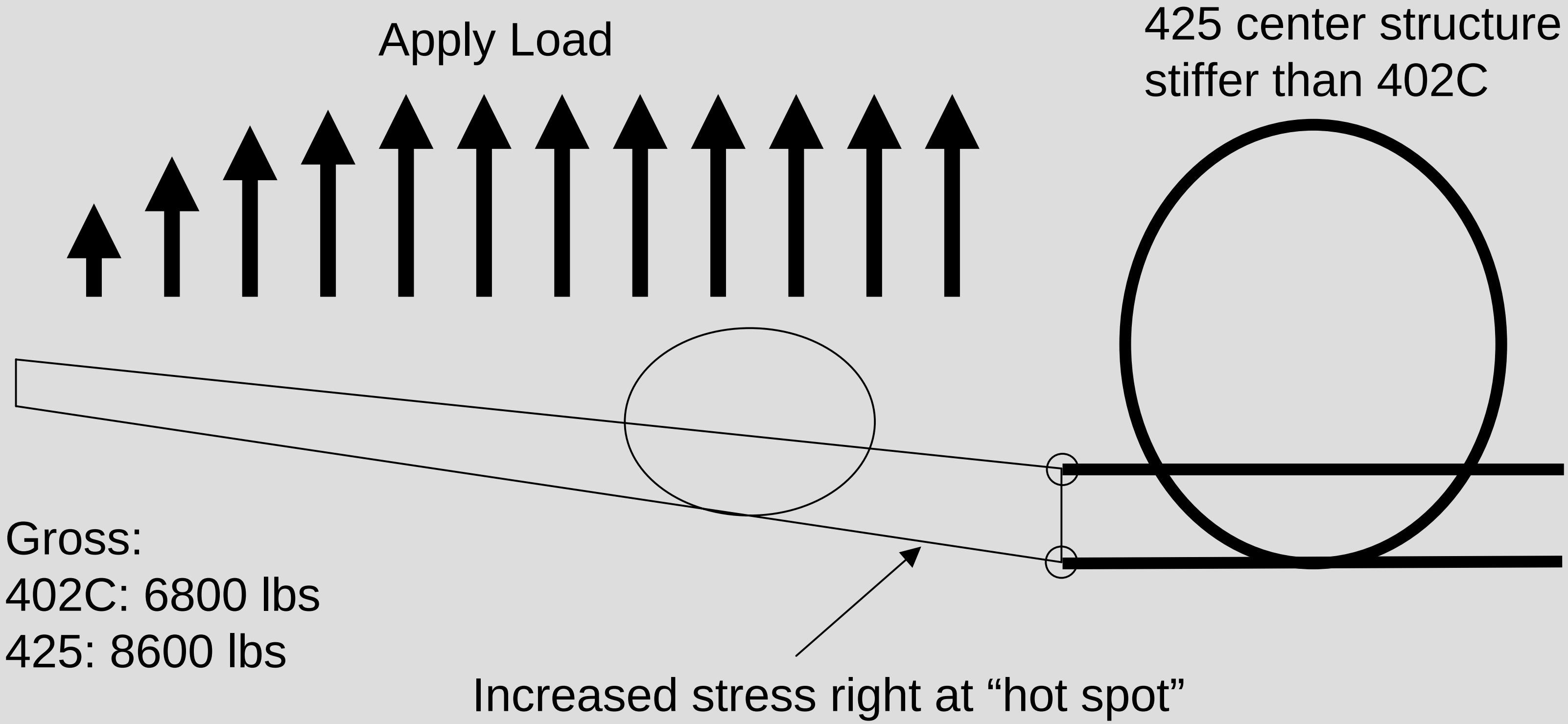
- Verification necessary due to FEA simplifications
- Only one test performed, on salvaged 402C wing
- Wing mounted on 425 fuselage
- Test: positive limit load

Load Test, Ideally



Adjust FEA model until theoretical equals measured

Load Test, Really

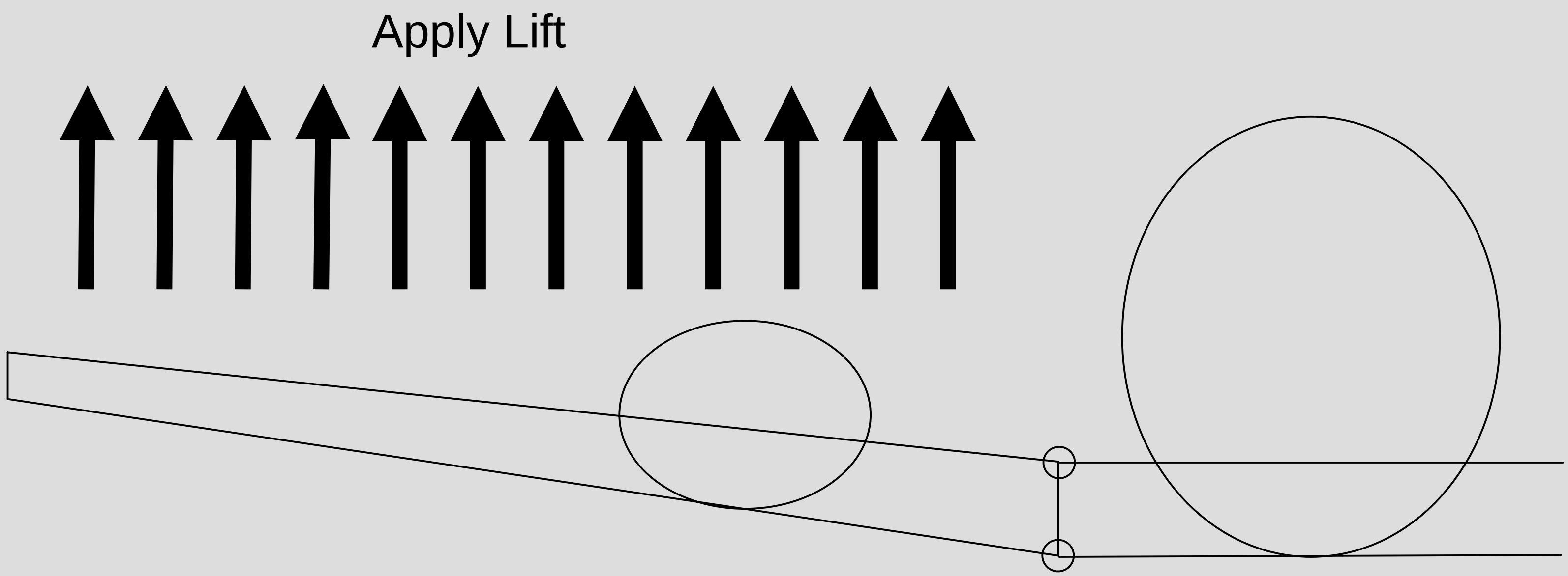


Using stiffer fuselage falsely concentrates stress on spar.

Lift Distribution

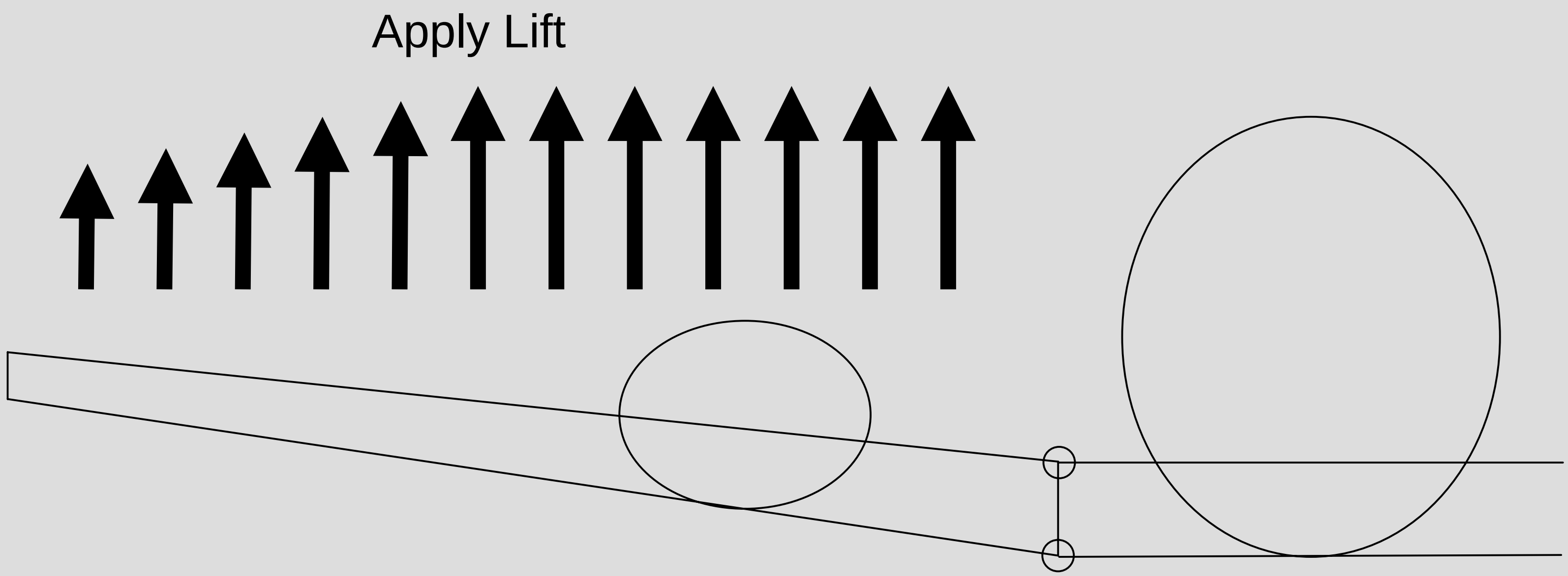
- For FEA and lab test, must apply lift to wing
- Lift distribution tell us where to apply lift and how much
- Lift distribution is complex so simple approximations are often used

Lift Distribution, Uniform



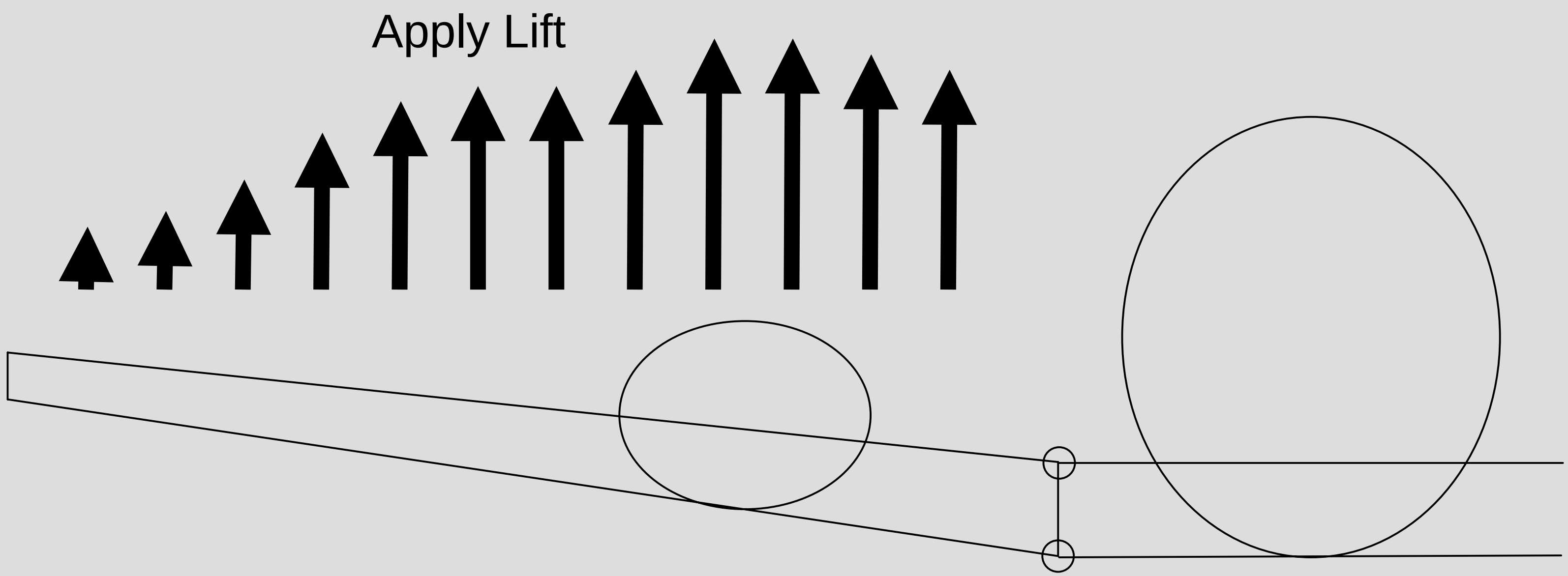
Uniform lift: Simple, but wrong.

Lift Distribution, Wing Area



Wing area lift: Better...

Lift Distribution, Realistic?



Many factors: wing washout, wing taper, wing area, nacelle lift, tip tank effects, prop wash, etc…

Nacelle Lift

- Twin Cessna noted for large nacelle area
- Nacelle produces lift beyond the “wing projection”
- Lift especially pronounced at high angles of attack, as would be found in strong gusts
- Nacelle forward area is pitch destabilizing, one factor resulting in huge stabilizers on a Twin Cessna
- Nacelle lift moves center of lift inboard and reduces moment and stress in spar

Lift Distribution

- Complex: varies with CG, indicated air speed, weight, engine power, prop wash, etc
- Most simplifications tend to move lift vector outboard thus increasing spar stress
- Lift distribution not detailed in Cessna report

Load Distribution

- Load distribution is the placement of weight throughout the aircraft
- Load distribution has a dramatic effect on spar stress, particularly in a twin (wing borne weight much higher than single)
- Includes: structure, engine, fuel, interior, people, cargo, etc
- Possible source of error

402/402A/402B Refinements?

- Cessna refined 402C model with actual 402C wing
- No test seems to have been done on 402/A/B wing model
- Did Cessna apply the “refinements” to the 402/A/B model?
  - If so, how given different structure
  - If not, then model is not “refined”
- How big is the “refinement” anyway?

Cessna Flight Survey

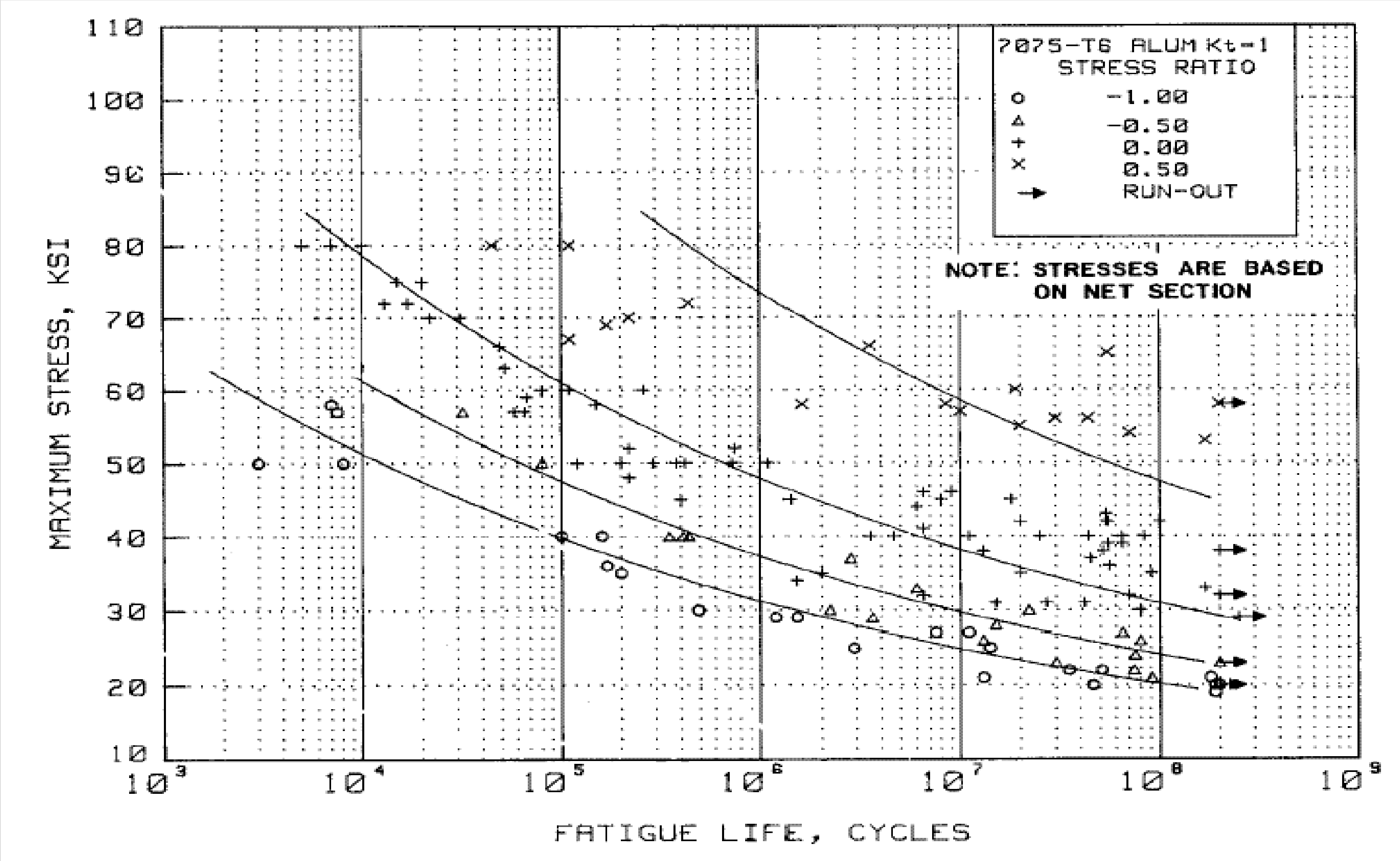
- Cessna did fly a 402C to measure strains
- Objective: determine stress equations for various configurations
- Subject to two adjustments:
  - NAF (net area factor)
  - TF (transfer factor)
- TF: depends on FEA model
- No other type flown, how does data apply to them?

Crack Growth

Material Properties

- Cessna tested six 7075-T6 pieces to establish crack growth
- Tested two pieces at 3 different stress ratios
- Subject to lab variations at Cessna
- High variance in such testing
- Six samples not enough to determine true material behavior

SN Curve Data Points



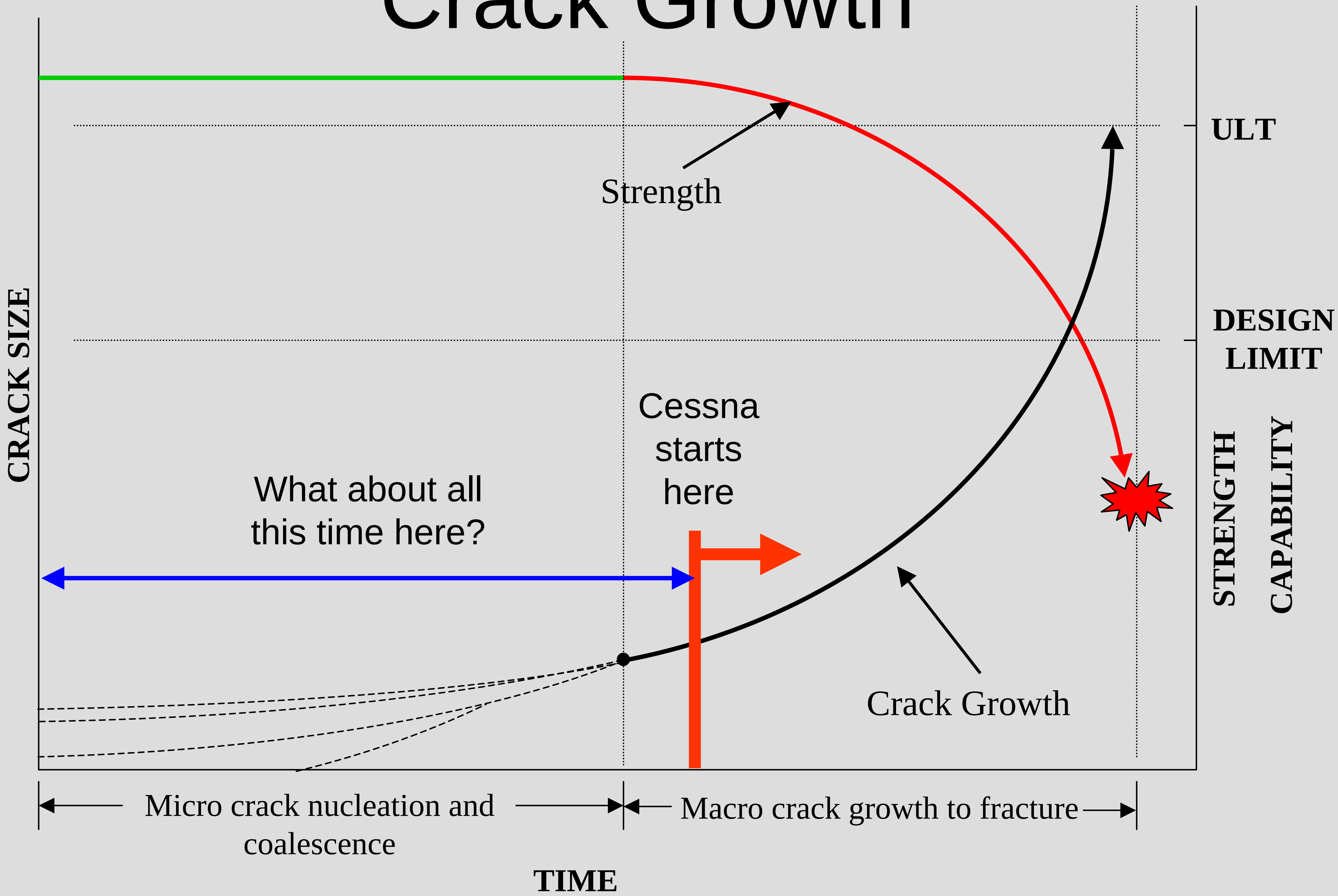
Source: MIL-HDBK-5J Figure 3.7.6.1.8(a)

Crack Growth

- Cessna assumes initial flaw sizes
  - 0.05” primary flaw
  - 0.005” secondary flaw
- Justification for those sizes?
- Cessna:

  “The initial flaws are assumed to exist … at the most unfavorable location and orientation with respect to the applied stresses and material properties.”

Crack Growth



Crack Growth

- Cessna put large flaws at the worst place
- Cessna then computed fatigue lifetime
- Fatigue lifetime applied to entire fleet
- Very unlikely that all airplanes have primary flaws in the worst place
- Thus, fatigue lifetime for the entire fleet is underestimated

The “Kf” Factor

- “Kf” measures how stress concentrates
- Cessna uses 3.0 to 9.0 based on cyclic testing
- If no cyclic data, Cessna defaults to Kf=6.0
- Cyclic testing subject to many possible errors
- Kf likely to have large impact on fatigue life yet little hard basis for choosing one value or another
- Huge variation in stress yields enormous variation in fatigue life

Analytical Mean Life?

- Cessna: “The analytical mean life predicted by the analysis is defined as the time when 50% of the fleet aircraft are expected to have developed small cracks (typically 0.05 inch in length)”
- But wait, didn’t we start with 0.05” cracks?
- So what is this “analytical mean life”?

The “Scatter” Factor

- Cessna computes fatigue life when 50% of fleet affected to some point
- Cessna divides this life by a “scatter” factor to find compliance time
- Cessna chooses “4” or “8” based on existence of “test data”
- Factor of two in fatigue lifetime based on this choice

Load Spectra

Usage Models

- 402 usage detailed in Cessna study
- Based on only 17 operators surveyed
- Vast majority of flights short hop, high cabin load, low altitude
- No such usage data collected for types other than 402
- Was 402 data used for 401, 411, 414?
- How do you get 9 people on a 414?

Gust Spectra

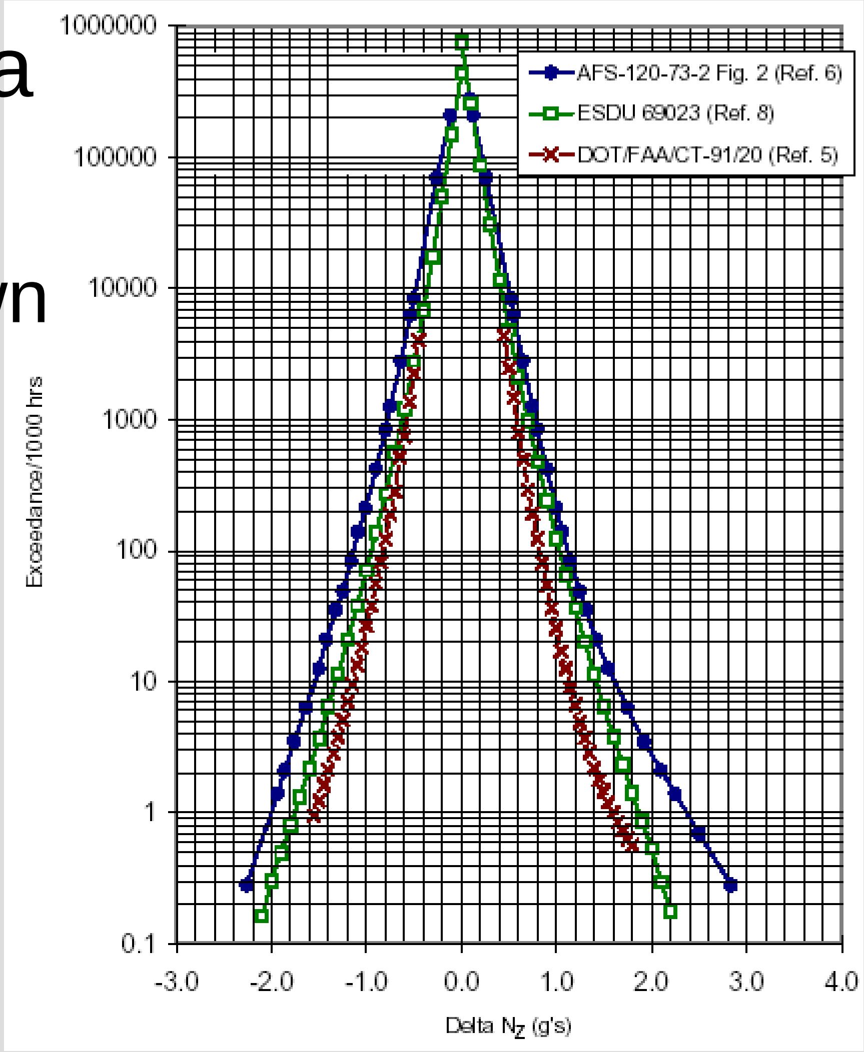
- Gust spectra is the expected distribution of turbulence an airplane suffers
- Probably the dominate cause of fatigue damage (not GAG cycle, taxi, maneuver)
- Gust spectra varies wildly with terrain, altitude, time of day, time of year, geography, weather

Cessna Gust Spectra

Three references shown
Appear to be similar?
No, not really…

At +1G: 210, 130, 26
At -1G: 210, 70, 26

Nearly 10:1 variation



Source: Cessna SID study, figure 29

Which Gust?

- How do you choose which spectra to use?
- Cessna simply chose the “middle one”
- Some evidence suggests these gust spectra overestimate airline usage
- “The gust load factor spectra prescribed in AFS-120-73-2 for use in the fatigue design of “general usage, twin engine” aircraft were considerably more severe than those encountered by this commuter airline in normal operations.”
  - **Statistical Loads Data for BE-1900D Aircraft in Commuter Operations**

Gust Diminishing Factors

- Higher altitude
  - Common for turbocharged (all)
  - Very common for pressurized (414A)
- Pilot discretion
  - Seeking smoother air
  - Flying around build ups
  - Schedule flexibility
- Longer Flights
  - Less time at low altitudes
- Part 91/135 versus 121

Error Sources

- Fatigue life very sensitive
- Structural analysis (FEA, tests, cyclic)
- Load/lift assumptions
- Crack sizing and growth
- Gust spectra
- Usage profiles

The Cessna computed fatigue lifetime could easily be in error by a factor of 10 or more

Field Data Analysis

Field Data Analysis

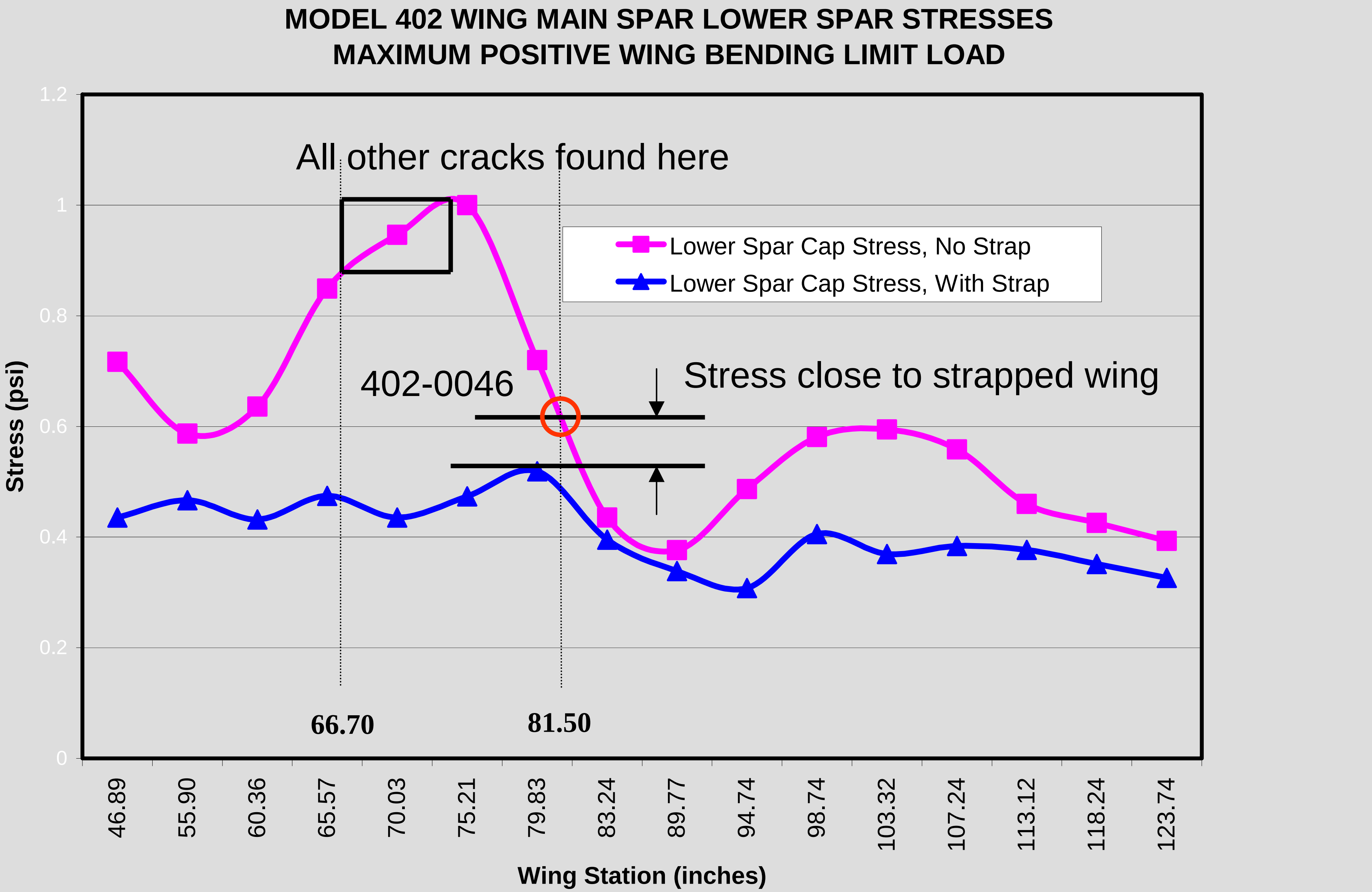
- Find airplanes with cracks
- Eliminate cracks due to causes other than fatigue in conforming airplanes
- Study those legitimate fatigue cracks to see if they support the study hypothesis and compliance times suggested
- Look at lab fatigue testing

402C (Goldsby, OK)

- Wing separated in flight
- NTSB: Manufacturing defect, inadequate maintenance
- Although failure was fatigue, the true cause was a manufacturing defect that greatly accelerated the fatigue
- Not a viable field sample
- FAA did not list (Easton, Slide 16)

402-0046

- Noted to have had engine fire that reduce spar cap to 50% (Easton, Slide 16)
- 50% strength greatly reduces fatigue life
- Crack location in relatively lower stress section
- Only crack located behind engine where fire would be a factor
- 402-0046 crack caused by the fire
- Not a viable field sample

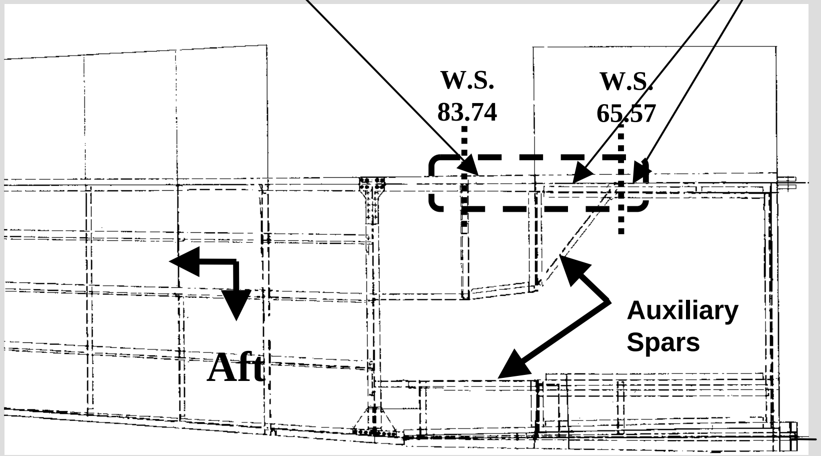


Source: Eastin Slide 20

402-0046 Crack Location

402-0046 only crack found behind engine nacelle

All other cracks are inboard from engine



Source: Eastin, Slide 17

What’s Left?

A/P Serial No.	Flight Hours	Wing Station	Location	Crack Discovery Date	Failure Mode
402-0295	8057	74.50	Aft Flg	1978	Complete cap failure – Left Wing
402A-0043	13824	67.14	Aft Flg	1990	.05” crack detected when evaluating new NDI equipment.
402-0101	16000	71.90	Fwd Flg	1992	Complete cap failure – Left Wing
402A-0080	13773	67.65	Fwd Flg	1992	Complete cap failure – Left Wing
402-0216	9012	67.14	Fwd Flg	1992	Spar cap ligament failure – Left Wing

Source: Eastin, Slide 16, and Gamble, Cessna (crack dates)

Oddities

- No cracks in other than 402/402A?
- Left wings?
- 3 cracks in 1992?
- No cracks since 1992?

No Cracks in Other Types?

- Given fleet exposure, one would expect cracks in other types
- But perhaps other types have different usage, loads, experience, age
- Okay, so how do we compare?
- Let’s create two populations: 402/402A and 402B

402B Reference

- To make things simple, let's ignore 401, 411, 414 and concentrate on 402B.
- 402B versus 402/402A:
  - Same weight (6300 lbs gross)
  - Same wing (per Cessna)
  - Same mission
  - Roughly same age (1967 – 1978)
- 402B should have similar crack history

Correct for Age Differences

- Youngest 402B is 26 years old (1978)
- Oldest 402 is 37 years old (1967)
- All have experienced the first 26 years
- Thus ignore cracks found in airplanes older than 26 and age is removed as a distinguishing factor between 402/402A and 402B

Age When Crack Found

A/P Serial No.	Flight Hours	Wing Station	Location	Crack Discovery Date	Aircraft Age When Crack Found
402-0295	8057	74.50	Aft Flg	1978	10 years
402A-0043	13824	67.14	Aft Flg	1990	21 years
402-0101	16000	71.90	Fwd Flg	1992	25 years
402A-0080	13773	67.65	Fwd Flg	1992	23 years
402-0216	9012	67.14	Fwd Flg	1992	24 years

All cracks found in aircraft younger than 26 years

No unfair age bias against 402/402A population if we consider all crack data

Flight Hours

- 402/402A and 402B sold for airline duty
- Probably got heaviest use early in life as it was reasonable to trade in for new aircraft through the 1970s (Cape Air flying only 402C now)
- FAA assigned 9000 hours average and did not distinguish between populations
- Assume flight hours accumulated in first 26 years of life roughly equal among 402/402A and 402B populations

Source: Nuss, Slide 10

Statistical Independence

- Hypothesis: "402/402A airplanes and 402B airplanes have the same probability of developing a fatigue crack during their first 26 years of life"
- In other words, being a 402/402A or a 402B should be statistically independent from your chance of developing a fatigue crack

Population Sizes

- Population size changes constantly (foreign registered, scrapped, retirement, accident, etc)
- Number built by Cessna
- FAA given numbers
- As long as the population relative sizes (402/402A versus 402B) remains the same, analysis produces meaningful results.

Population Sizes, Built

- 401/402 serial numbers mixed, 321 units built, assume even split (roughly the split for 1969 401A versus 402A)
- 402: 160 airplanes (estimate)
- 402A: 128 airplanes
- 402B: 827 airplanes
- Population 402/402A is 288/1115 or 26%
- Population 402B is 827/1115 or 74%

Source: Cessna Wings for the World III, Thompson

Population Sizes, FAA

- 402: 50 airplanes
- 402A: 49 airplanes
- 402B: 267 airplanes
- Combine 402 and 402A into 99 airplanes
- Population 402/402A is 99/366 or 27%
- Population 402B is 267/366 or 73%
- 402Bs outnumber 402/402A by 3 to 1

Source: Nuss, Slide 10

Population Similarity

- Ratio of 402/402A to 402B remarkably stable over a very long time
- Rate of deregistration nearly exactly the same: 402/402A/402B 34% left (414A, 60% left)
- Suggests similar risks, uses, customers, economics
- Suggests the two populations have similar life experiences, should have similar fatigue exposure

Test the Hypothesis

- We have 5 cracked airplanes
- What is the chance all 5 would end up being from the 402/402A population and none from the 402B population?
- $(0.27)^5 = 0.0014 = 0.14\%$
- Or, 99.86% chance that it does **NOT** happen, or 700 to 1 odds against

It is at least 99.86% likely that 402/402A and 402B are *DIFFERENT*

The real safety question is *WHY*?

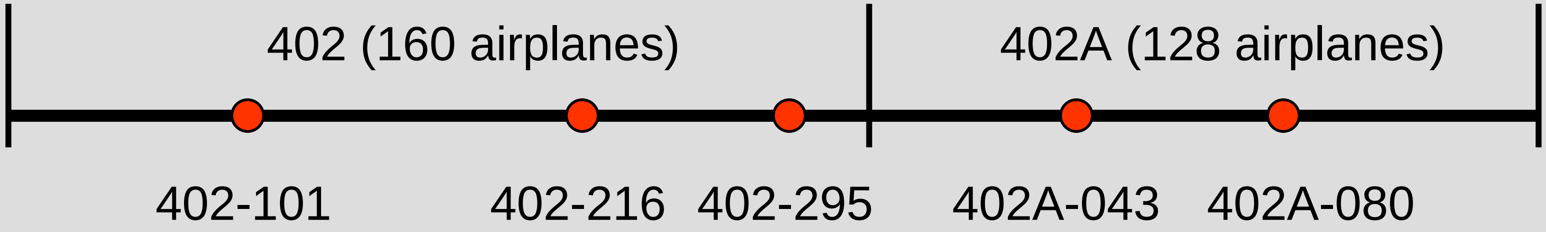
It is dangerous to ignore this question

402/402A Relative Risk

- How much imbalance is the risk of a crack between 402/402A and 402B?
- If 402/402A was 4 times more likely to crack, the chance all 5 cracks would be 402/402A is still only 7%, or 93% against
- For 50/50 odds, the risk ratio goes to 18
- It would be extraordinary to find a non machine related reason for this

402/402A

- 402/402A are extremely likely to be different structurally
- Difference is likely to be design, manufacturing, or materials
- I suspect a consistent error due to amazingly uniform distributions of cracks:



What About 401?

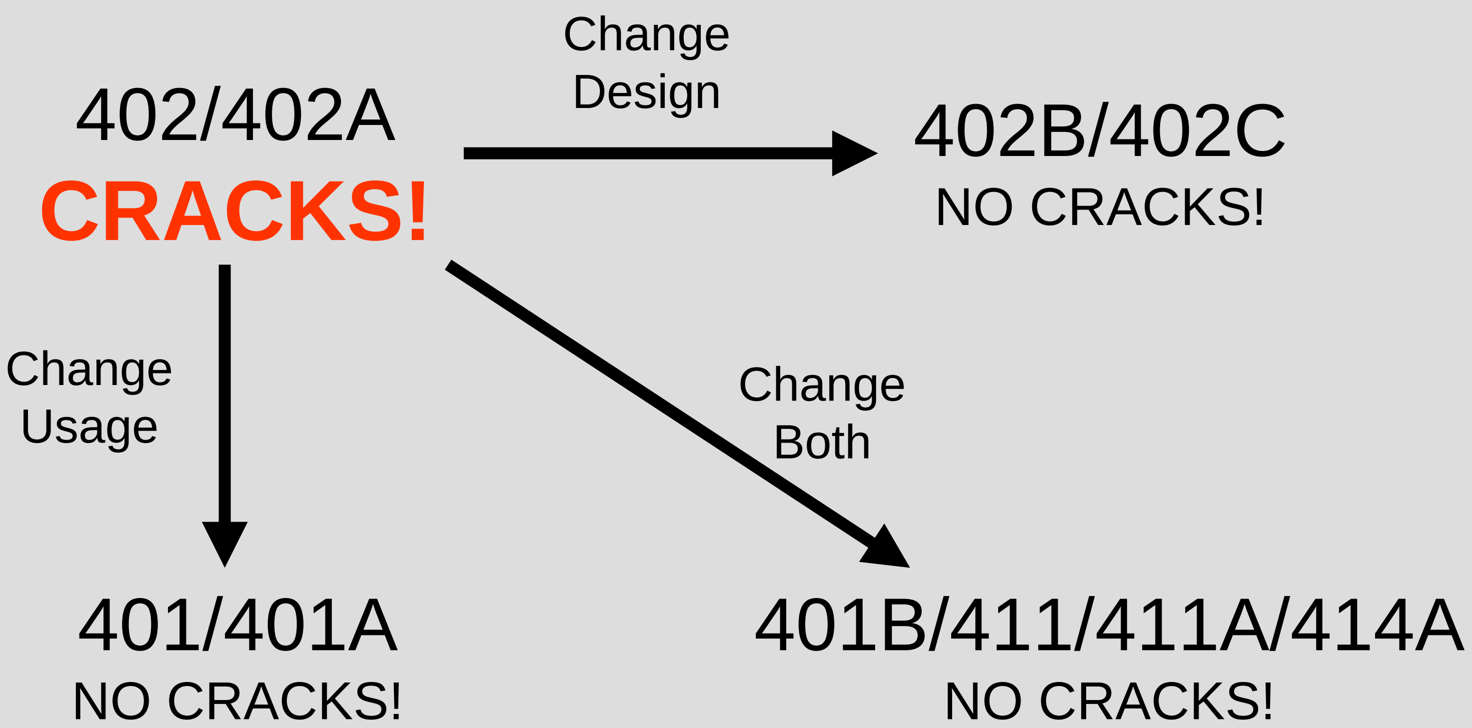
- 401/401A are the same airplane as 402/402A with different interior
- 401 usage is executive transport, higher fuel load, lower cabin load, longer flights, smoother air
- 401 sees reduced spar stress as a result
- I suspect the same deficiency in 402/402A exists in 401/401A airplanes (made on same assembly line)

No 401/401A cracks?

- No reported 401/401A cracks even though fleet size now larger than 402/402A
- 401 registration rate: 54% (34% for 402)
- 401 usage pattern causes reductions in stress
- Small reductions in stress yield large improvements in fatigue life
- 401 will have significantly longer fatigue life than 402 for that reason

Changing design **or** usage eliminates cracks

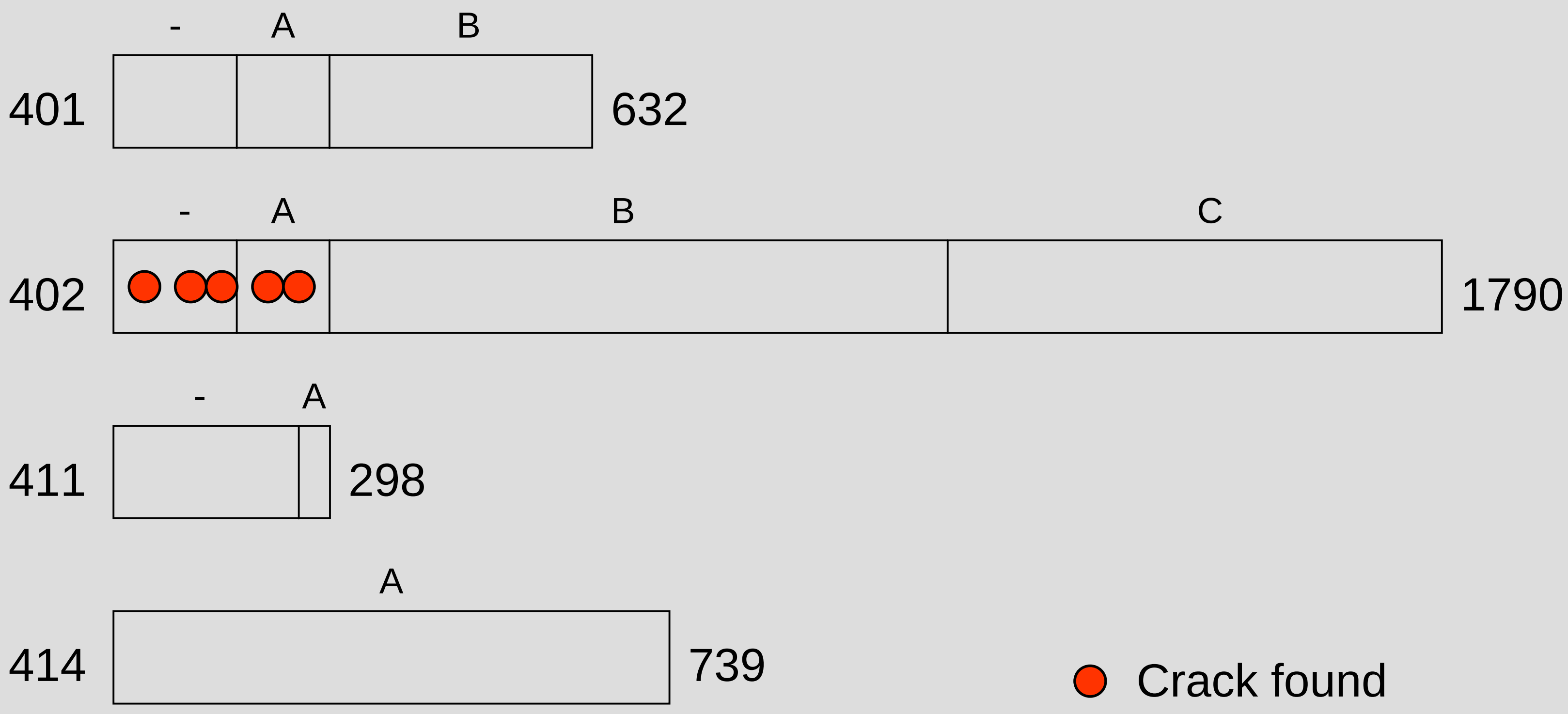
Doing **both** significantly improves fatigue life



Other Types?

- No cracks have been reported in 401, 401A, 401B, 402B, 402C, 411, 411A, or 414A
- No cracks have been reported in any other twin Cessna
- If 402/402A cracks are compared against more than just 402B, it is unbelievably unlikely that it was random chance, >99.9% against

Crack Concentration



402/402A is 288 out of 3459 airplanes built (8%)

Represents 100% of the cracked airplanes

Left Wings?

- Notice that 4 of the 5 cracked wings are left wings.
- The 5th is not known and is different (NDI 0.05” crack)
- It would seem that there should be minimal left/right variation
  - Same flights
  - Same gusts
- So why left wings?

Left Wings?

- Can’t be design, left is mirror copy of right
- Unlikely to be material, spar cap used on both left and right wing
- Could be manufacturing, perhaps a particular tool or jig causing problems, but I think that is unlikely
- I suspect that left wings do experience slightly higher stress than right wings

Left Wing Stress Adders

- Pilot sits on left
  - Could be as much as 3% additional stress if no copilot (common in cargo operations)
- Engine torque
  - Turns airplane left, need more lift on left side, 2%
- Prop wash
  - Moves left wing center of lift slightly outboard, maybe another 2%
- CG biased left
  - Battery, fuel, door, options, etc
- Totals maybe 7% stress difference

Left/Right?

- Is 7% enough?
  - 7% reduction in stress is almost 3 times the fatigue life at high G, could be 5 times at low G and high stress ratio
- If right wing fatigue life is 4 times longer, then seeing at least 4 lefts out of 5 is not that odd
- So, not so odd perhaps, but analysis is weak
- Once again underscores the sensitivity of fatigue life to even very tiny variations in stress

3 Cracks in 1992?

- 3 of 5 cracks found in 1992
- One would expect relatively even distribution of discovery dates
- Some common thread among the cracks that year?
- Better equipment?
- Recording error?
- Odd…

No Cracks Since 1992?

- Fatigue crack rate should increase over time as damage accumulates
- 12 years have passed without another crack despite recent heightened awareness
- Balancing factor: 402/402A airplanes down to 34% of original numbers, so while fatigue rate goes up, airplanes go down
- Balancing factor: high time airplanes more likely to be retired than low time
- Still somewhat odd…

Cyclic Testing

- Cap failed at 14,000 hours
- Cyclic testing is subject to the very same errors in assumptions (load, lift, gust) as the theoretical analysis
- Cyclic testing subject to laboratory errors
- A match between cyclic testing and theoretical analysis does not confirm many of the assumptions
- One cyclic fatigue test is too random

Source: Easton, Slide 16

Conclusions

Conclusions

- Cessna fatigue lifetimes could be wildly in error
- Very unlikely to be overestimates due to field data
- Very likely to be underestimates due to nature of error sources
- 402/402A are different and must be treated differently
- No cracks in any other type

There has never been a fatigue crack* in any twin Cessna spar other than 402/402A

* Which was not otherwise explained by causes other than normal use

FAA: AC 91-56B

Excerpt from AC 91-56B Draft:

7. MANDATORY MODIFICATION PROGRAM.

a. The mandatory modification program was based on the premise that to ensure the structural integrity of older airplanes, there should be less reliance on repetitive inspections when certain criteria exist. These criteria included:

-- The likelihood that known structural cracking problems exist and are not just theoretical or predicted.

Fatigue cracking of spars
is purely theoretical
for all models other than
402/402A

Suggestions

#1 Don’t Panic!

- No airplanes have cracked in 12 years
- Rushing to fix a problem we don’t fully understand may create further problems
- Problem appears to be extremely localized to 402/402A airplanes
- Heightened awareness will promote safety
- We have the time to get this RIGHT!
- We can’t afford to get this WRONG!

#2: Study 402/402A

- We have to find out why these 5 airplanes cracked
- These planes are extremely likely to be different structurally than 402B, yet used for the same mission
- Crack rate is very high, 1 in 60 airplanes built
- This is the *REAL* safety issue

#3: Professional Review

- Hire highly qualified professional and independent reviewer
- Reviewer given detailed access to Cessna proprietary data (NDA)
- Reviewer examines methods and results of Cessna study to report to the FAA and the public
- Review results could lead to compliance time revisions

#4: Factor Usage

- Not clear Cessna changed usage model for low seat count airplanes
- Apply usage profile from owner survey to adjust spar stress
- Adjust fatigue life based on new usage data

#5: Measure Real Airplanes

- Instrument and measure each type with various loads
- Corrects for a large number of errors (load, lift, structure, etc)
- Will provide most accurate stress per G equations possible
- Use new equations to adjust compliance times

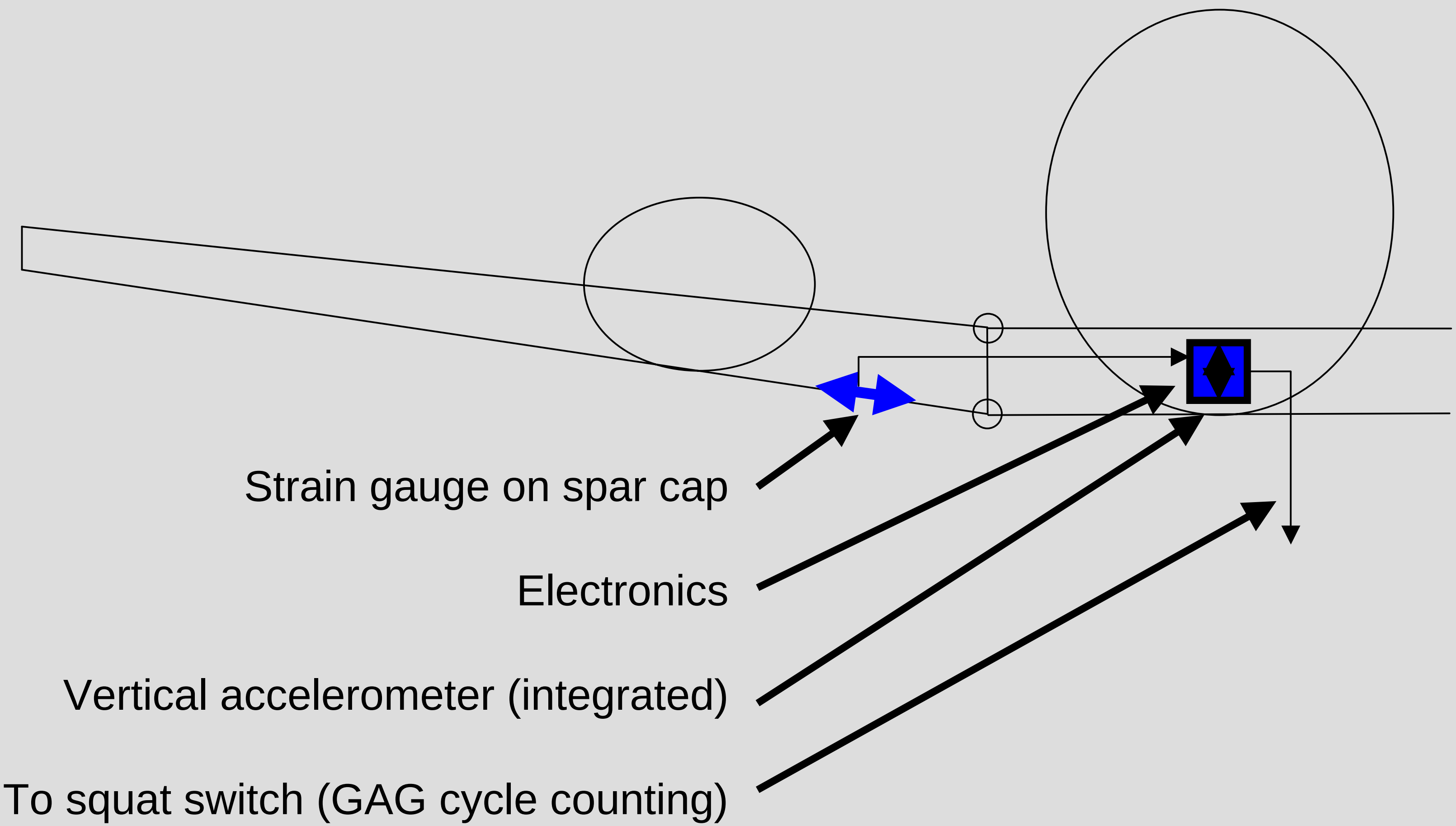
#6: ZFW AMOC

- Establish or lower zero fuel weight (ZFW) on models with time left before compliance
- Use lowered spar stress to compute life improvement factor
- Apply life improvement factor to remaining life before compliance
- Near zero cost, zero effort, zero risk to provide for near term mitigation

#7: Fatigue Meter AMOC

- Measure actual fatigue stress on spar
- If measured stress differs from assumed stress in study, then fatigue life improves
- Small changes in stress yield large life improvements
- Must be used before compliance time expired
- Provides potentially much larger life improvement than ZFW treatment

Fatigue Meter AMOC



Fatigue Meter

- Accurately measures gusts and stress
- Records data over time
- Accumulates a “fatigue hour” counter
- 1 fatigue hour = 1 real hour when airplanes experiences exactly the same conditions as Cessna study
- When conditions differ, fatigue hours accumulate slower or faster than real hours

Fatigue Meter

- Fatigue hours very likely to accumulate at a much slower rate than real time
  - Lower gust spectra
  - Lower loads
  - Lower GAG cycles (longer flights)
  - Small stress reduction is large increase in life
- Would very likely provide 3 times the life, and 10 times would not be unusual

Logistics

- Records both elapsed and fatigue hours
- Every annual, record both in logbook
- Resistant to tampering
- Compliance time computation:

$$CT = ACTT - EH + FH$$

CT = compliance time

ACTT = aircraft total time

EH = elapsed hours of FM monitoring

FH = fatigue hours reported by FM

Field Data Collection

- FM includes download means
- Data from actual use can be collected, downloaded, and used to generate more accurate usage models
- Potential forensics for accident investigation
- Could lead to more accurate management of aging aircraft issues

Spar Warning

- FM measures spar stress versus G loads
- For any given load, the ratio of stress to G remains constant
- If that ratio increases significantly, then spar is failing (wing getting weaker)
- Relatively straightforward to provide that information to the pilot: SPAR
- Could be used for high time planes

FM Feasibility

- Conceptually simple
- Similar devices already exist
- Requires no modification of aircraft structure
- Low cost, $2-3K per aircraft
- Technology for accelerometers, strain gauges, processing, storage exist

FM Issues

- Need detailed Cessna assumptions
- Failing that, must derive new fatigue model from basic strain data
- Fatigue computation non trivial to develop even if hardware simple
- Spar warning needs research
- Catch-22 for planes at or beyond compliance (new data won't help in time)

Questions?