Fatigue

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Fatigue

Part-4: Aircraft level design considerations for fatigue

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Airframe design considerations

- Airframe design philosophies
- Materials & manufacturing
- Operational environments
- Detail designs

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Airframe Design Philosophies

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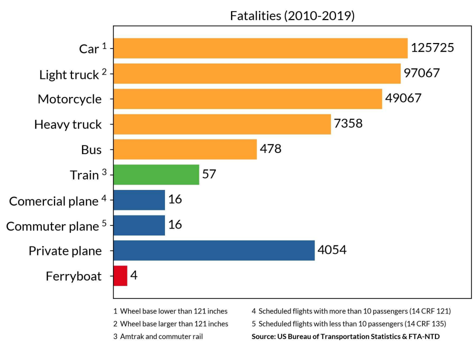
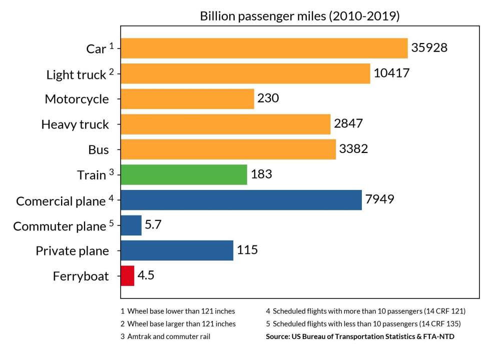
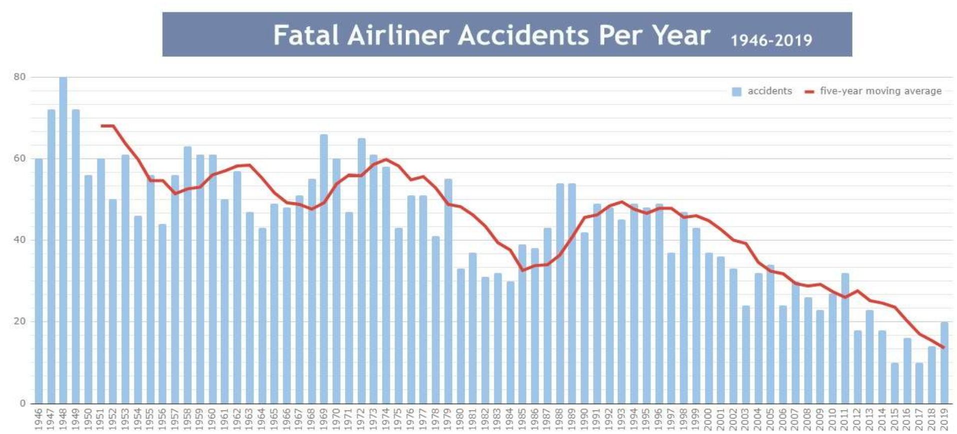
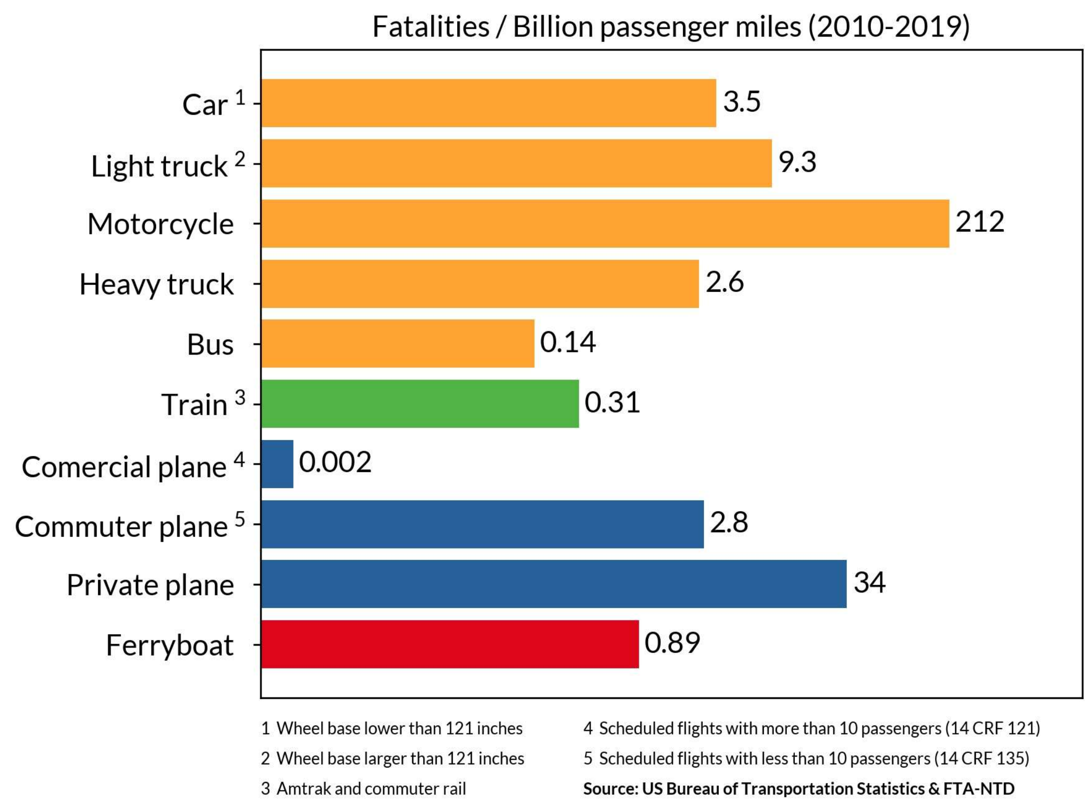
Aviation safety statistics





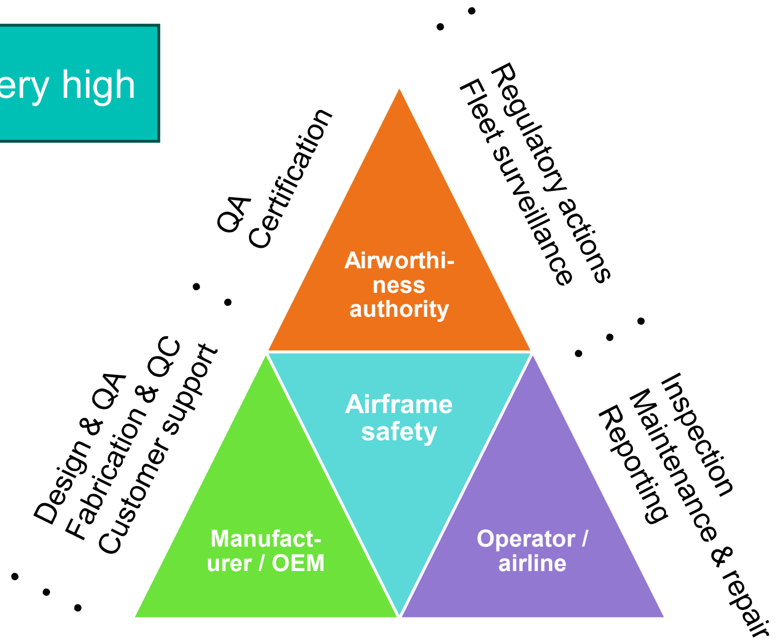




Design / safety philosophies

Crash due to structural failure is rare; reliability assumed to be very high

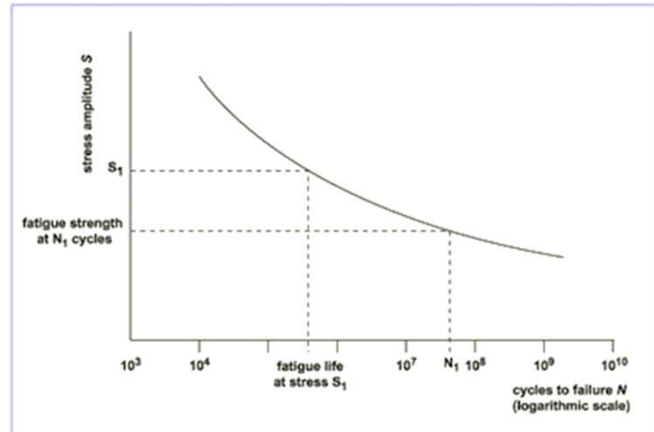
B747 cargo aircraft crash in Netherlands (1992) due to fatigue & overload failures in airframe

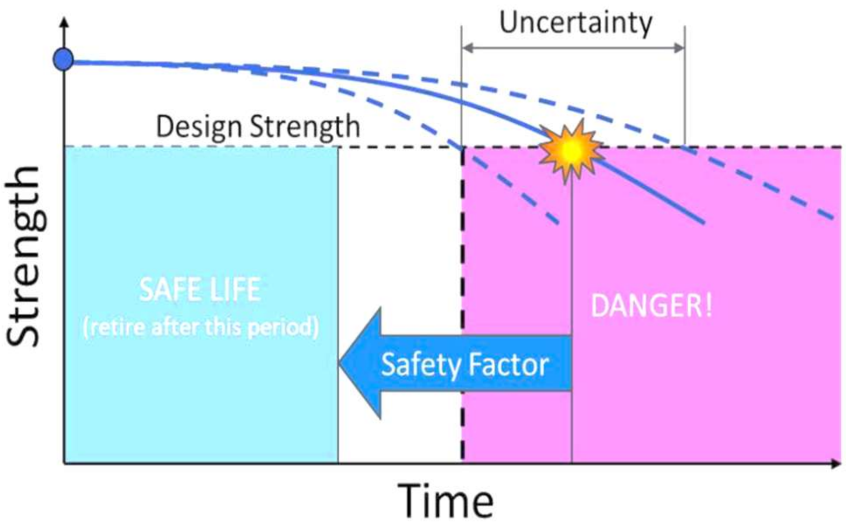


Safe life	Fail safe	Damage tolerant
Safety by retirement	Safety by design	Safety by inspection

Safe life design

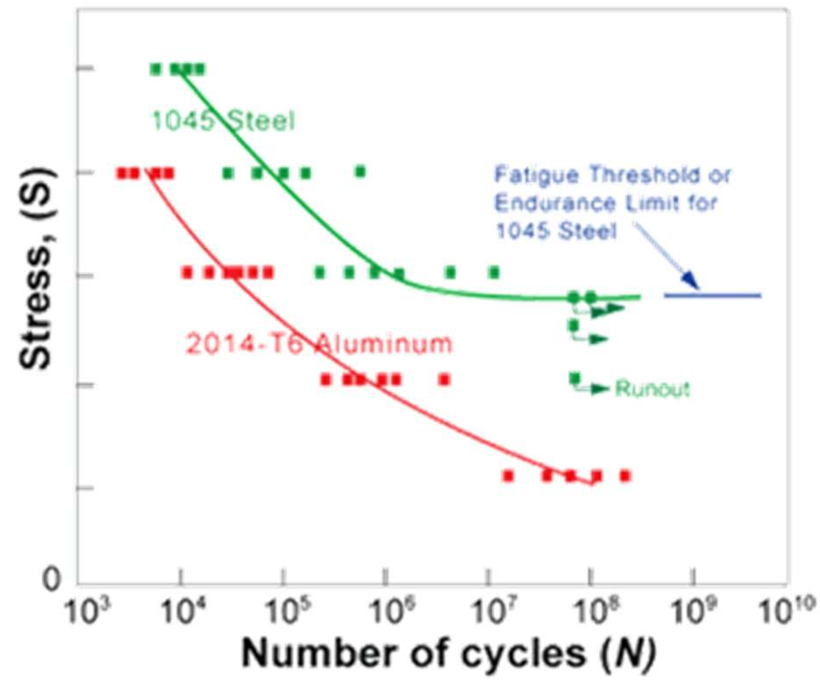
- Safe LIFE: Number of flights / landings / flight hours, during which there is a low probability that strength will degrade below design strength (1950s)
  - No. of flights: Pressurized fuselage
  - Distance traversed: Engine components
  - Calendar life: Rubber parts
- Design criteria
  - **Safety by retirement**
  - Fatigue failure is not likely to occur during design life (i.e. up to crack initiation stage)
  - Safe-life interval = projected lifetime of aircraft = crack free service life
- Challenges
  - Limitations of testing (La Havilland Comet 1)
    - ➢ 16000 as per test Vs. around 1000 in actual (3 crashes in 1 year)
    - ➢ Strain hardening @ window corners during static overload (2P) tests and same airframe used for fatigue
  - Life extension
  - Load increase (capacity extension)





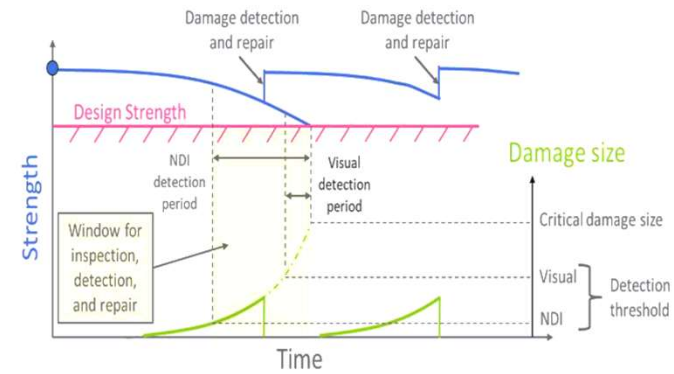
Fail safe design

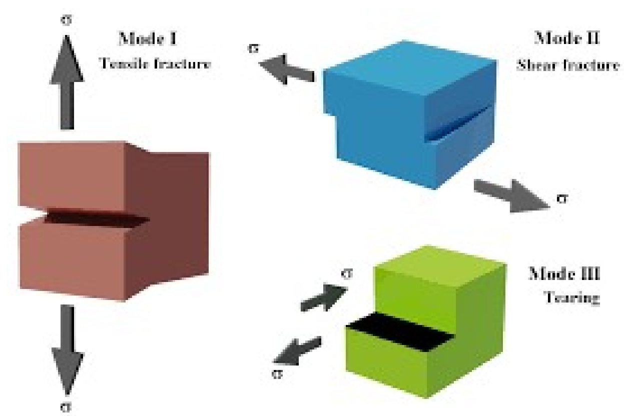
- Designed NOT to fail (**safety by design**) (1970s)
  - Case 1: Infinite life
  - Case 2: Redundant load paths
  - Case 3: Residual strength-based design
- Design criteria
  - Max stress < FEL (fatigue crack propagation stage)
  - Multiple redundant spars in wing etc.
  - Compression after Impact (CAI) as design allowable for very conservative design
- Generally, economical & safer than safe life
- Challenges
  - Unforeseen damage
  - Multiple site damage
  - Gradual degradation of redundant member
  - **FMEA necessary**



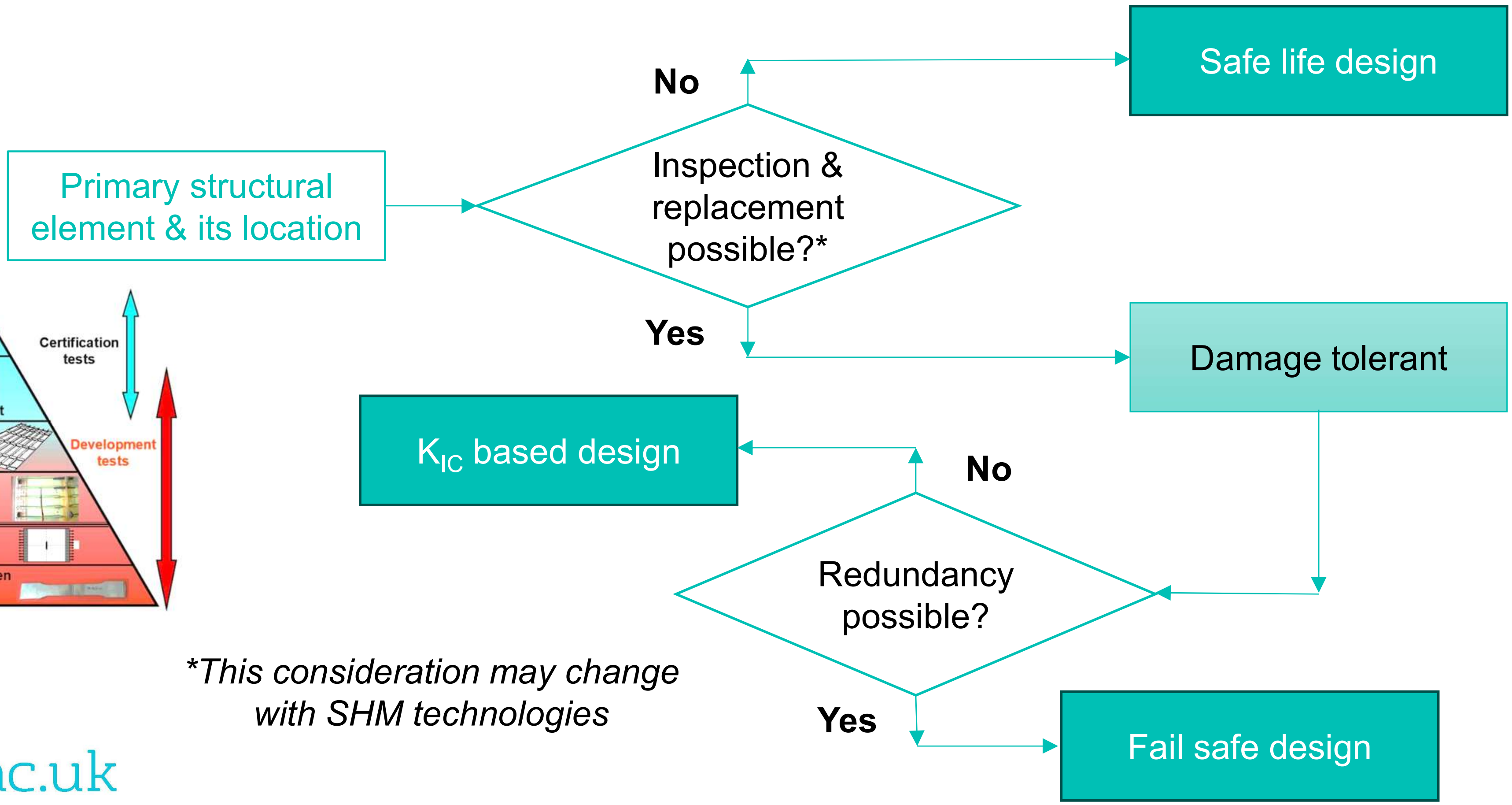
Damage tolerant design

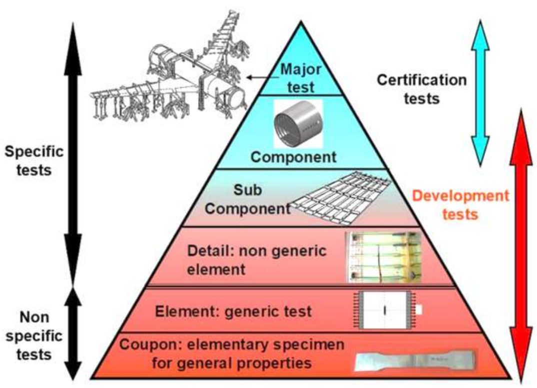
- Designed with maintenance (detection capability & inspection schedule) in the loop (current)
  - Design assuming presence of damage (extension of fail safe)
  - Sustains loads till a critical size of the damage (extension of safe life)
  - Detect damages before they attain the critical size through inspection protocol, i.e. fail safe interval (**safety by inspection**)
  - Repair should restore original strength
- Design criteria
  - Stress conc. factor (Kt) = σ(peak)/σ(nominal) = $1 + 2(a/r)^{0.5}$ where a=damage size & r=damage radius, **not suitable for sharp defects**, but applicable for stress build-up from any repair
  - Stress intensity factor (K) = $\sigma.(\pi.a)^{0.5}$; $a_{crit} = (K_{IC}/\sigma_{crit})^2/\pi$ for sharp defects
    - ➢ Fracture toughness is a material property indicating the sensitivity for cracks under static loading
    - ➢ Related to material ductility and critical stress via geometry





Safety design approach

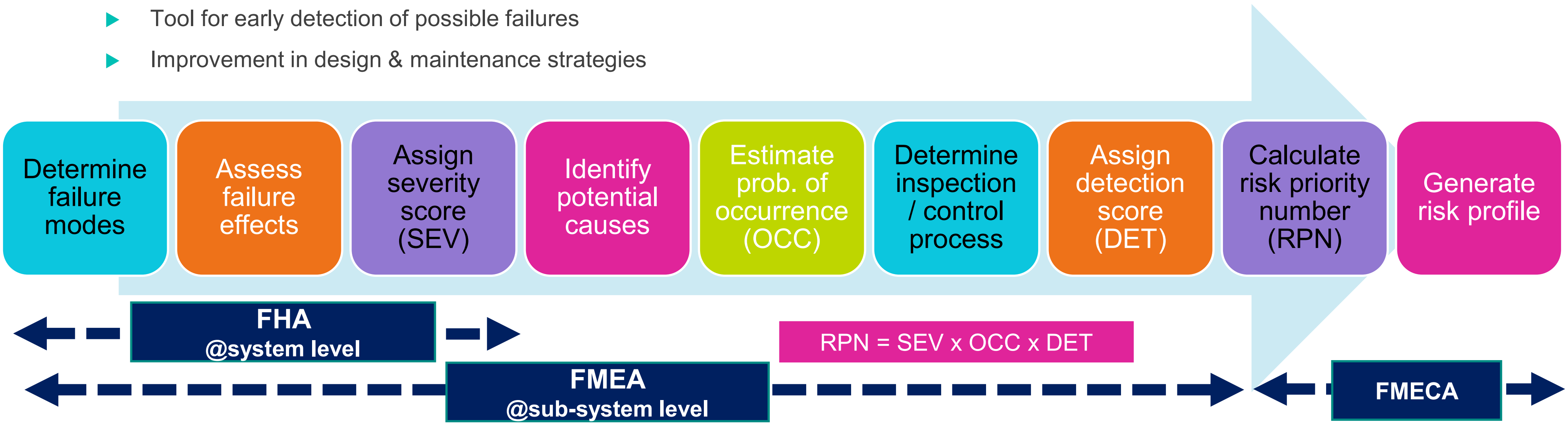




**This consideration may change with SHM technologies*

FHA / FMEA / FMECA

- Structured engineering practice to analyze potential causes of operational failure
  - Tool for early detection of possible failures
  - Improvement in design & maintenance strategies



Scores	↓	1	2	3	4	5	6	7	8	9	10
SEV	Redundant / damage tol.	None	Very minor	Minor	Very low	Low	Moderate	High	Very high	Hazardous w warning	Hazardous w/o warning
OCC	More MTBF, MIL grade	Fail safe (P=0)	No failure / only isolated failures in identical system		Isolated / occasional / frequent failures in similar system			Possible / likely / inevitable failure in new design			New technology
DET	More O Level, IVHM	Almost certain	Very high	High	Moderately high	Moderate	Low	Very low	Remote	Very remote	Uncertain

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Materials & Manufacturing

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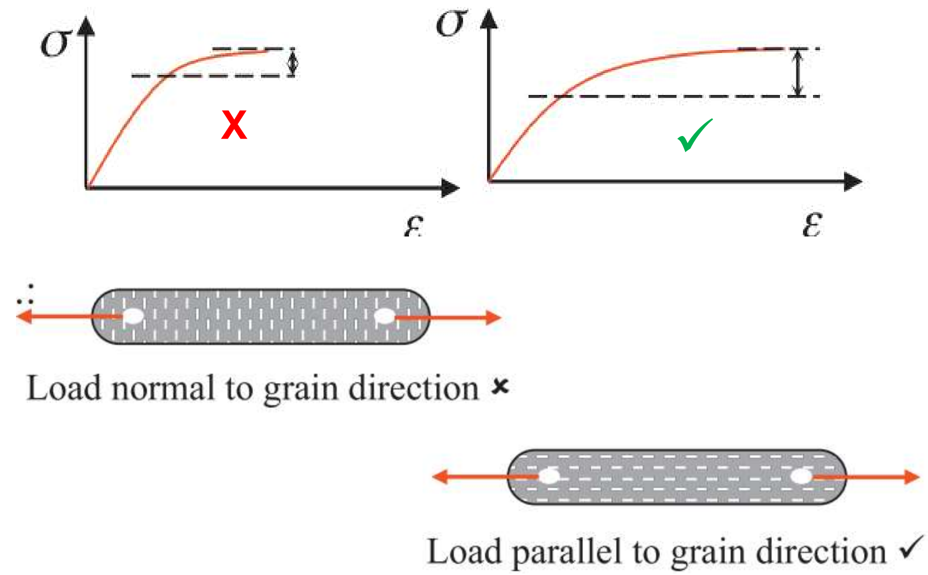
Materials & processing

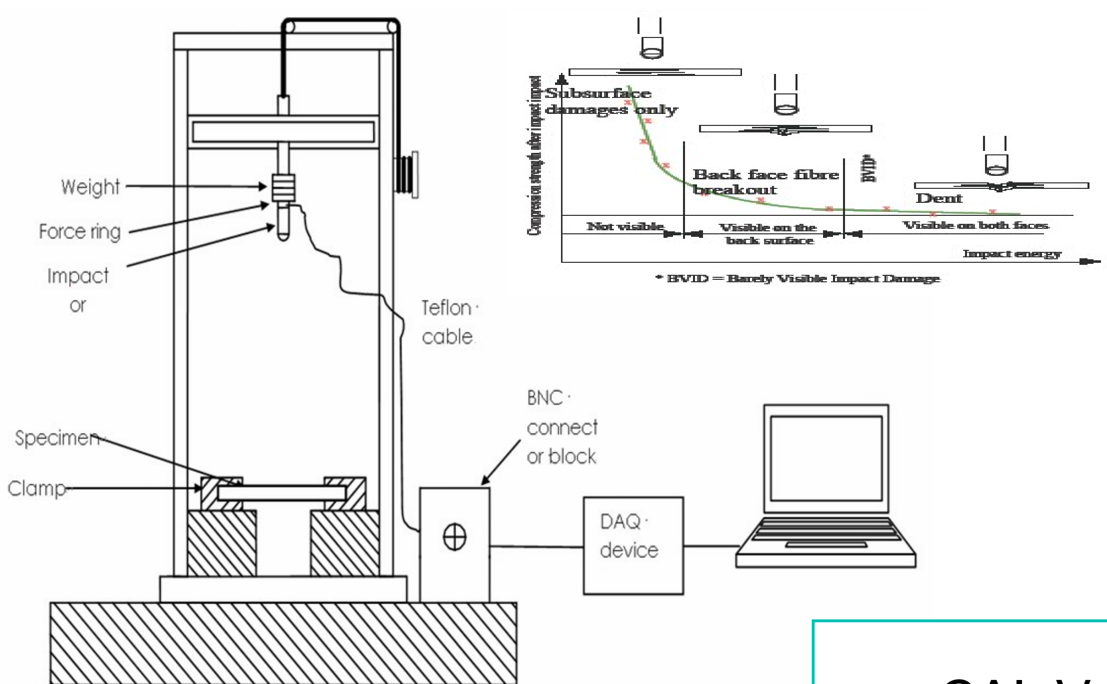
- Higher yield strength (improves N_i as well as N_{SP})
  - Al alloy 2024-T3 for tensile loading (lower wing skin, fuselage etc.)
  - Avoid Al alloy with high YS/UTS ratio (plastic safety margin)
  - Ensure proper heat treatment (T6 vs T3)
  - Grain boundaries vis-à-vis loading direction
- Case hardening after shot peening (improves N_{SP})
- Specific to composites
  - **<u>Ply drop protocols</u>**
  - Use advanced processes (V_0<2%)
    - Hand layup ~ >10%
    - Autoclave molding of prepregs ~ <0.5%
  - Residual compressive strength based design
  - 3d Composites

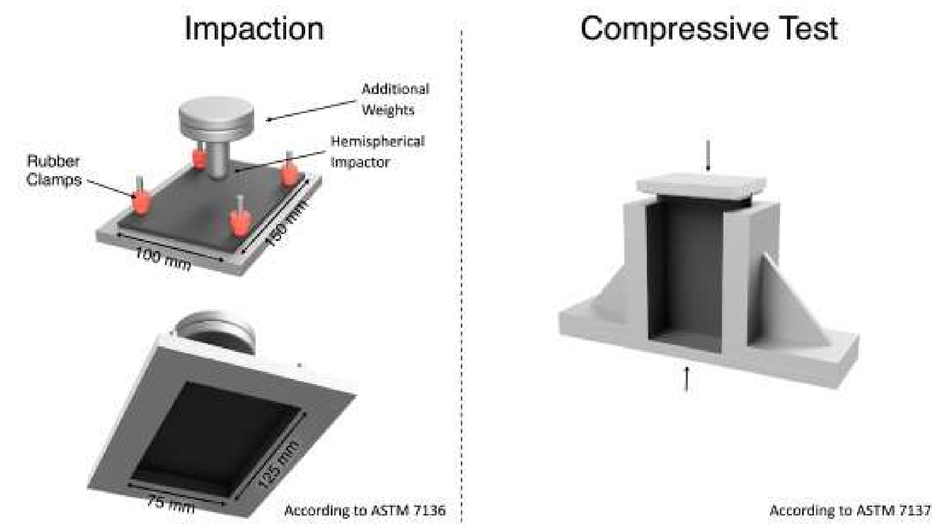


Ply-drop protocols (thumb-rules)

1. For primary structures: Ply-drop length = 20 x CPT x n
2. For secondary structures: Ply-drop length = 10 x CPT x n
3. Only inner surface ply-drops allowed
4. Symmetry & balance to be maintained in ply-drops

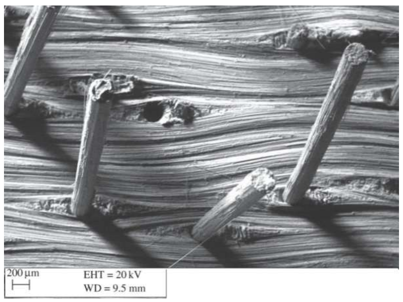
Compression after Impact

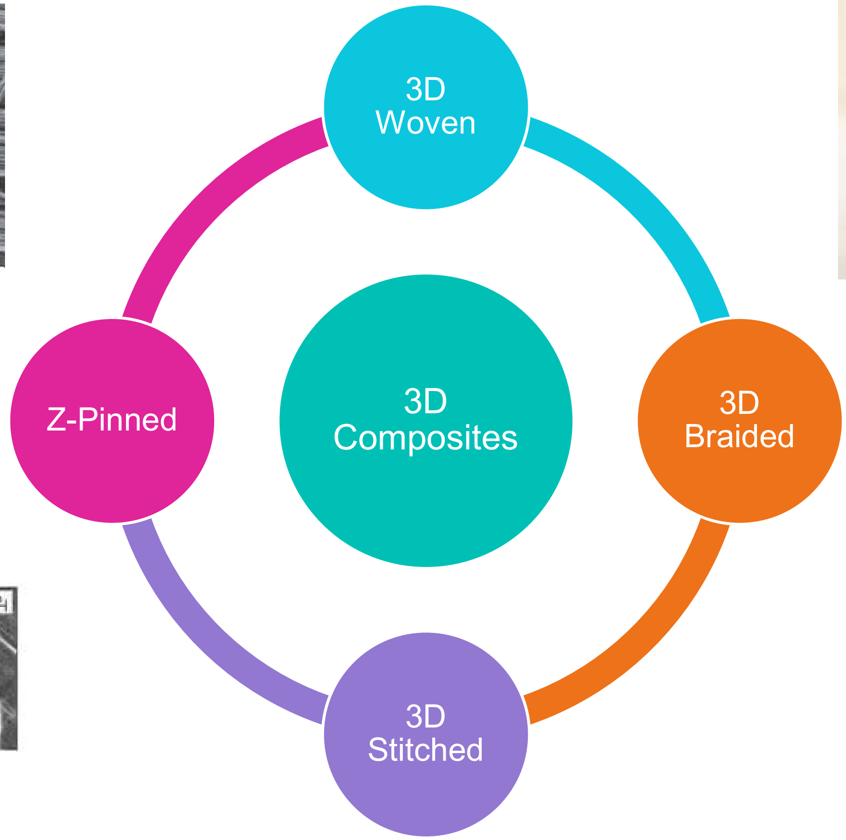


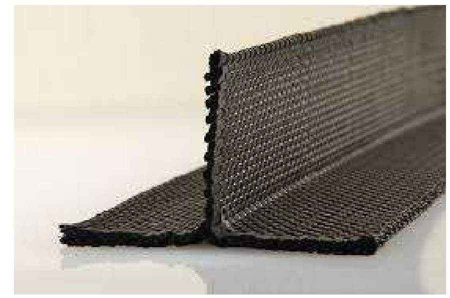


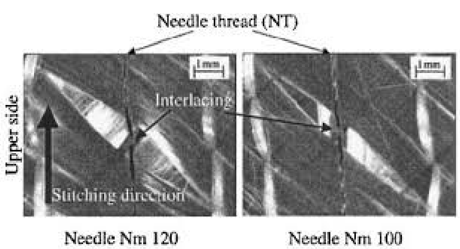
CAI: Very conservative design approach
(typically 1/3rd of tensile strength)

Commonly used 3d composites



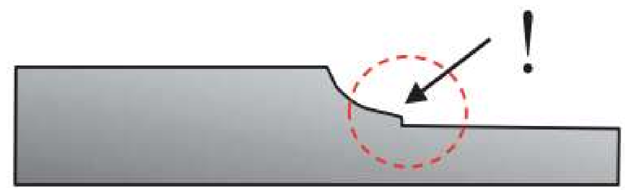


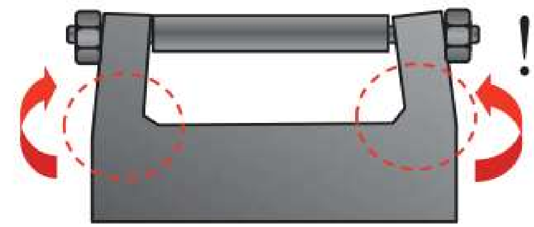


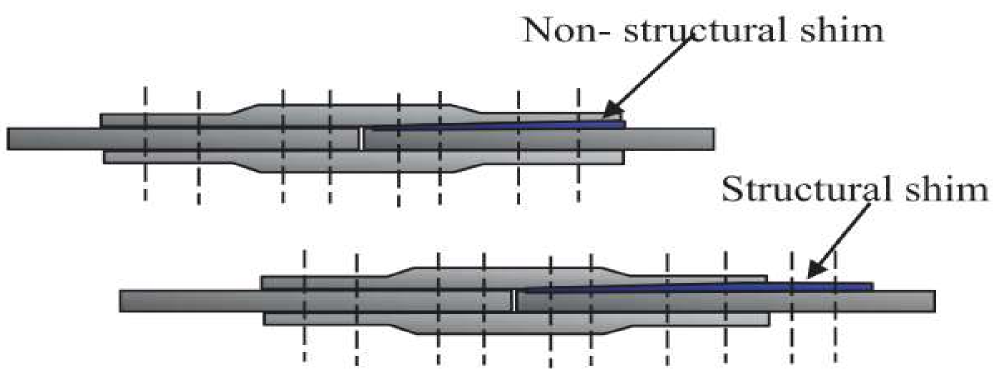


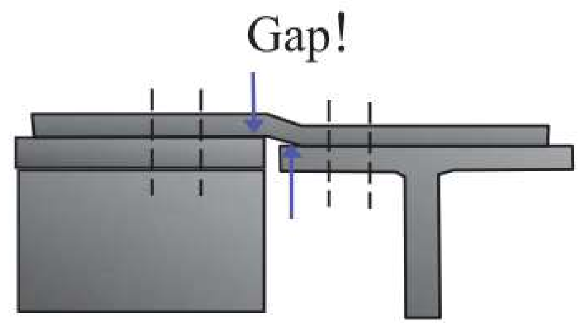
Manufacturing & assembly

- Minimize chances of stress raisers on surface (improves N_i)
  - Clean the surface off etchants, dye etc.
  - Protective finishing
- Minimize surface roughness and other discontinuities arising out of machining operations (improves N_i)
- Minimize gaps, check fit-up and use shims (improves N_i)









Operational Environments

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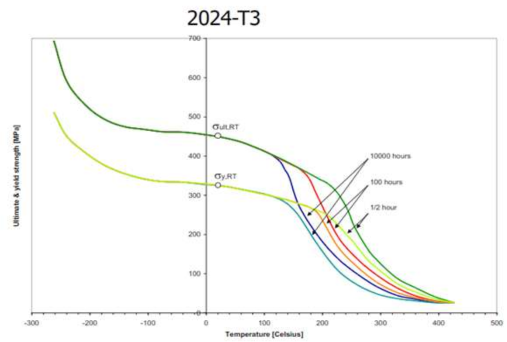
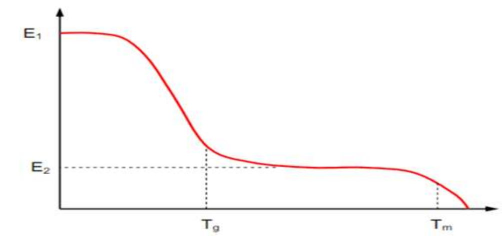
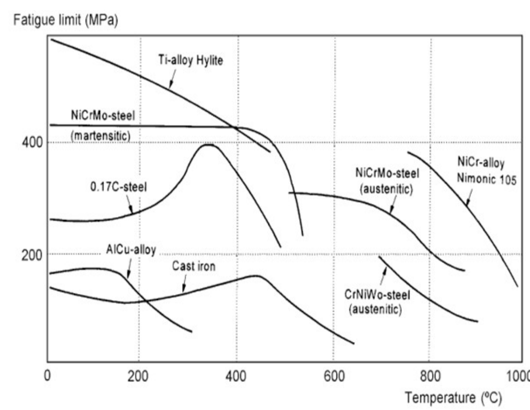
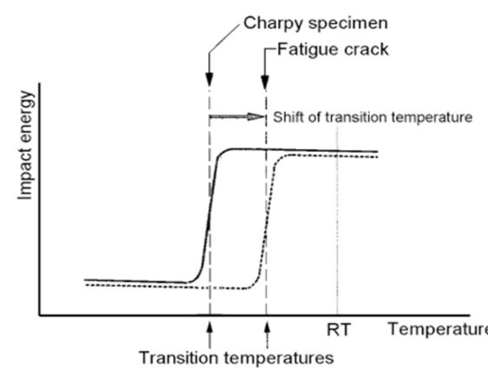
Effects of temperature

- High temperature
  - Caused by hot parts (engine) / skin friction (supersonic drag) / trajectory (re-entry) etc.
    - Creep
    - Decrease in strength & modulus
    - Glass transition
    - Melting
    - Thermal expansion
    - Fatigue life
- Low temperature
  - Caused by space / high altitudes / cryogenics etc.
    - Embrittlement (fracture toughness)



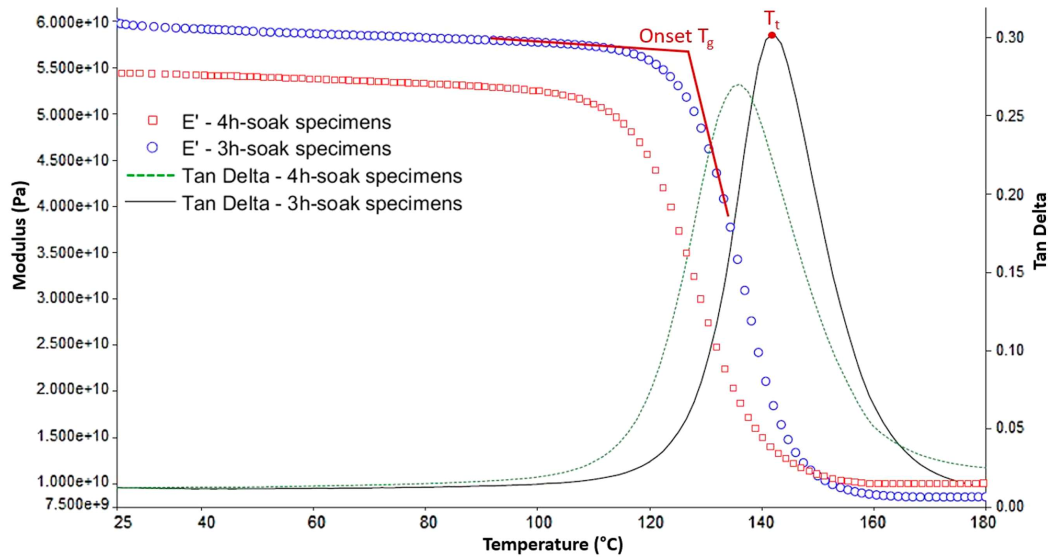






Material operational limits in composites

- Moisture saturation of samples in environmental chamber
  - Typically 70°C & 95% RH as per ASTM D5229
- Glass transition temperature (Tg) measurement (DMA / DSC etc.)
  - Identify onset of wet Tg from storage modulus tangents



MOL = Onset of wet Tg - 28°C

Effects of other environments

- Humidity
  - Metal: Corrosion
  - Composites: Reduction in matrix cohesion, matrix to fibre adhesion and Tg
- Others
  - Salty / marine environment
  - Space (UV, Vacuum, Free radicals (O+))
  - Fuel / hydraulic oil
  - Cleaning agents / solvents

- Galvanic corrosion (Del V = 0.1 V allowed; CFRP-Al = 1.2V, CFRP-Cu = 0.6V, CFRP-SS=0.1V)
  - Electrical isolation
  - Sacrificial anode (Zn for steel in marine env.)

Design allowable

1. Ambient temperature tensile testing for 0 & 90 deg
2. Find Mean & normalize
3. Find statistical scatter (σ, n) & calculate A/B basis
4. Open hole tensile test for QI
5. Find NKDF
6. Moisture condition QI samples till saturation
7. ETW tensile test
8. Find EKDF
9. Calculate tensile allowable

Similarly for compression & IPS tests, except normalization (not applicable)

Refer ASTM / MIL standards for test / conditioning conditions

B-basis calculations

- Method -1 (MIL/CMH HDBK 17F)
  - The original method was developed for metallic materials (Ref: MIL-HDBK-5c) with the following assumptions.
    - Normal probability density function
    - All data belong to a single statistical population (no batch-to-batch variability).

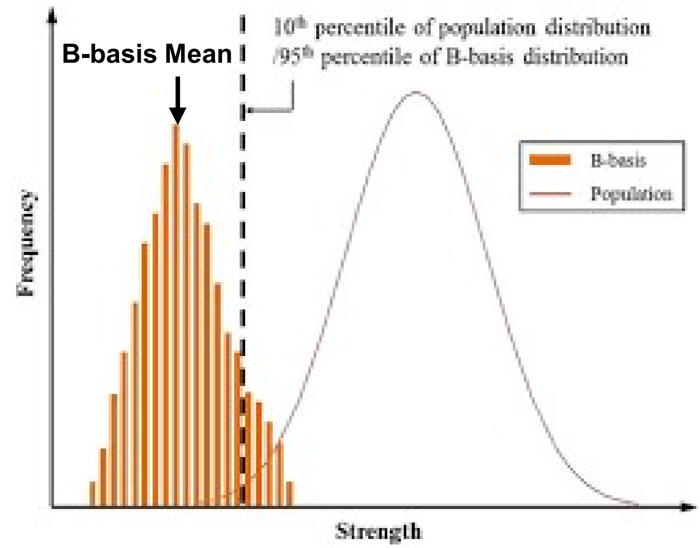
$$B - value = \bar{X} - Kb.\sigma$$

- Kb = Function of sample size, as per Table 8.5.10 in MIL-HDBK-17-1F (copy of the same given at the end)
- σ = Standard deviation

- Method – 2 (Gökgöl method – Airbus Design Office, Germany)

$$B - value = \left[\frac{\{1 - (Kb.CV)\}}{\left\{1 + \left(conf.\frac{CV}{\sqrt{n}}\right)\right\}}\right]\bar{X}$$

- Kb = 1.2816
- CV = Coefficient of variation = (Mean / Standard deviation)
- Conf.= 1.6449
- n = batch size of the sample



Carbon-epoxy allowables (typical)

Knock-downs	EKDF	NKDF
Tensile	0.96	0.60
Compressive	0.69	0.83
In-plane Shear	0.92	1.00

Poisson's ratio	0.3
Density (Kg/m^3)	1.8

Modulus	Orientation	Mean
Tensile (GPa)	0	130
	90	10
Compressive (GPa)	0	120
	90	15
Shear (GPa)	-	4.5

Test Details		Material / Design allowables @ V_f = 60% (MPa)				
Type	**Orientation**	**Mean**	**Normalized @ 60% V'f**	**B-value-Gökgöl**	**After EKDF**	**After E&NKDF**
Tensile	0	1850	1800	1600	1536	922
	90	100	97	80	77	46
Compression	0	1300	NA	1150	794	659
	90	200	NA	160	110	91
Shear (IPS)	$\pm$45	85	NA	80	74	74

Material allowable

Design allowable

Detail Design

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Stress levels

- Use high fidelity stress analysis to capture stress gradients and concentrations from holes, cut-outs, notches etc.
- Use actual loads if possible (from FTI or SHM)
- Use allowable strength values only
- Use local reinforcements wherever necessary (doubler plates, taper straps etc.)
- Limit fuselage hoop stress
- Design to allow for fuselage panel quilting or pillowing
- Avoid initial buckling of webs
  – No buckling up to 1g & 1.5 g for civilian and fighter A/c resp.
  – Use design ratio $\tau_{crit} / \tau_{ult} > 20\%$
  – Use limit minimum t/b panel sizing for lightly loaded webs (avoid in-plane shear)

Wing design - buckling

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

where

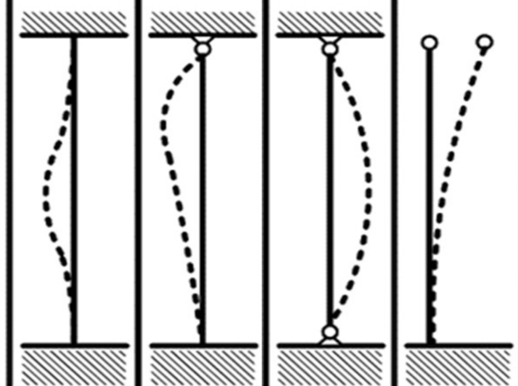
P_{cr} = Euler's critical load (longitudinal compression load on column),

E = modulus of elasticity of column material,

I = minimum area moment of inertia of the cross section of the column,

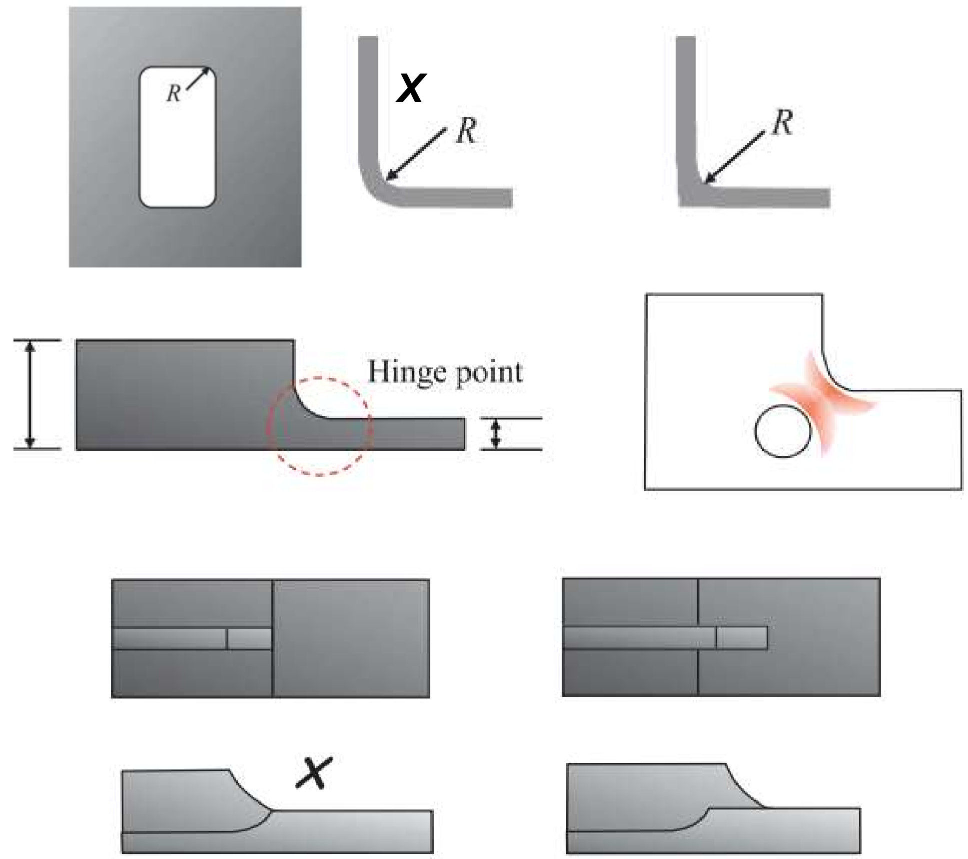
L = unsupported length of column,

K = column effective length factor

Buckled shape of column shown by dashed line				
Theoretical K value	0.5	0.7	1.0	2.0
Recommended design value K	0.65	0.80	1.0	2.10
Boundary conditions	Fixed-Fixed	Fixed-Pinned	Pinned - Pinned	Fixed-Free

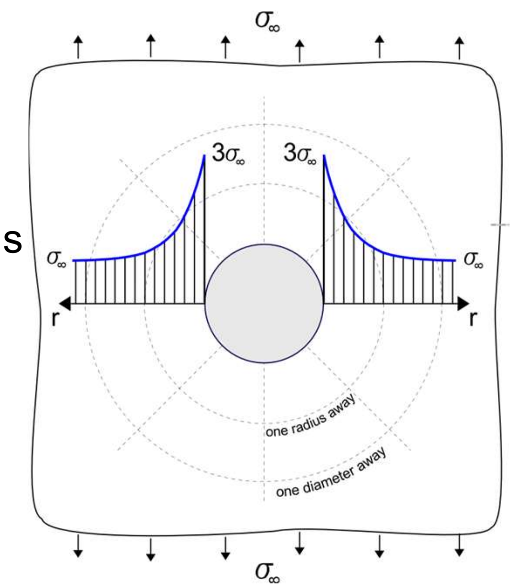
Detail engineering

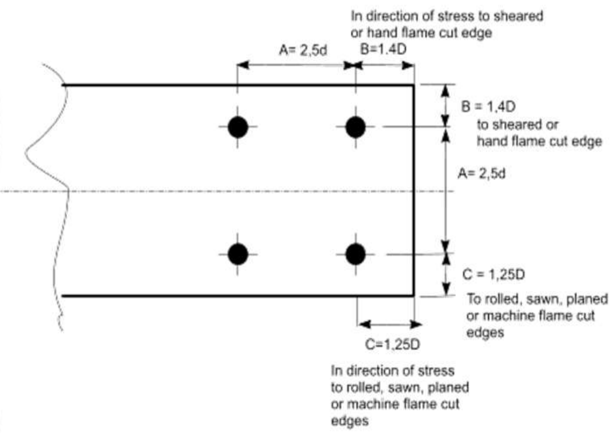
- Use large cut-out radii & corner / bend radii (min. 2t)
- Avoid sudden discontinuities in sections
- Avoid interacting stress concentrations
- Avoid change in sections at same location
  - Example: Stringer run-outs
- Use fatigue quality index
  - Proprietary index capturing previous experience
  - Embed manufacturing damages, holes, scratches, repairs in design process
- Composite lay-ups ply drops

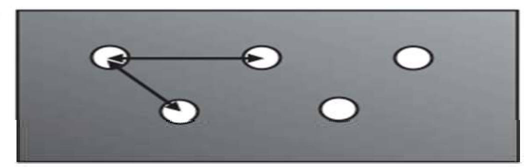


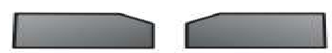
Joint & edge design

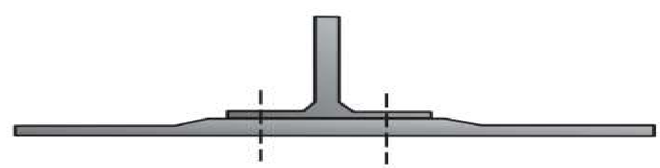
- Use sufficient pitch between fastener holes & edge distances
  - To prevent stress concentration interactions
- Limit counter sink depth
  - Increase edge distance to cater for CSKs
- Use thickening / pad-up
  - To reduce stress levels
- Use cold worked holes
  - For residual compressive stress
- Use correct fastener & installation
- Avoid blind areas
- Avoid eccentricities

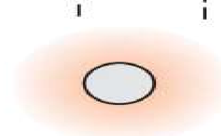


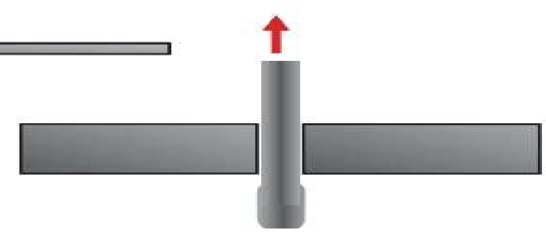












End of Part-4

Fatigue

Thank you

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