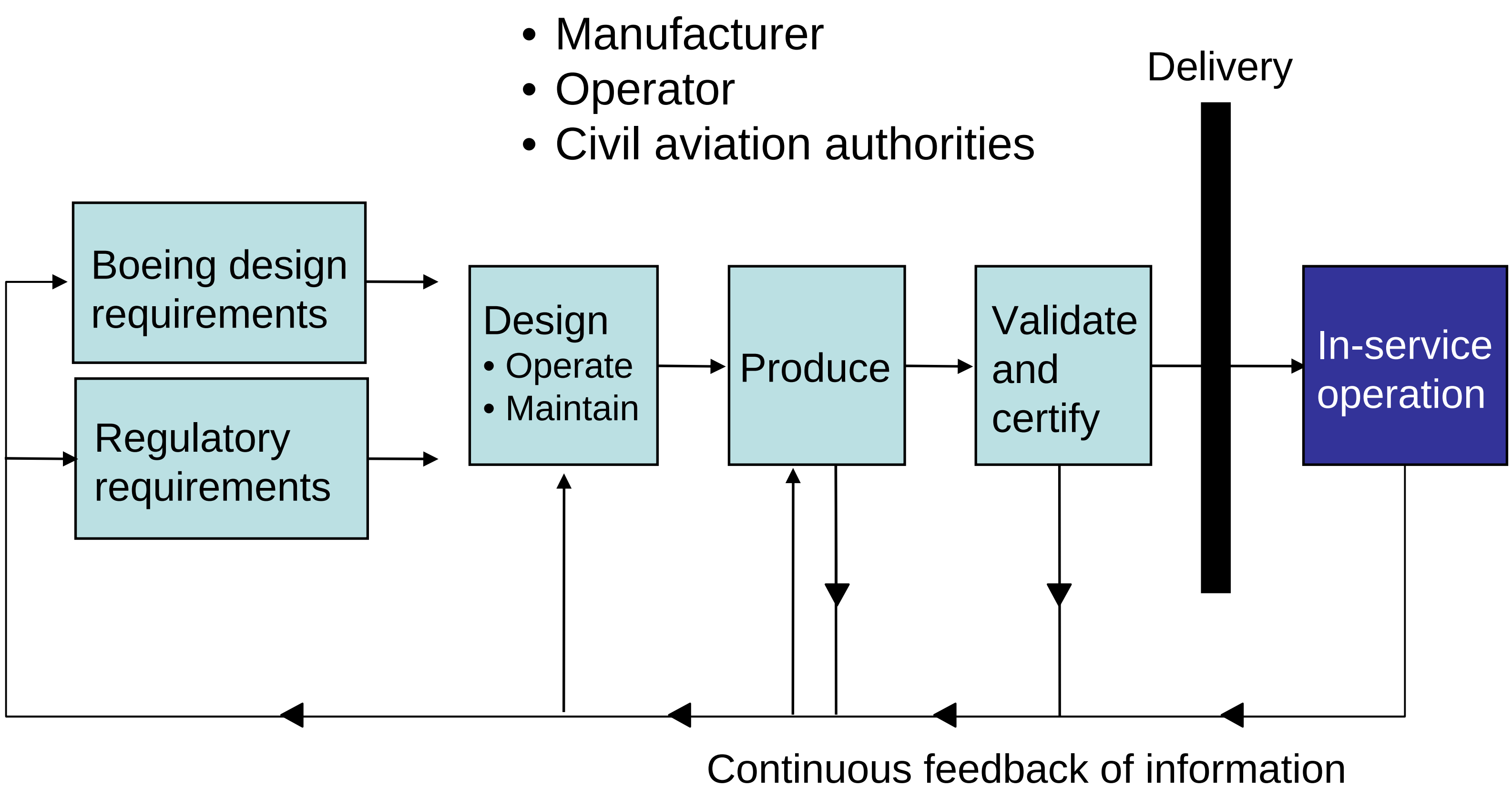
# Design Philosophy

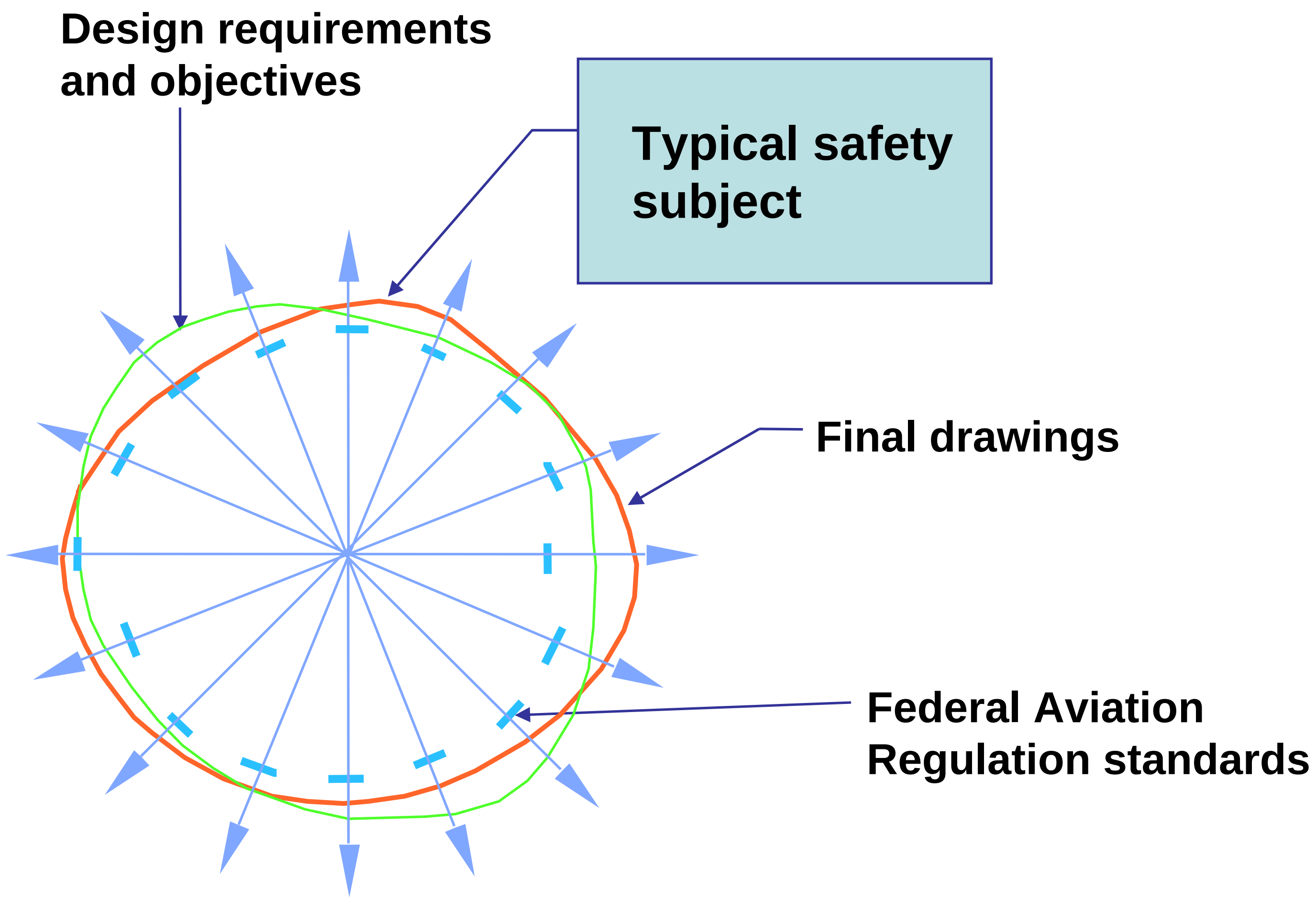
# Class Objectives

- Clear understanding of design, analysis, and validation requirements for aircraft structures
- Exposure to Structures Engineering processes and tools

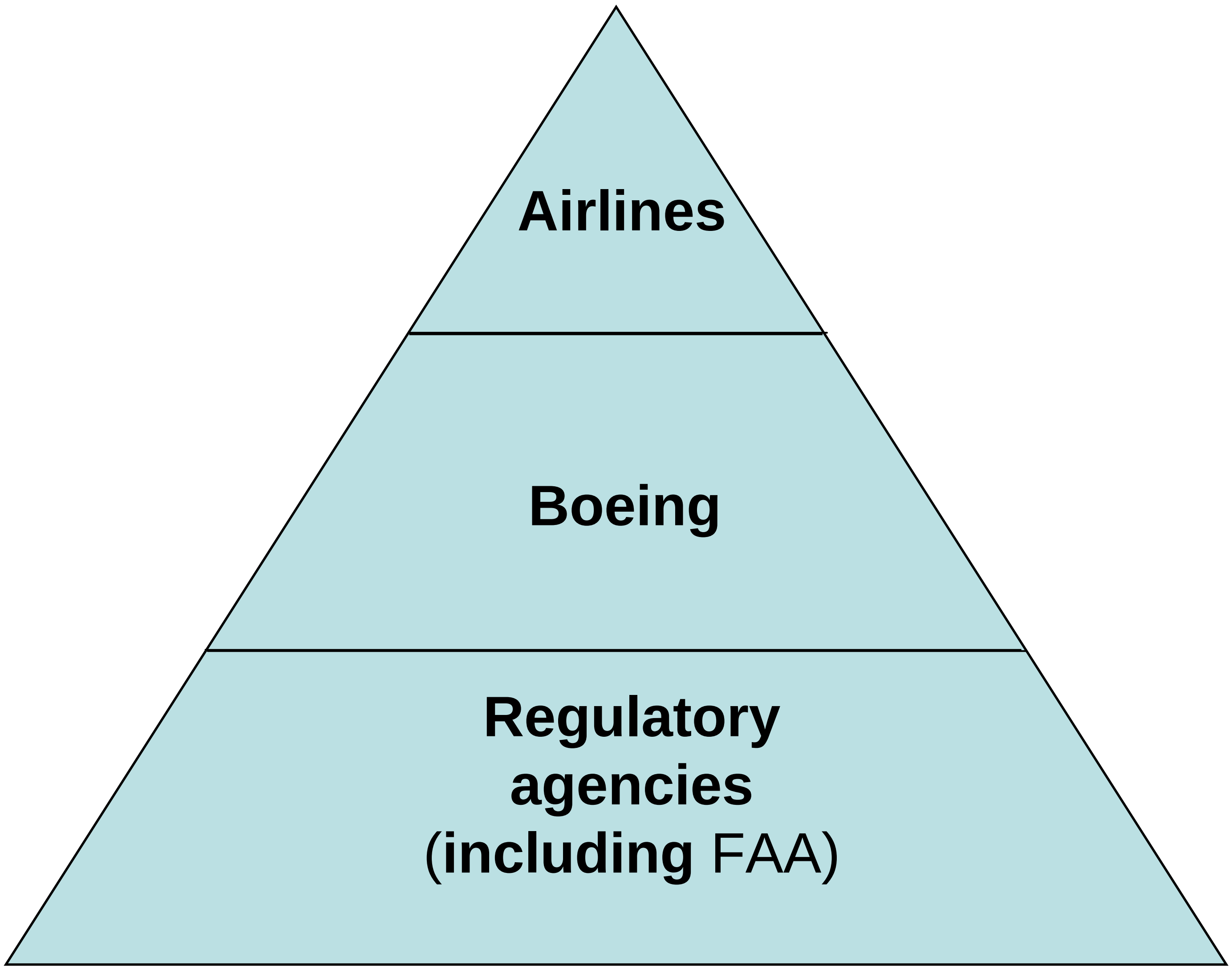
# Lifetime Safety Cycle



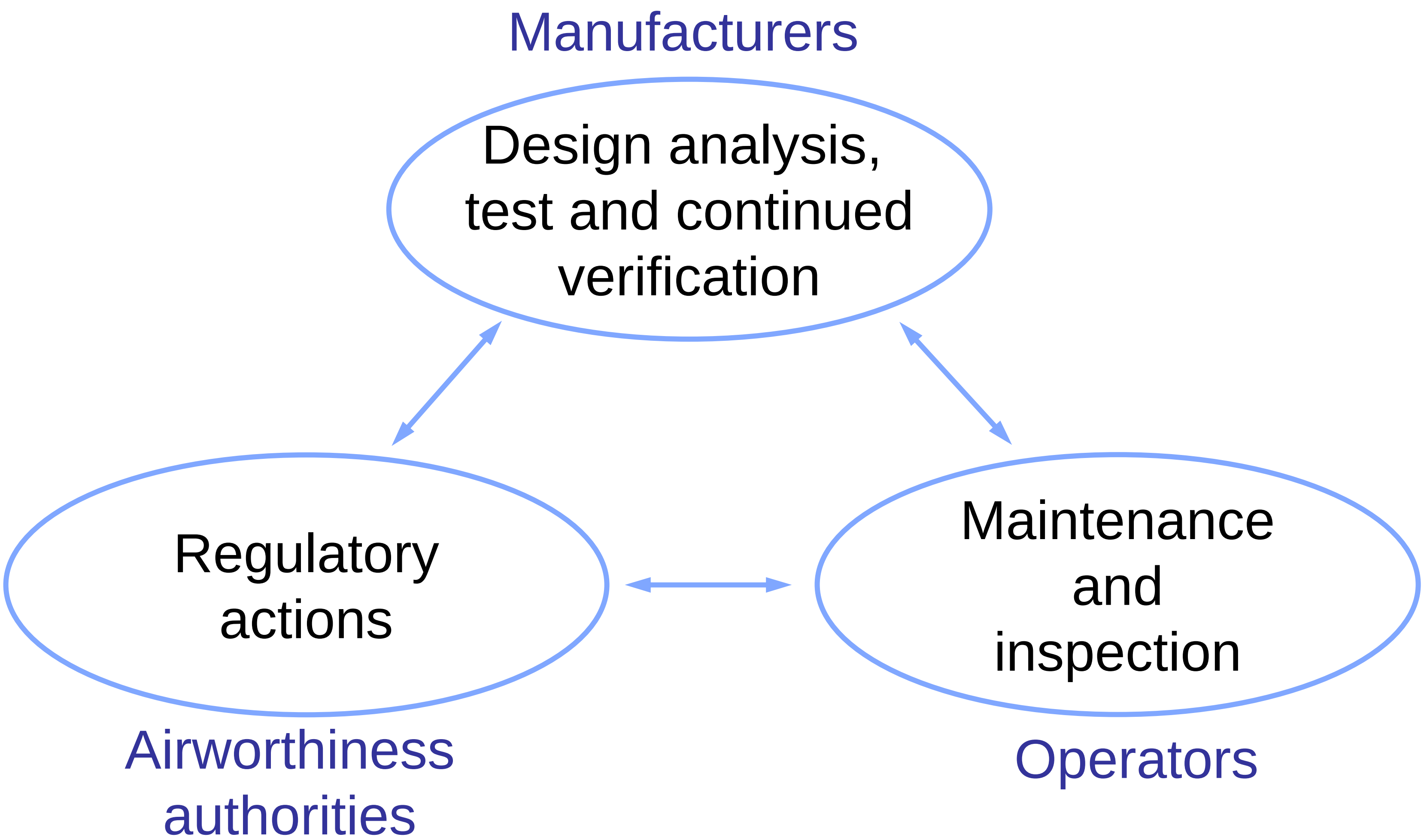
# Safety Wheel



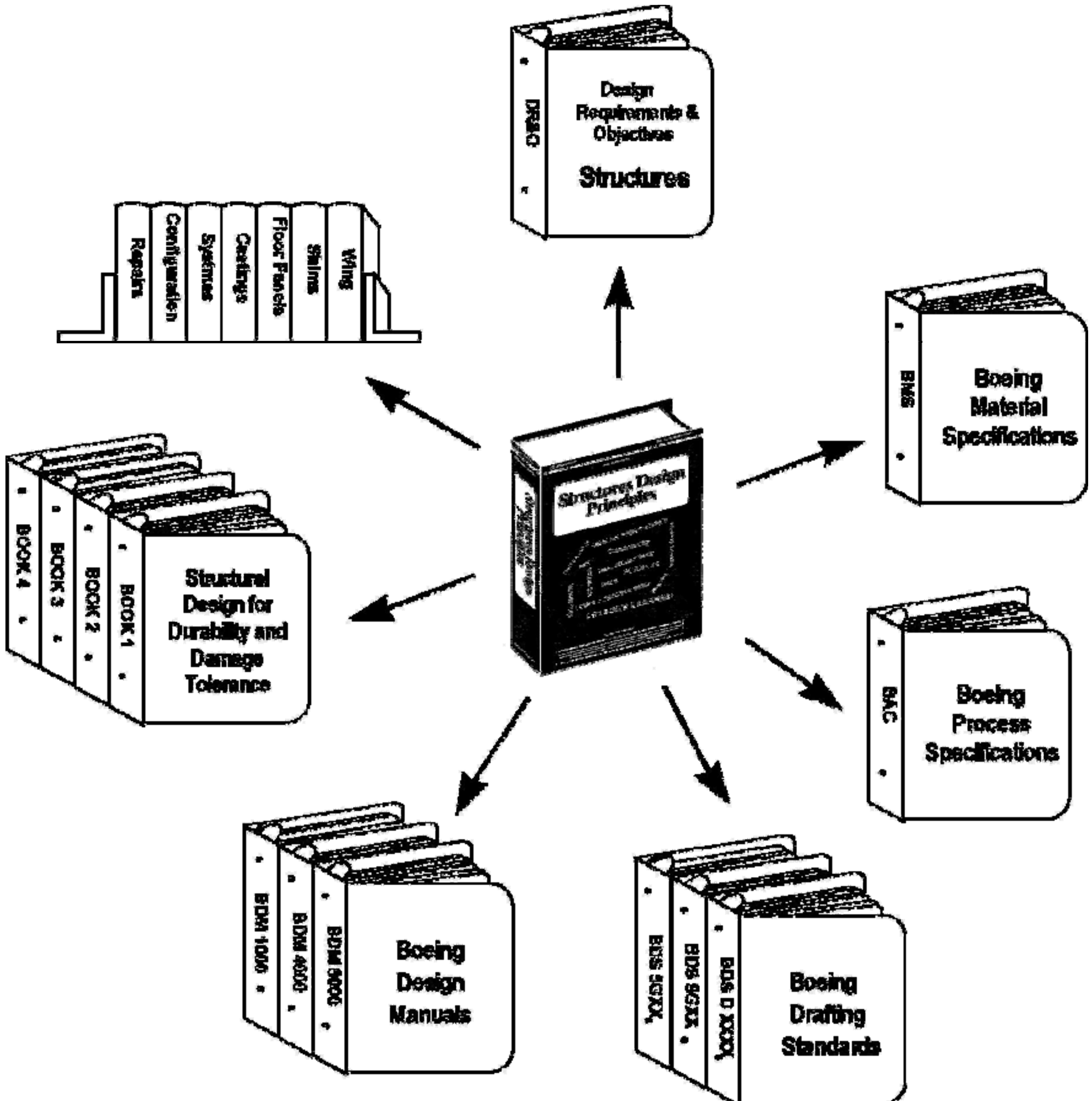
# Sources of Design Criteria



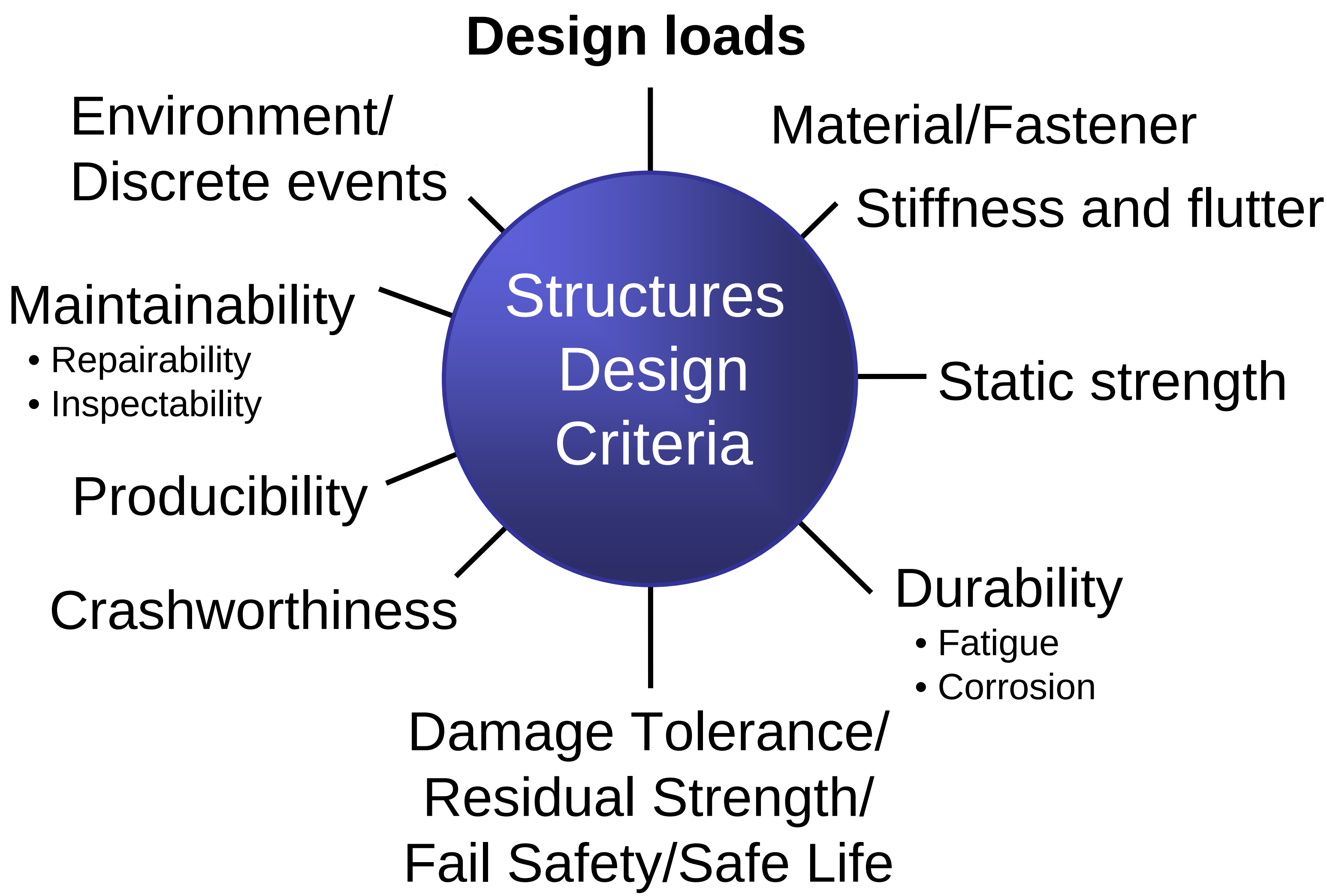
# Safety Requires Diligent Performance by All Participants



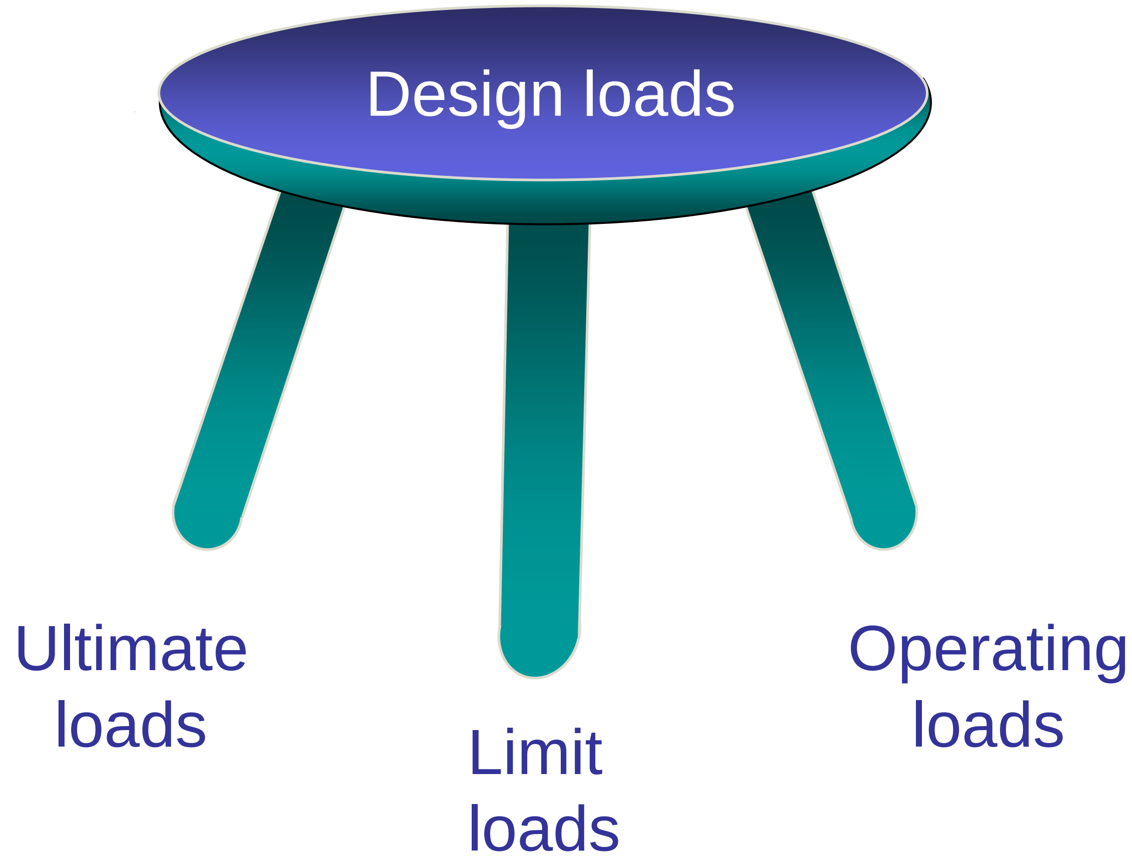
# Principal Guidance Documents



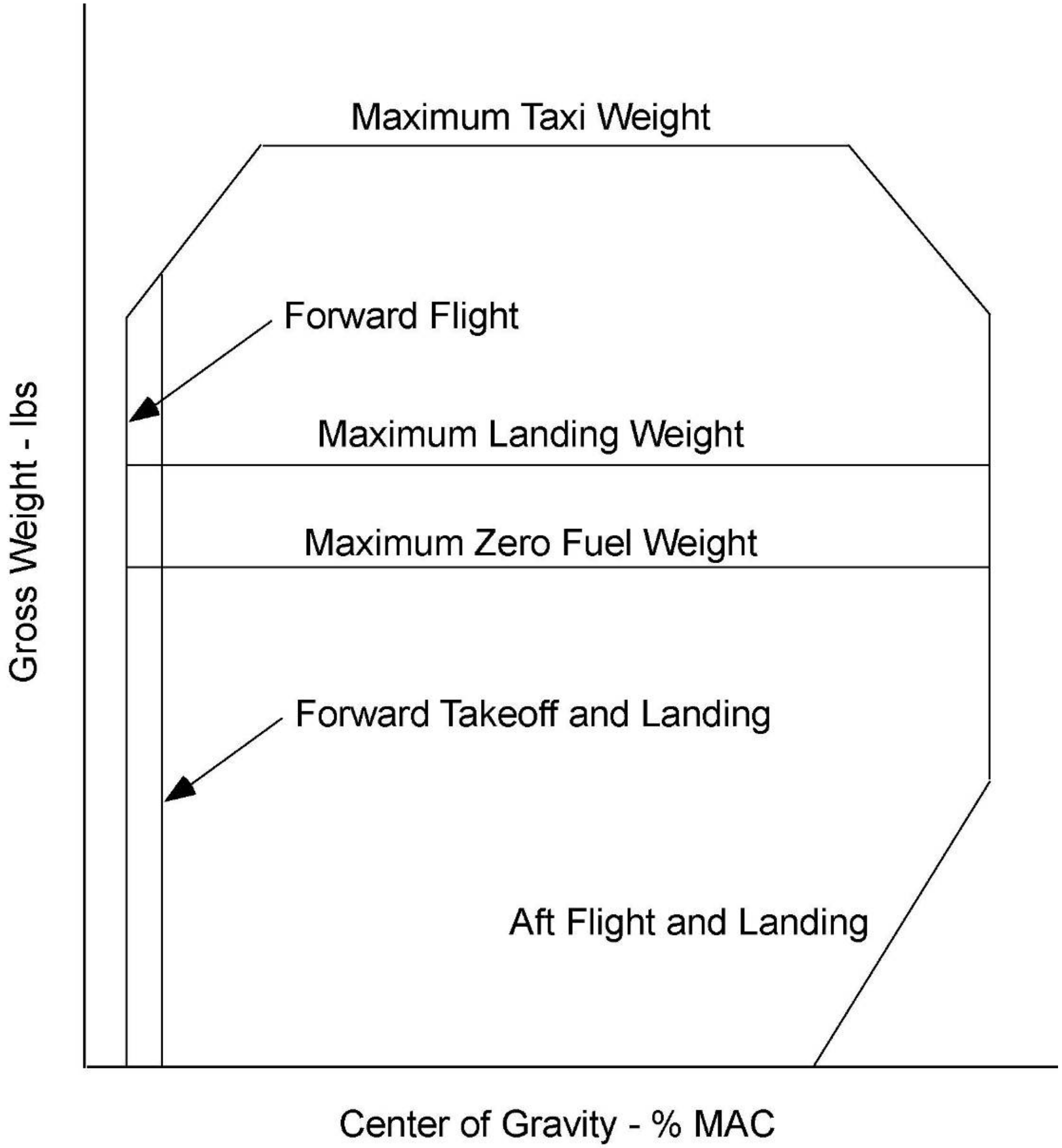
# Structural Design Criteria Consist of Ten Major Elements



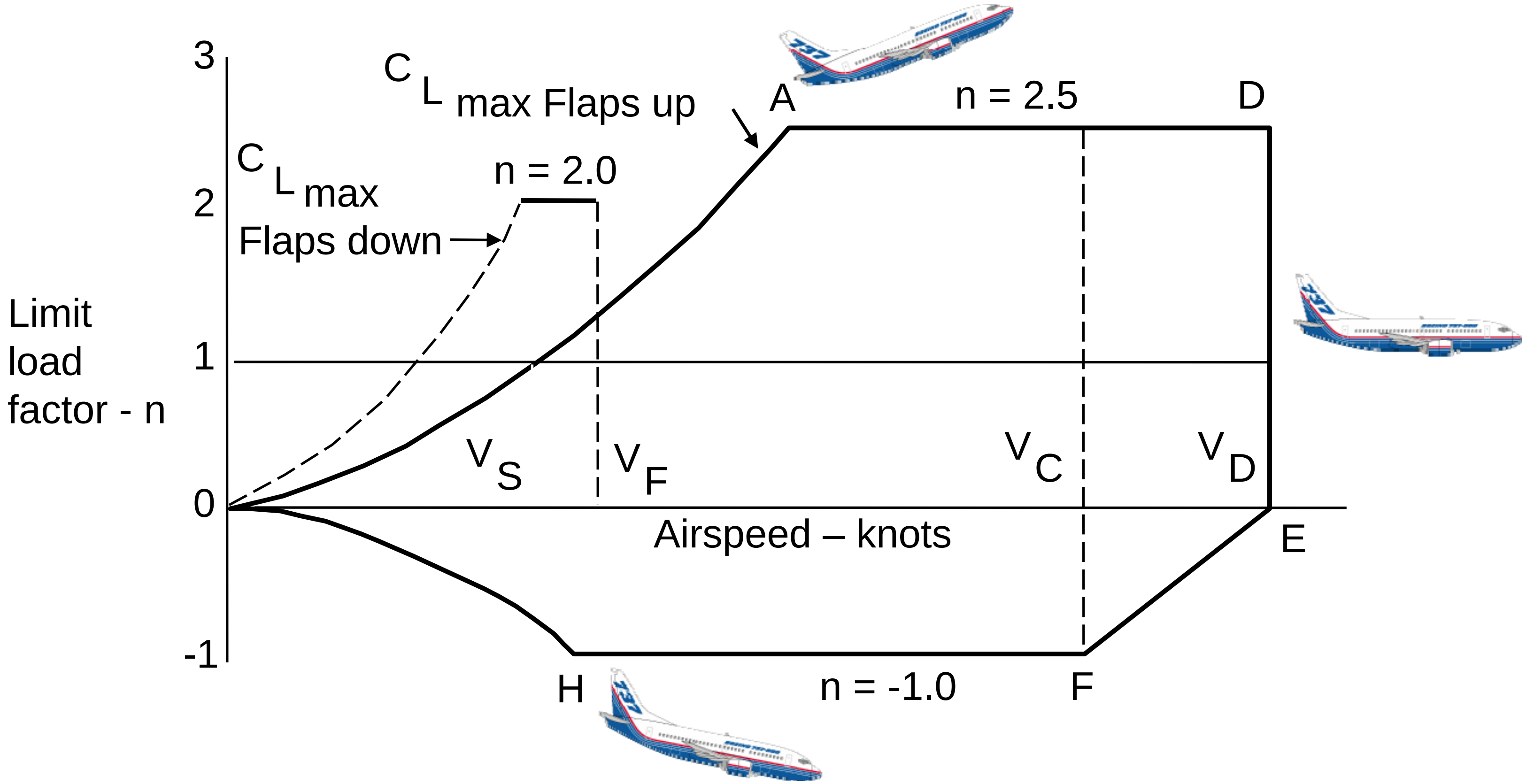
# Loads Are the Foundation of Airplane Design



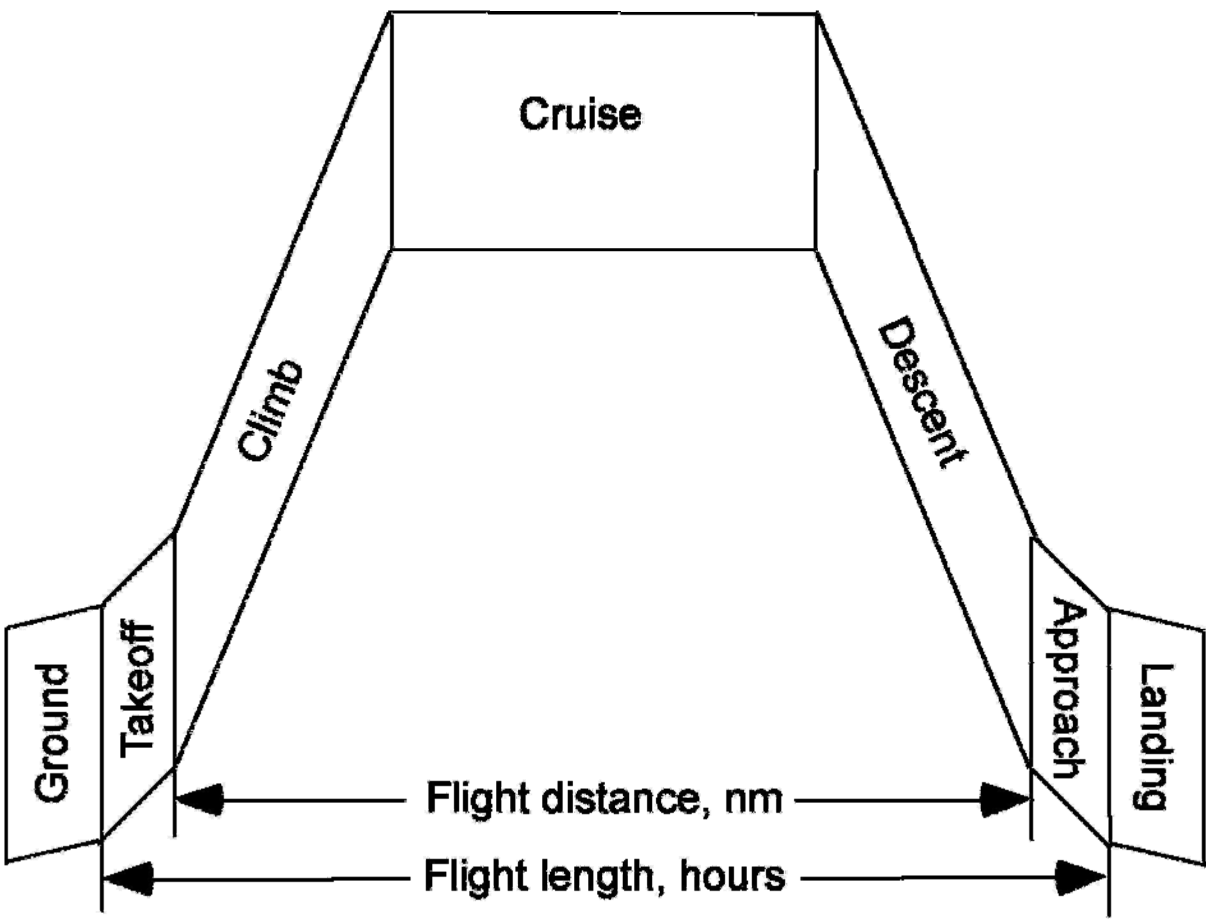
# Center of Gravity/Gross Weight Envelopes



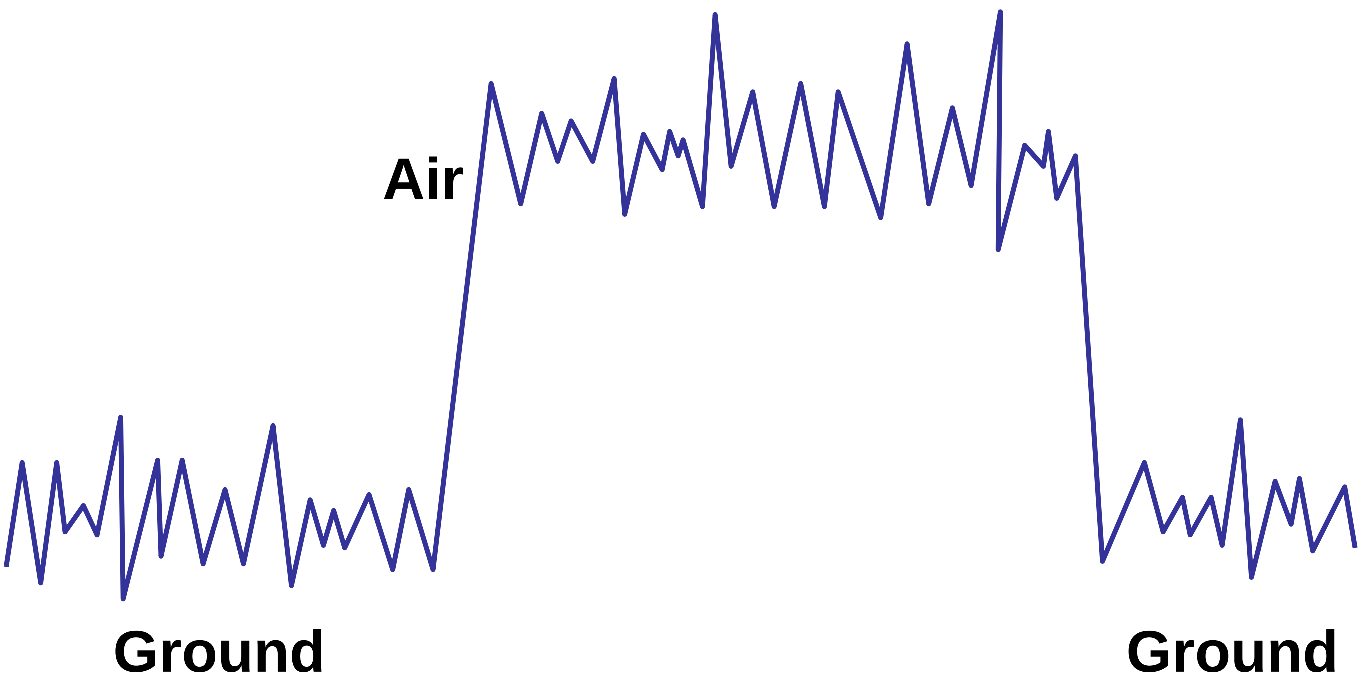
# Design Loads Are Based on Load Factors



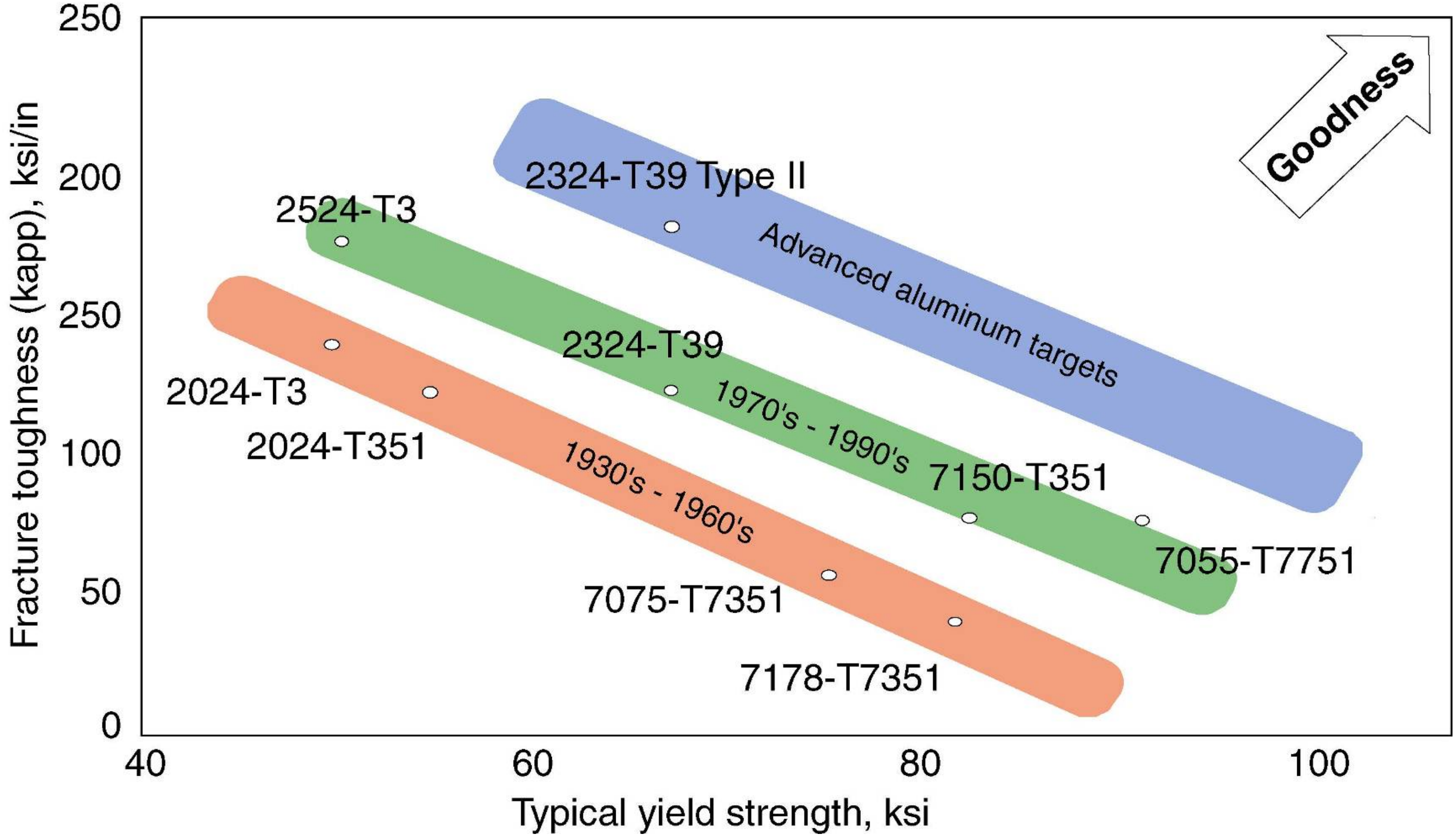
# Flight Profile



# Operating Loads Consist of Random Cycles



# Boeing Structural Aluminum Alloy Improvements



# Material/Process Properties Checklist - Metals

| Materials/Processes | Producibility | Static | Damage Tolerance and Fatigue | |
|---|---|---|---|---|
| Material specification | Forming | Tension | Fatigue crack growth rate | Air Environment |
| Process specification | Machining | Compression | Residual strength | $K_{IC}$ |
| Corrosion property | Trimming | Shear | | $K_A$ |
| Repair specification | Joining | Bearing | Stress corrosion | $K_{ISCC}$ |
| Safety | Assembly | Buckling | | |
| | Chemical processing | Crippling | Fatigue stength | Incidental damage |
| | Real time process | Joint | | Open hole |
| | Inspection | Environmental factors | | Joints |
| | Disposal | | Fatigue factors | Finish |
| | Cleaning | | | Environment |

# Material/Process Properties Checklist - Composites

| Materials/Processes | Reliability | Static | Damage Tolerance and Fatigue | |
|---|---|---|---|---|
| Material specification | Layup | Laminate | Damage tolerance | |
| Process specification | Cure | Part specific layup | Damage growth | Delamination |
| Repair specification | Handling | Joint | | Impact |
| | Finishing | Interlaminar shear | | Notch |
| | Machining | Crippling | Residual strength | Delamination |
| | Joining | Environment factors | | Impact |
| | Assembly | Sandwich | | Notch |
| | Real time process control | | Durability | |
| | Chemical safety | | Post impact | |
| | Inspection | | Open hole | |
| | Disposal | | Bearing | |
| | | | Environment factors | |

# Aircraft Must Be Free From Flutter and Service Vibration

## Design requirement

- **Aircraft is designed to be flutter free up to 1.15 times maximum design dive speed envelope (Vd/Md) up to Mach 1.**

## Analytical approach

- **Unsteady aerodynamics and flutter finite element component and airplane analyses are conducted.**

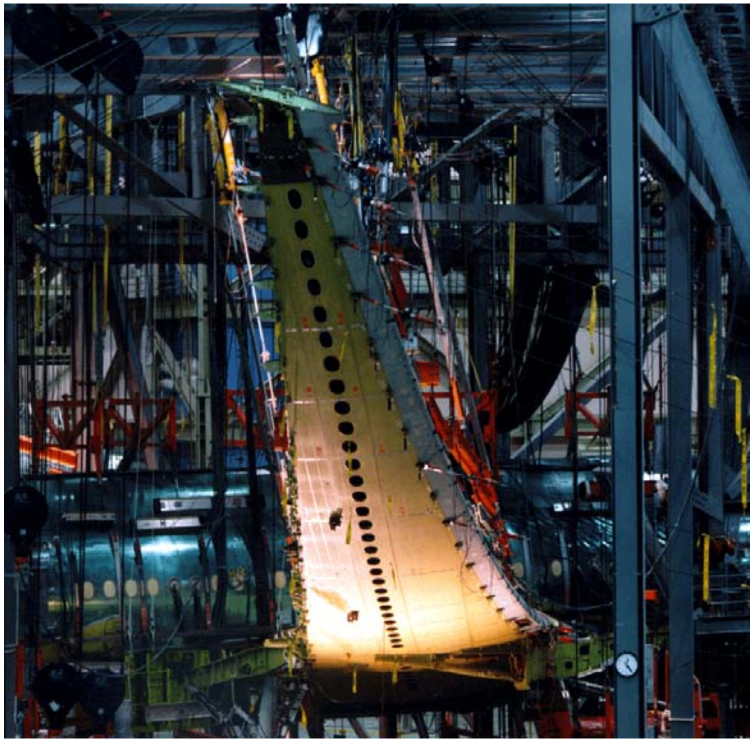
## Validation

- **Analysis is verified by wind-tunnel models, ground vibration, and flight tests up to Va/Md.**

# Structure Must Have Adequate Static Strength

## Design requirements

- **Structure must remain elastic up to limit loads**
- **Structure must carry ultimate loads.**



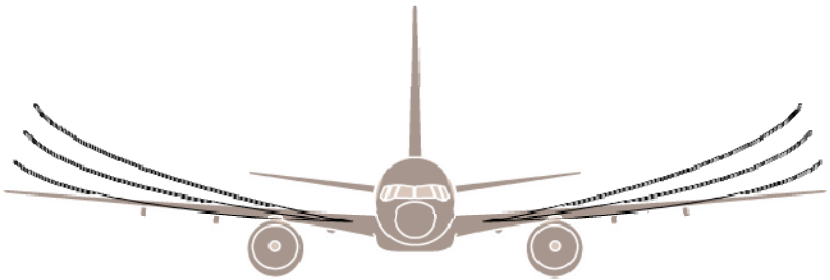
## Analytical approach

- **Margins of safety are computed for all members based on maximum stresses and structural allowables to verify designs.**

## Validation

- **Design is validated by limit loads, ultimate loads, and destruction tests.**

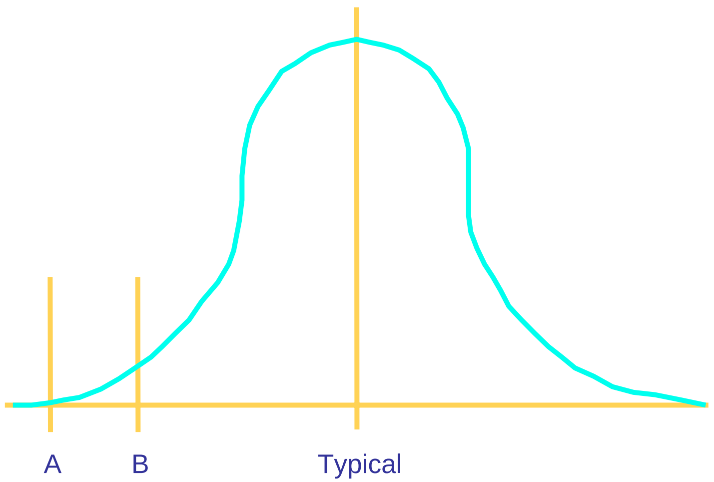
# Static Margins of Safety (MS) Are Computed Based on Maximum Applied and Allowable Stresses and Structural Allowables



**Allowable stress or strain; material or structural allowables**

$$MS = \frac{F}{f_{max}} - 1$$

**Maximum applied stress or strain; developed from finite-element analysis or traditional procedures**



# Aircraft Are Designed for 30 Years of Service

## Design requirements

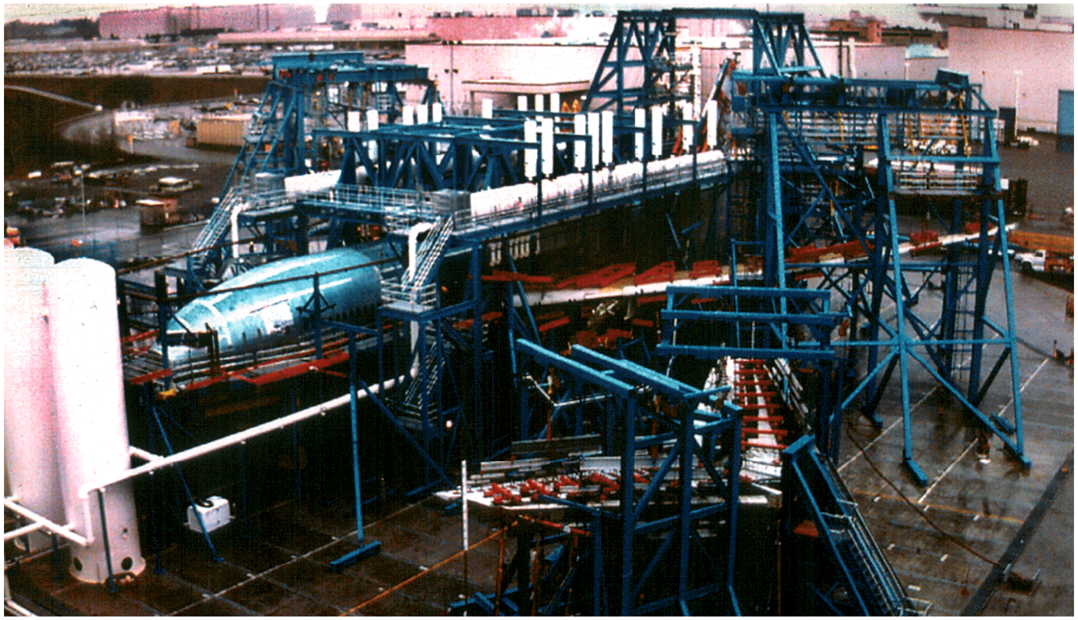
- **Structure must meet or exceed the design service objective with minimum service corrosion or cracking**

## Analytical approach

- **Margins of safety are computed for all members based on maximum and allowable operating stresses**

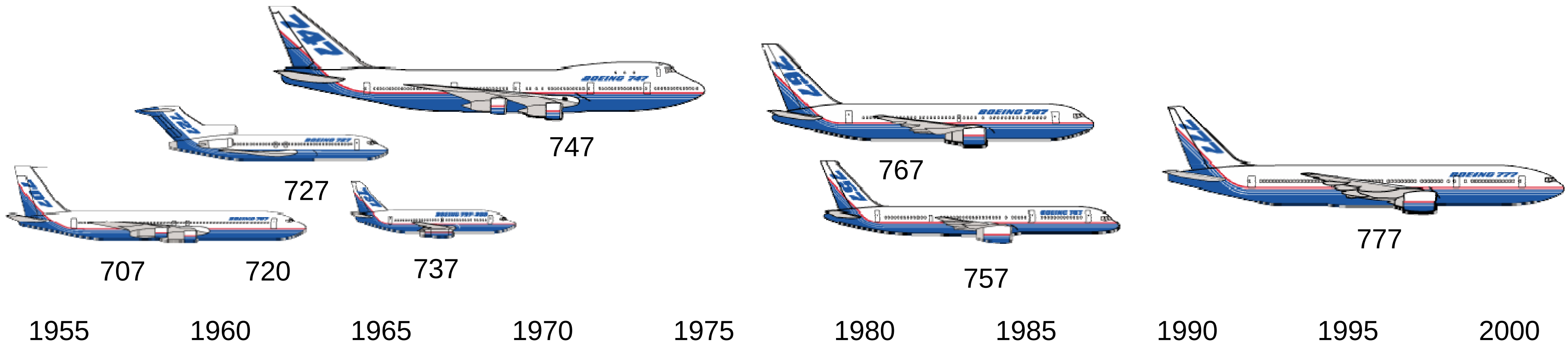
## Validation

- **Panel, component, and full scale airplane testing**



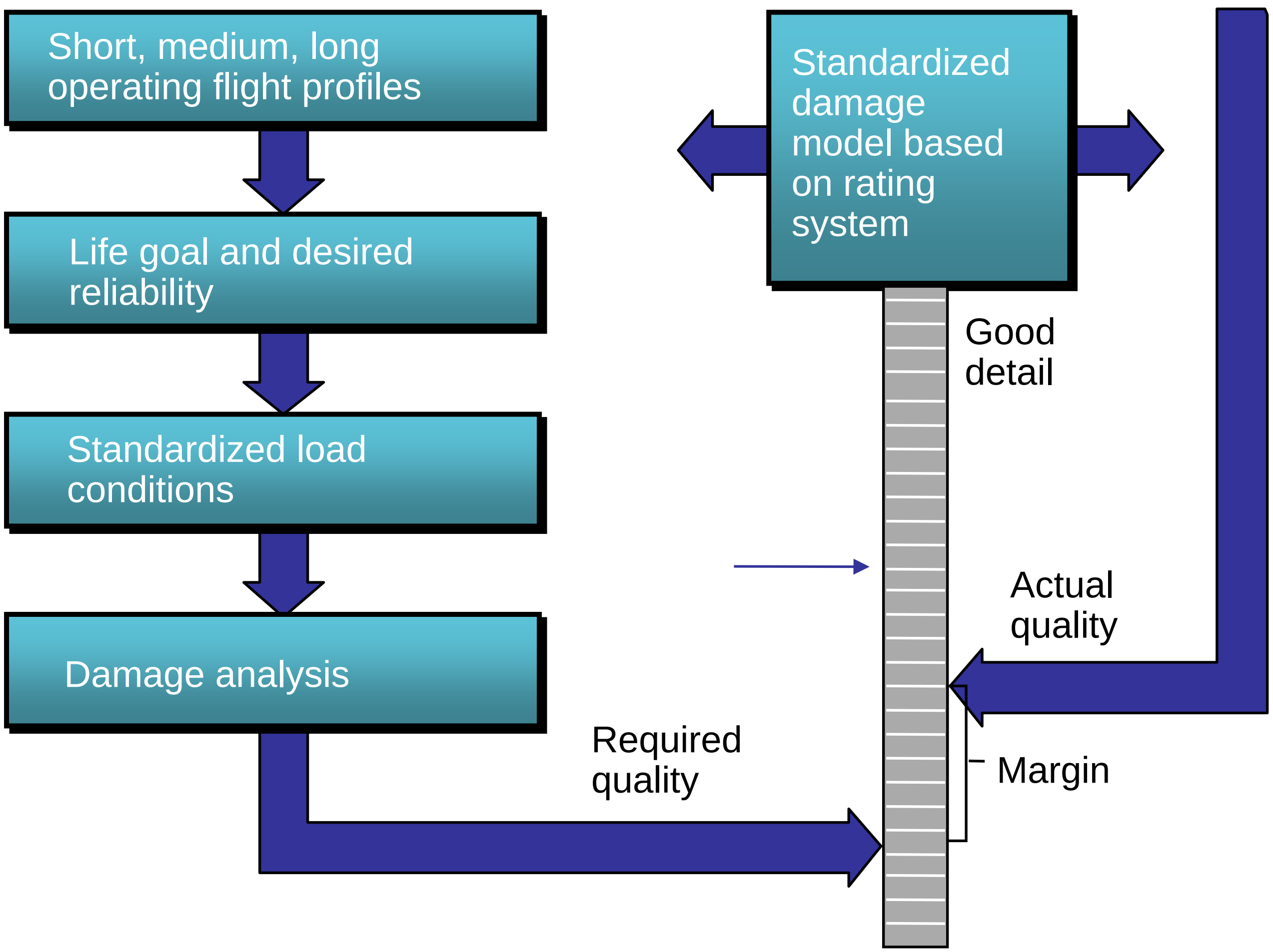
# Economic and Market Conditions Result in Use of Airplanes Beyond Original Economic Design Life Objectives

Boeing Commercial Jet Fleet Summary October 31, 2004 Data




| Model | Total airplanes | Minimum service design objectives | | High time airplanes | |
|---|---|---|---|---|---|
| | | Flights | Hours | Flights | Hours |
| 707 | 735 | 20,000 | 60,000 | 39,800 | 98,700 |
| 720 | 153 | 30,000 | 60,000 | 45,000 | 69,300 |
| 727 | 1,822 | 60,000 | 50,000 | 87,700 | 93,700 |
| 737 | 4,585 | 75,000 | 51,000 | 97,300 | 99,700 |
| 747 | 1,336 | 20,000 | 60,000 | 39,100 | 119,000 |
| 757 | 1,040 | 50,000 | 50,000 | 35,400 | 74,200 |
| 767 | 916 | 50,000 | 50,000 | 40,300 | 79,100 |
| 777 | 493 | 40,000 | 60,000 | 18,000 | 38,100 |
| 737NG | 1,489 | 75,000 | 51,000 | 16,600 | 27,500 |

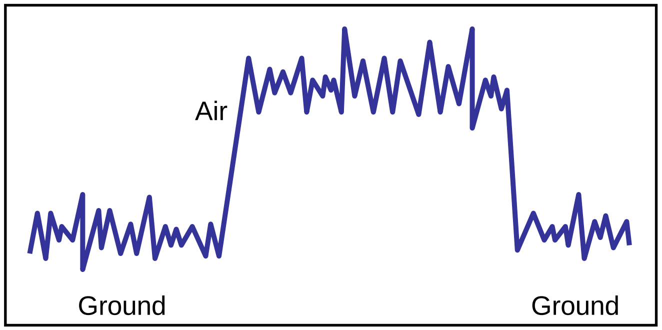
# Configuration Capability Must Meet Operating Requirement




Calculated detail quality based on

- Material
- Fastener fit
- Load transfer
- Stress concentration

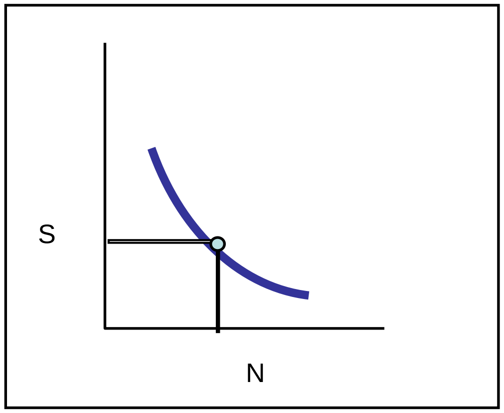
# Fatigue Margins of Safety Are Computed Based on the Fatigue Allowables and Maximum GAG Stresses



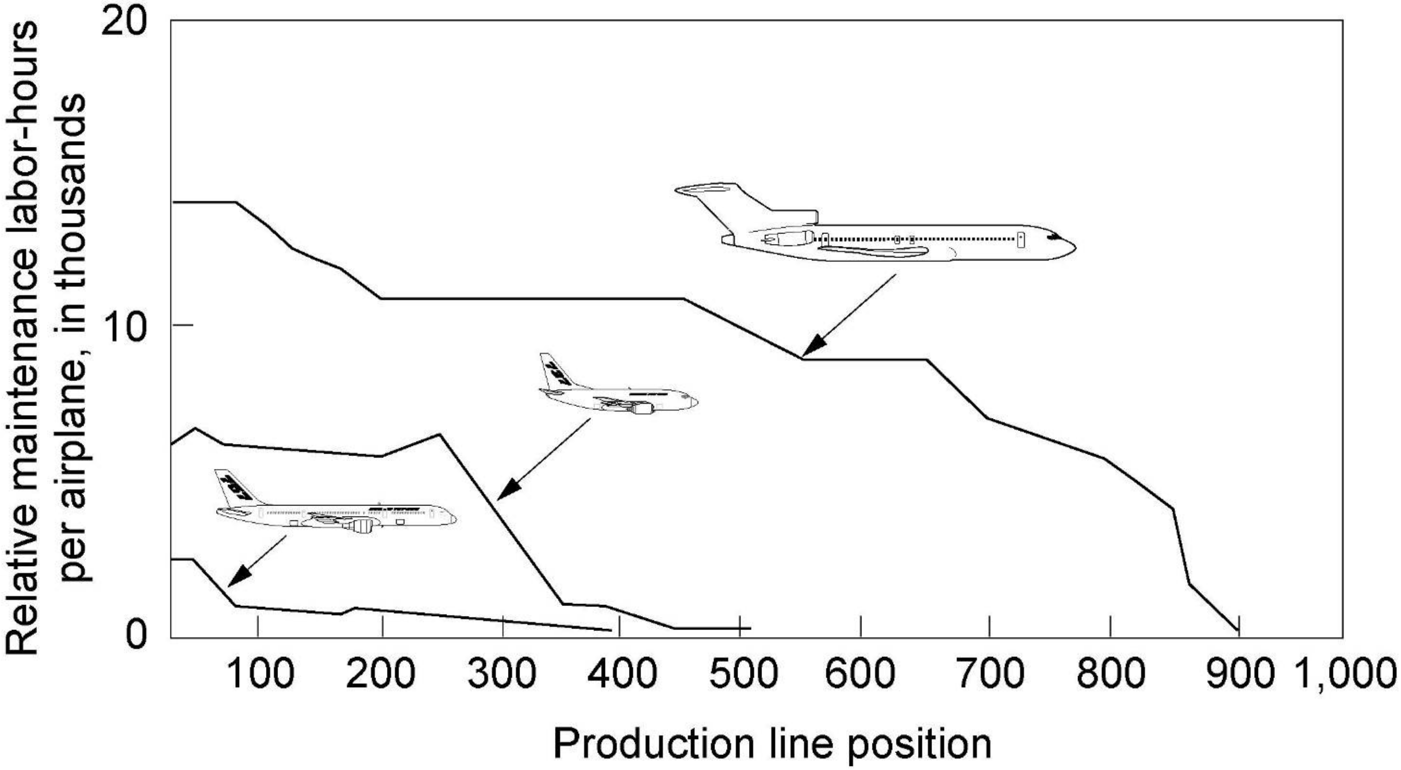

**Allowable ground-air-ground stress**

$$MS = \frac{F_{max}}{f_{max}} - 1$$

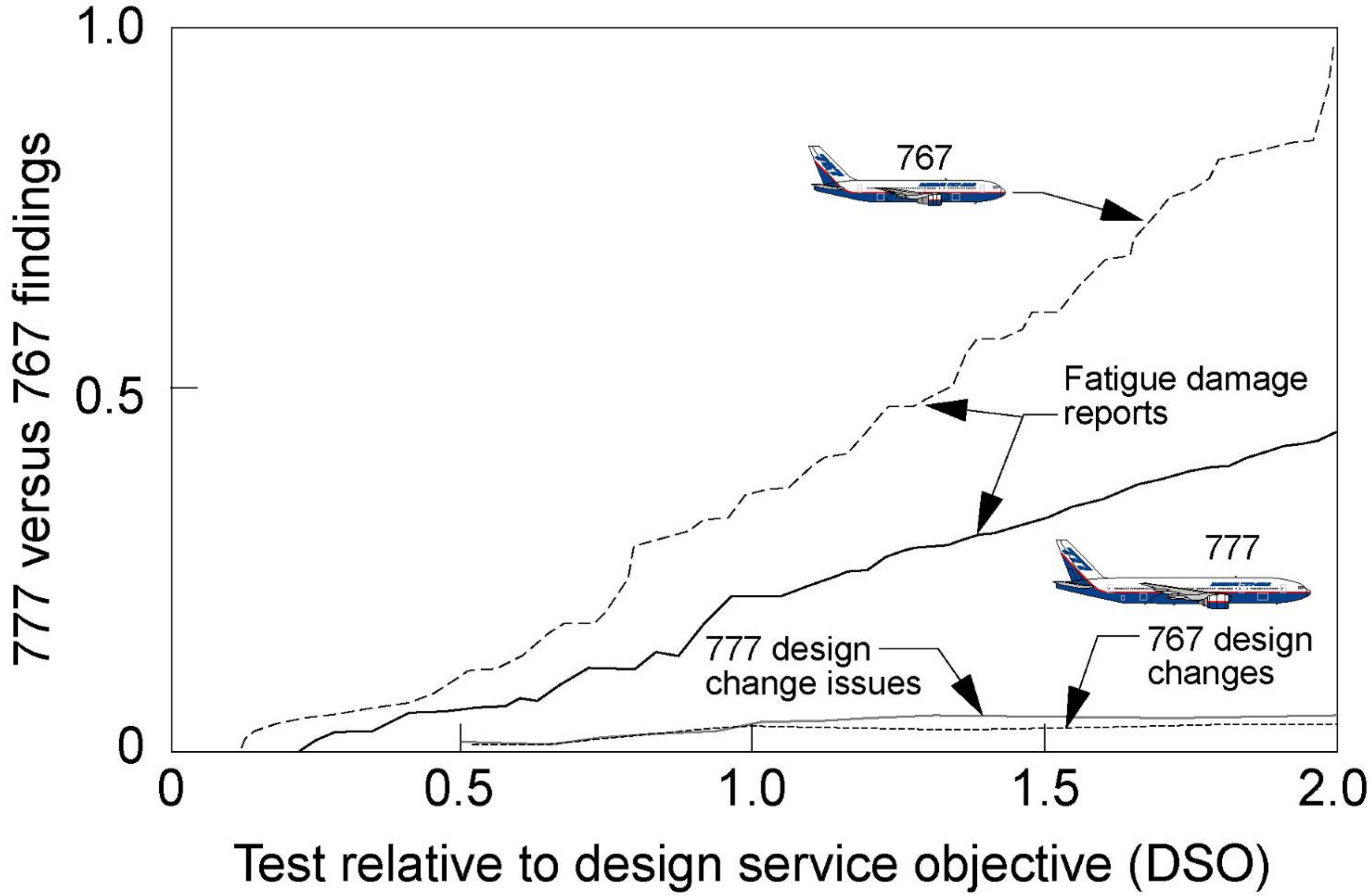
**Actual ground-air-ground stress**



# 10-Year Comparison of Service Bulletin Labor-Hours (727, 737, and 757)



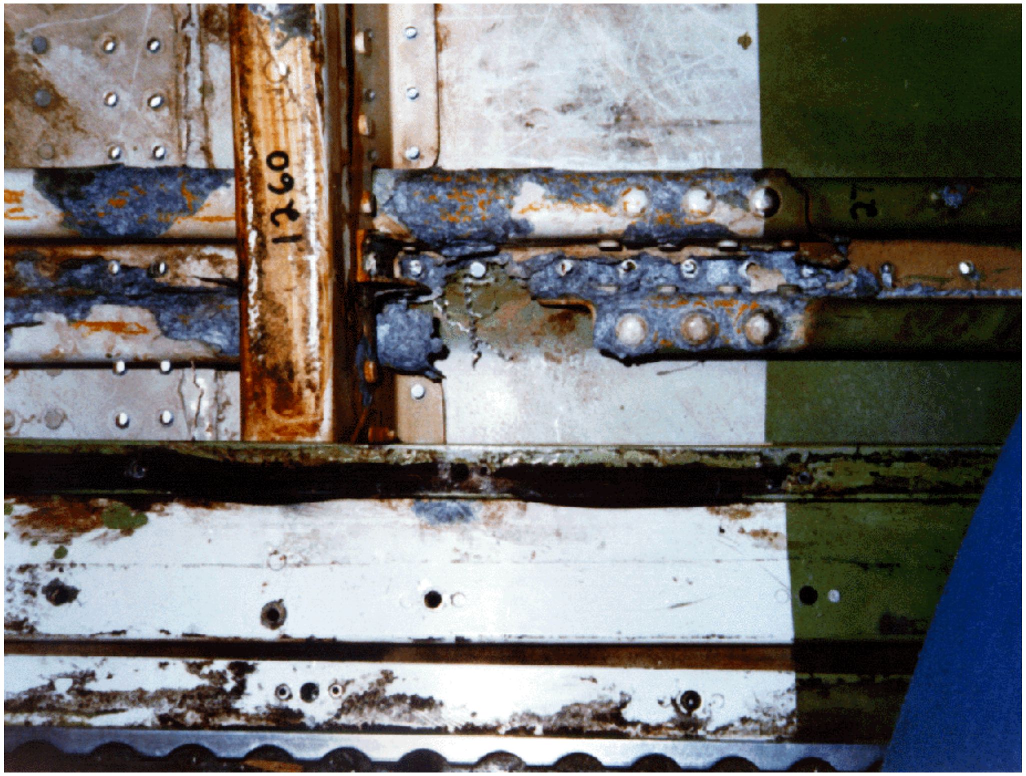
# Comparison of 767 and 777 Fatigue Test Findings



# Aircraft Are Designed for Corrosion Prevention

## Design requirement

- **The design objective is to be free from significant corrosion during the operational life of the airplane.**



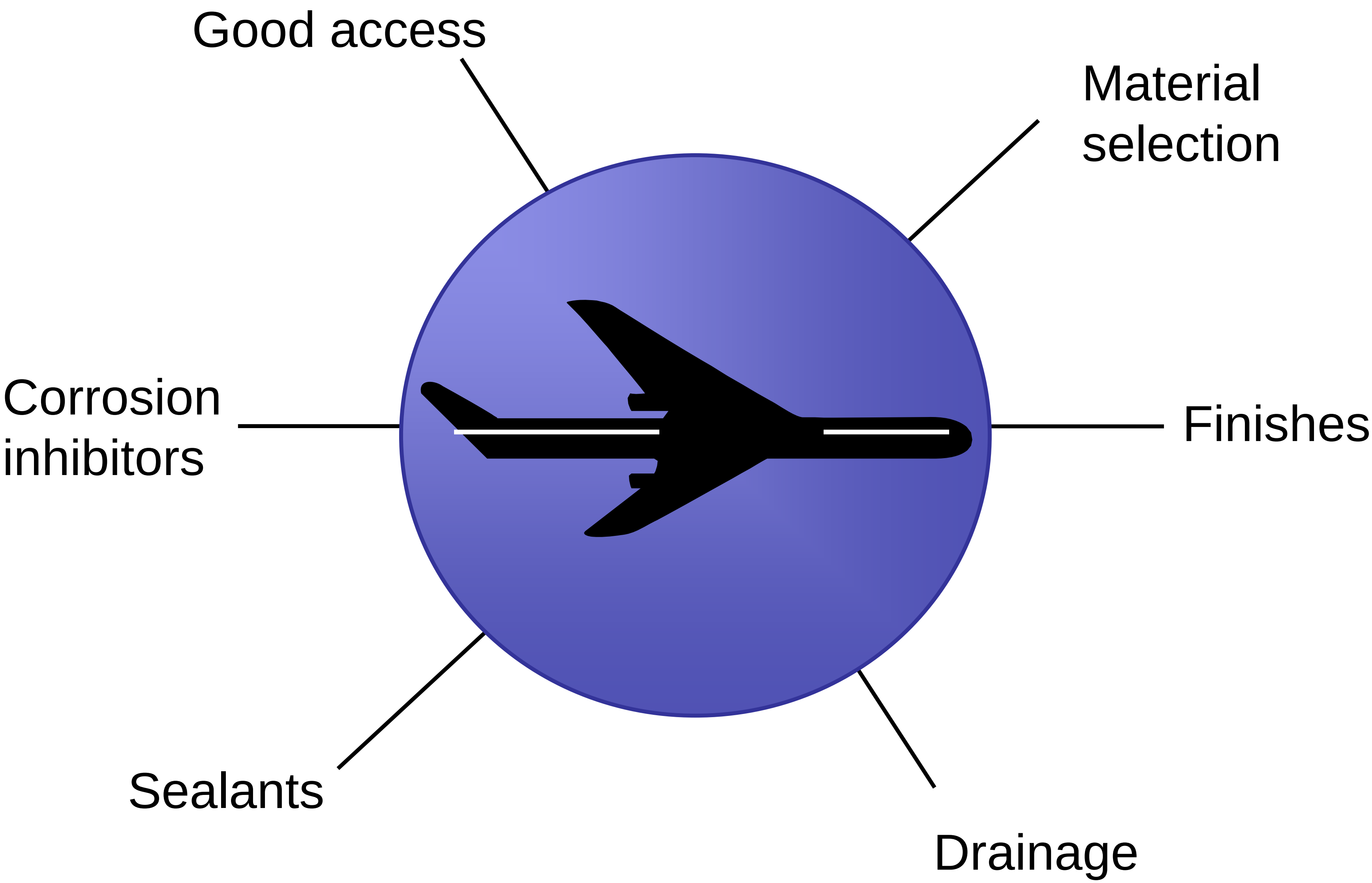

## Maintenance

- **Specified preventive maintenance must be performed.**

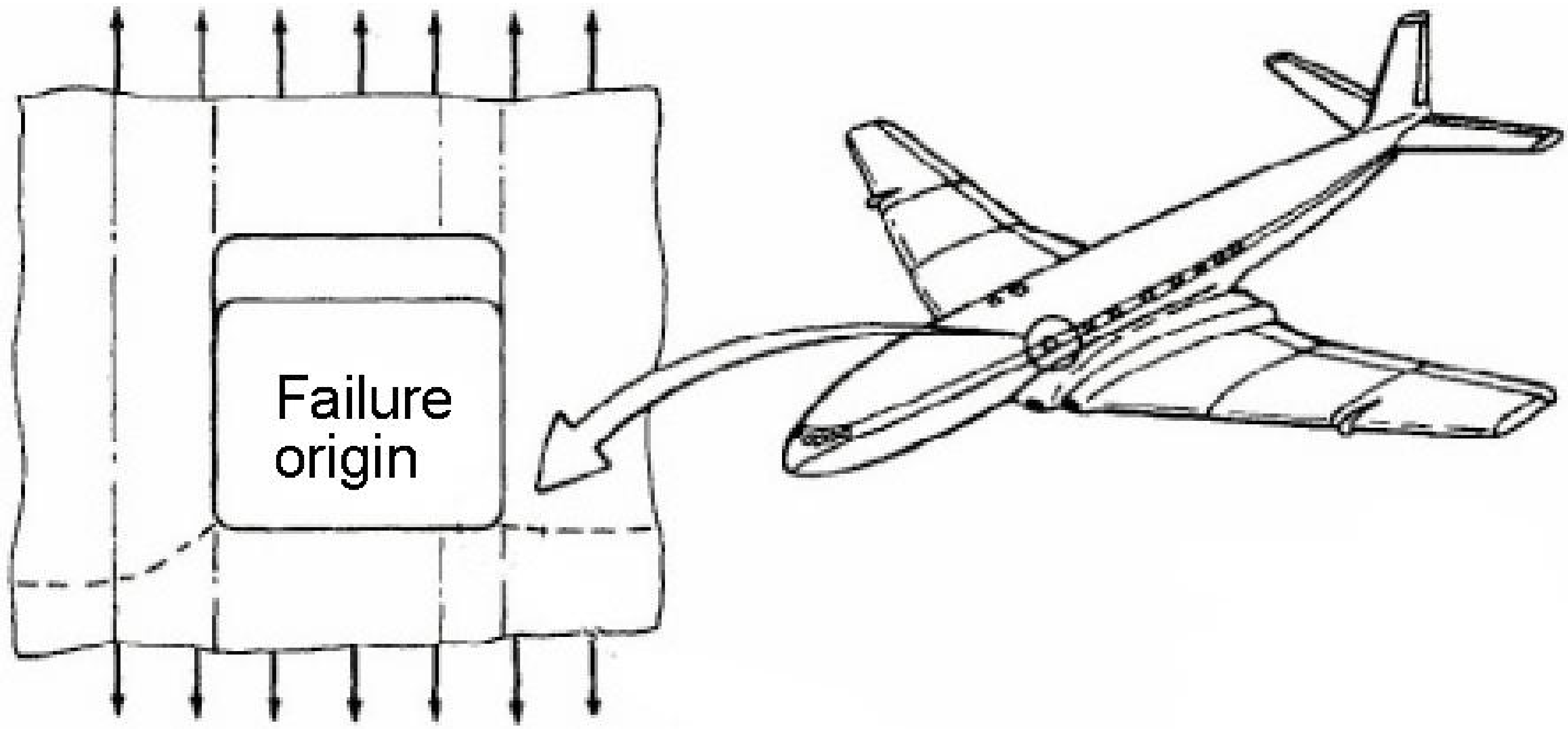
## Validation

- **Operator feedback is used to improve prevention measures.**

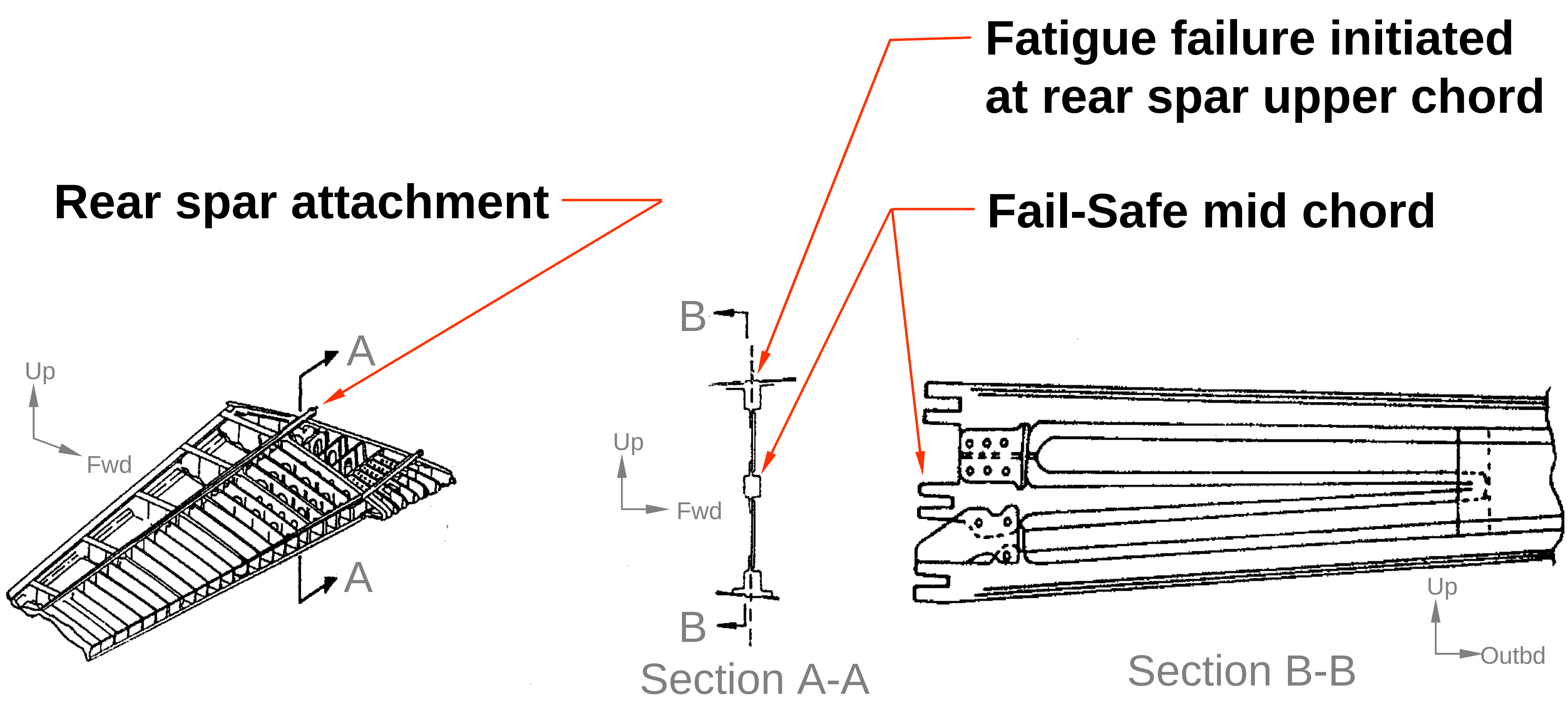
# Design Features for Corrosion Prevention



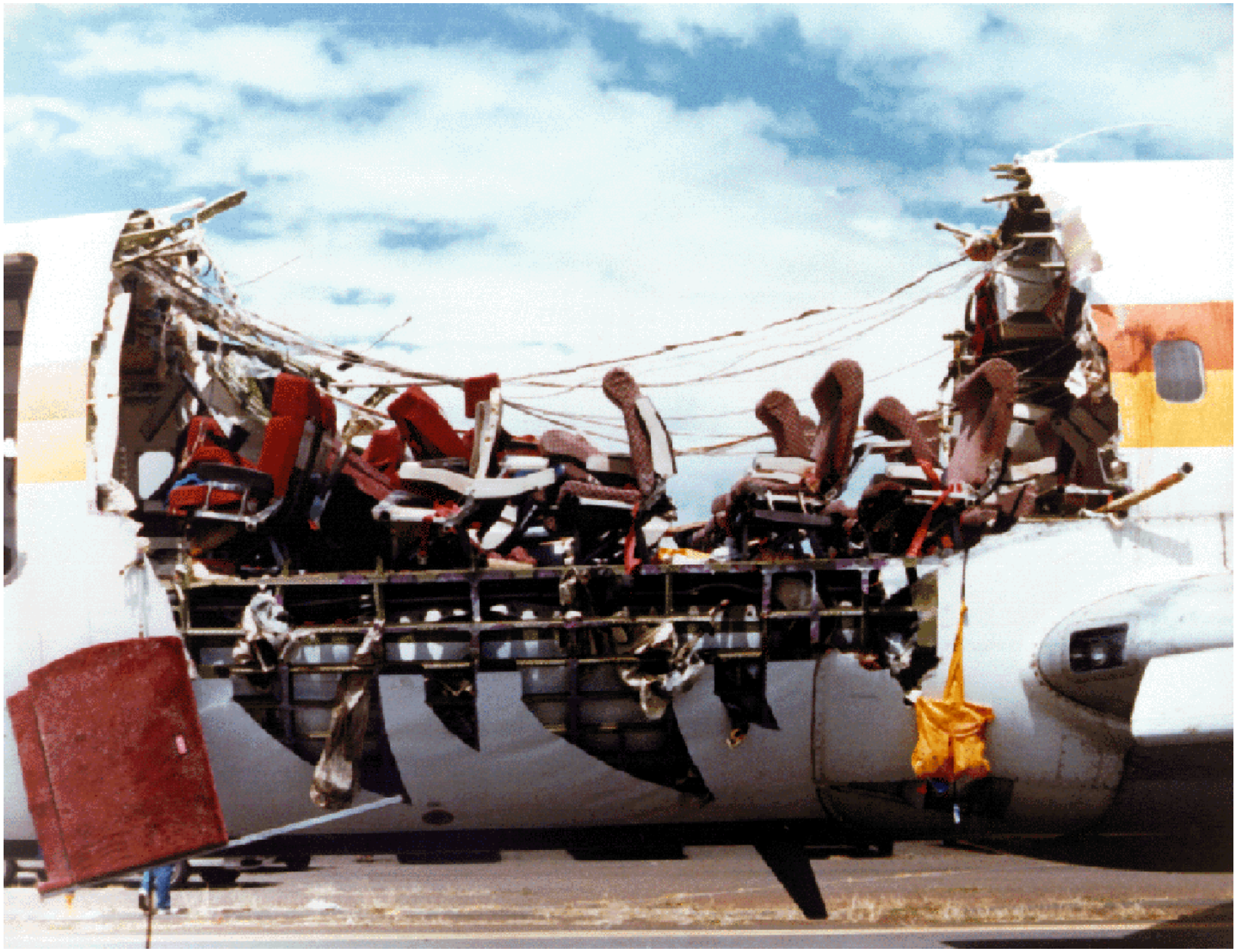
# Comet Accident



# 707-300 Horizontal Stabilizer Rear Spar Failure



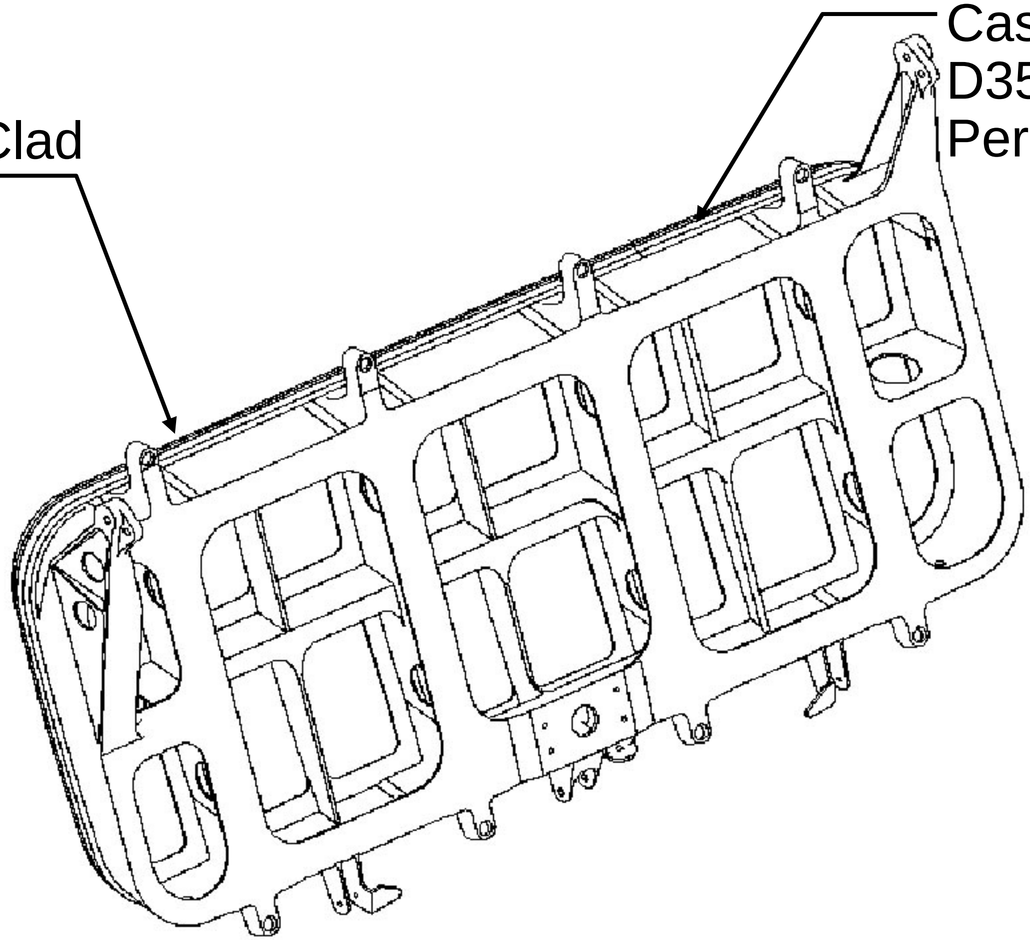
# Safety Is the Most Important Goal



# FAR 25.571 Amendments Related to Fail Safety and Damage Tolerance

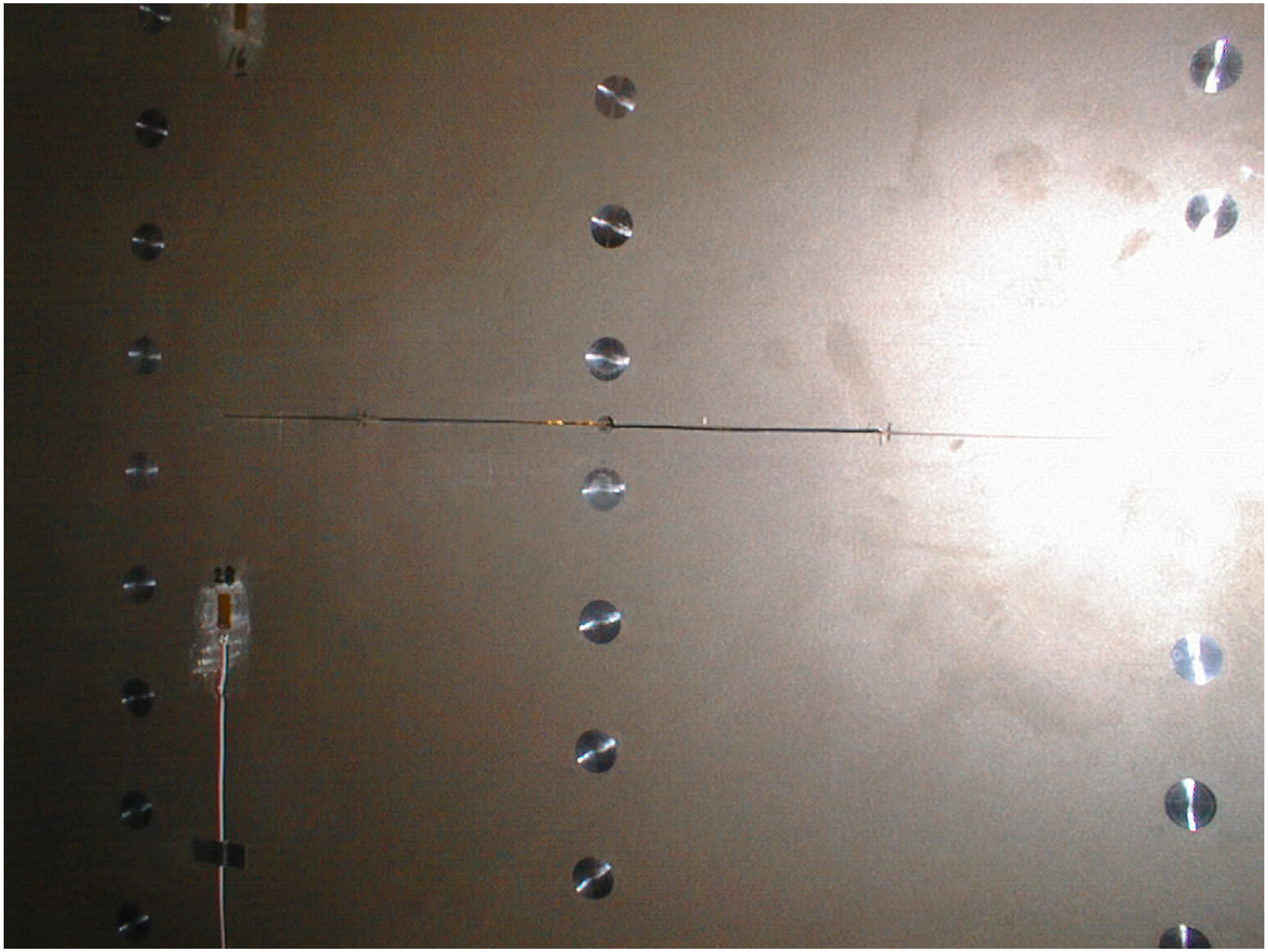
| Amendment Level and Date | Title | Summary of Changes to section 25.571(b) or (c) |
|---|---|---|
| 25-0<br>(12/24/64) | **Fatigue evaluation of flight structure** | **(c) Fail safe strength**<br>“It must be shown by analysis, tested, or both, that catastrophic failure or excessive deformation, that could adversely affect the flight characteristics of the airplane, are not probable after fatigue or obvious partial failoure of a single PSE. |
| 25-45<br>(12/1/78) | **Damage-tolerance and fatigue evaluation of structure** | **(b) Damage-tolerance (fail-safe) evaluation.**<br>“The evaluation must include a determination of the probably locations and modes of damage due to fatigue, corrosion, or accidental damage. The residual strength evaluation must show that the remaining structure is able to withstand loads corresponding to…” |
| 25-96<br>(4/30/98) | **Damage-tolerance and fatigue evaluation of structure** | **(b) Damage-tolerance evaluation.**<br>Initial flaw of maximum probable size from manufacturing defect or service induced damage used to set inspection thresholds; sufficient full scale fatigue test evidence must demonstrate that WFD will not occur within DSO (no airplane may be operated beyond cycles equal to ½ the cycles on fatigue test article until testing is completed). |

# Monolithic Structure is Used to Improve Producibility

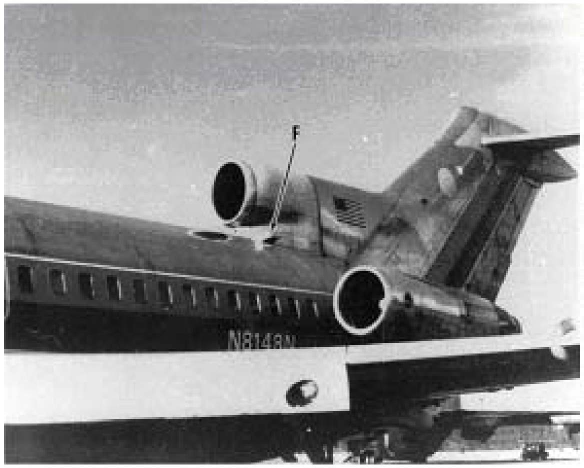


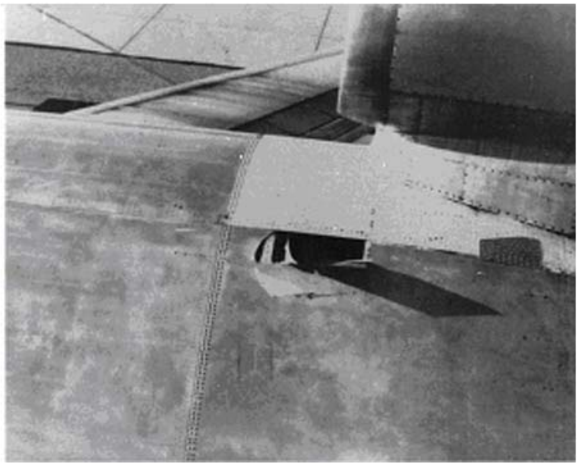

737-600/700/800 Airstair Door

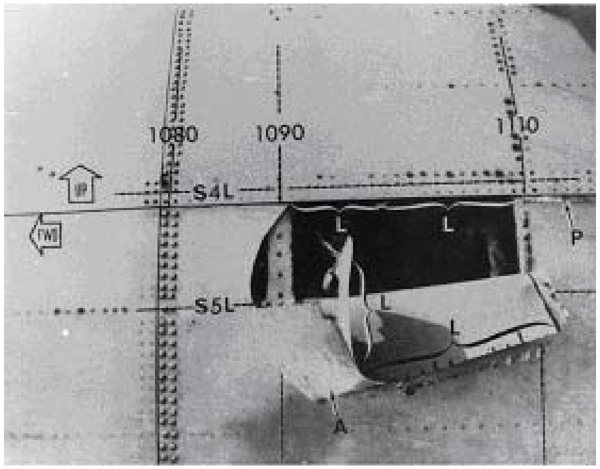
# Two-Bay Crack in the Wing Lower Surface



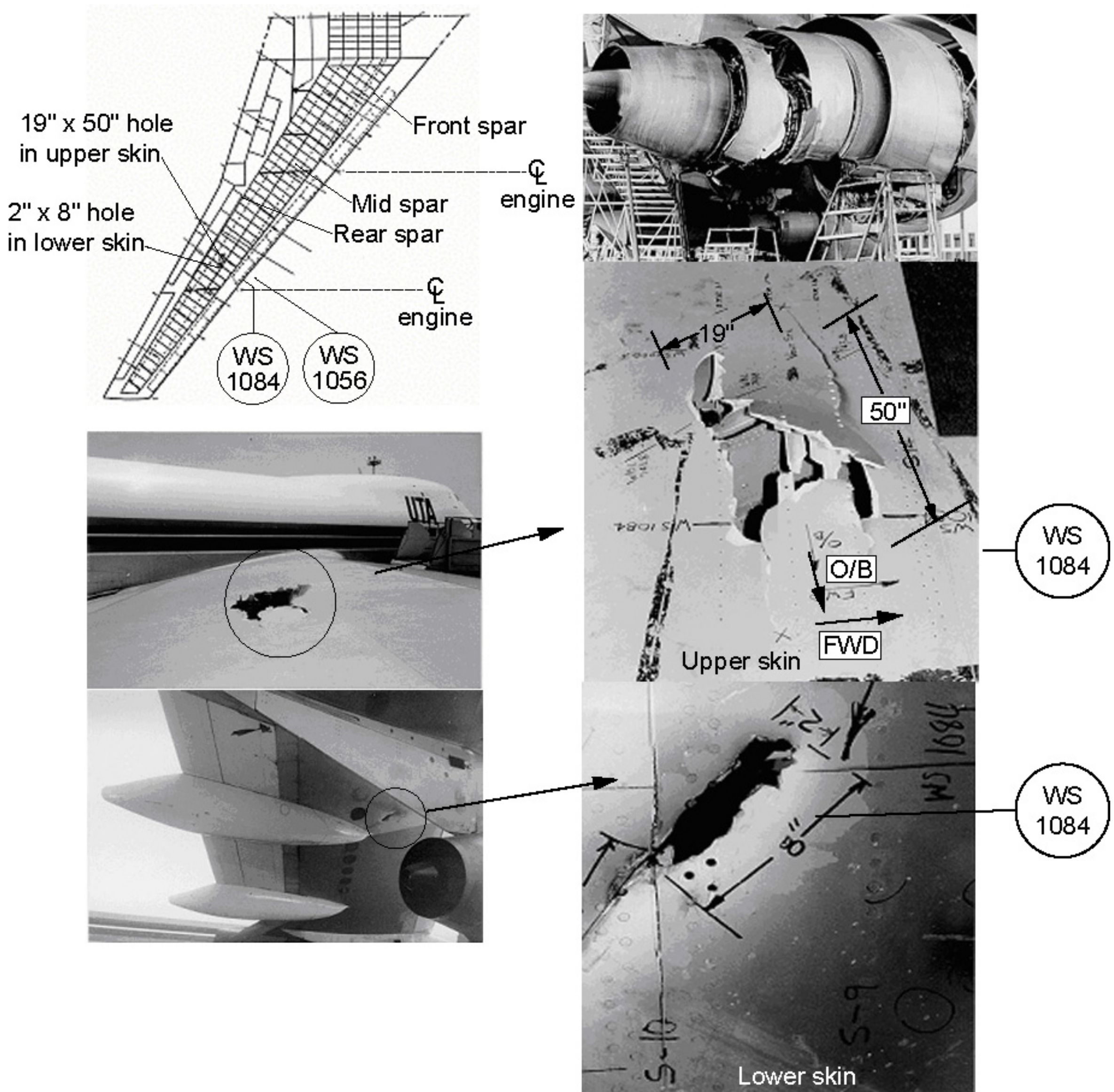
# Example of Safe Fuselage Decompression



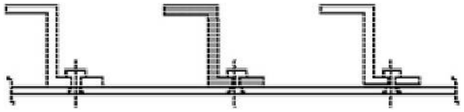
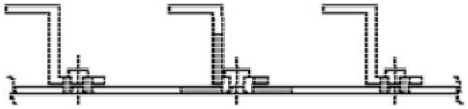





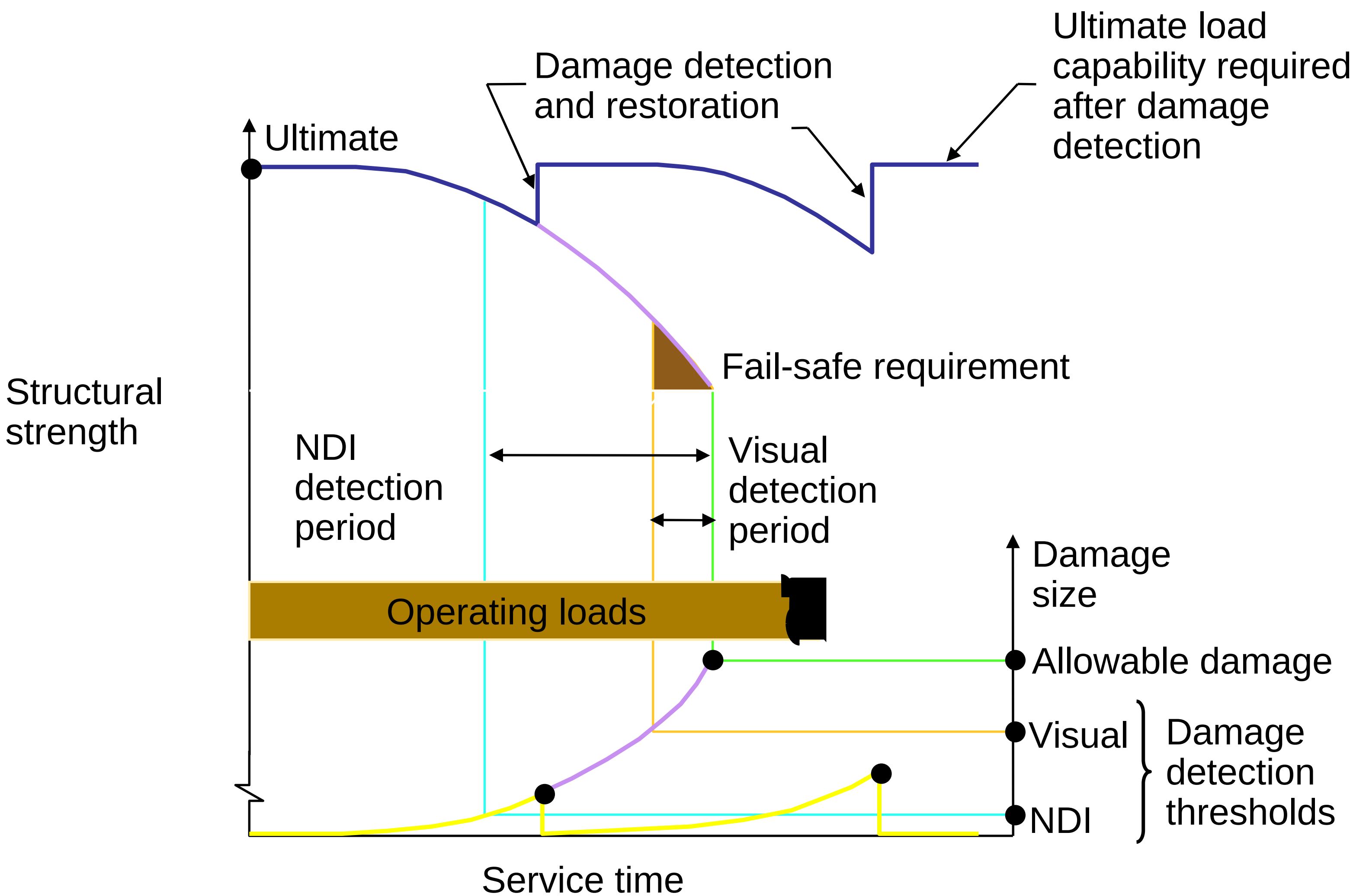
# Example of Save Wing Penetrations



# Damage Tolerance Regulation Comparison

| Analysis | FAR 25.571 (before 1978) | FAR 25.571 (after 1978) |
|---|---|---|
| Residual strength | • Single element of obvious failure | • Multiple active cracks |
| Crack growth | • No analysis required  | • Extensive analysis required  |
| Inspection program | • Based on service history<br>• FAA air carrier approval | • Related to structural damage characteristics and past service history<br>• Initial FAA engineering and air carrier approval |

# Safety is Maintained by Damage-Tolerant / Fail-Safe Structures



# Structure Must Be Damage Tolerant

## Design requirement

- **Structure must have capability to withstand damage until detected and repaired.**

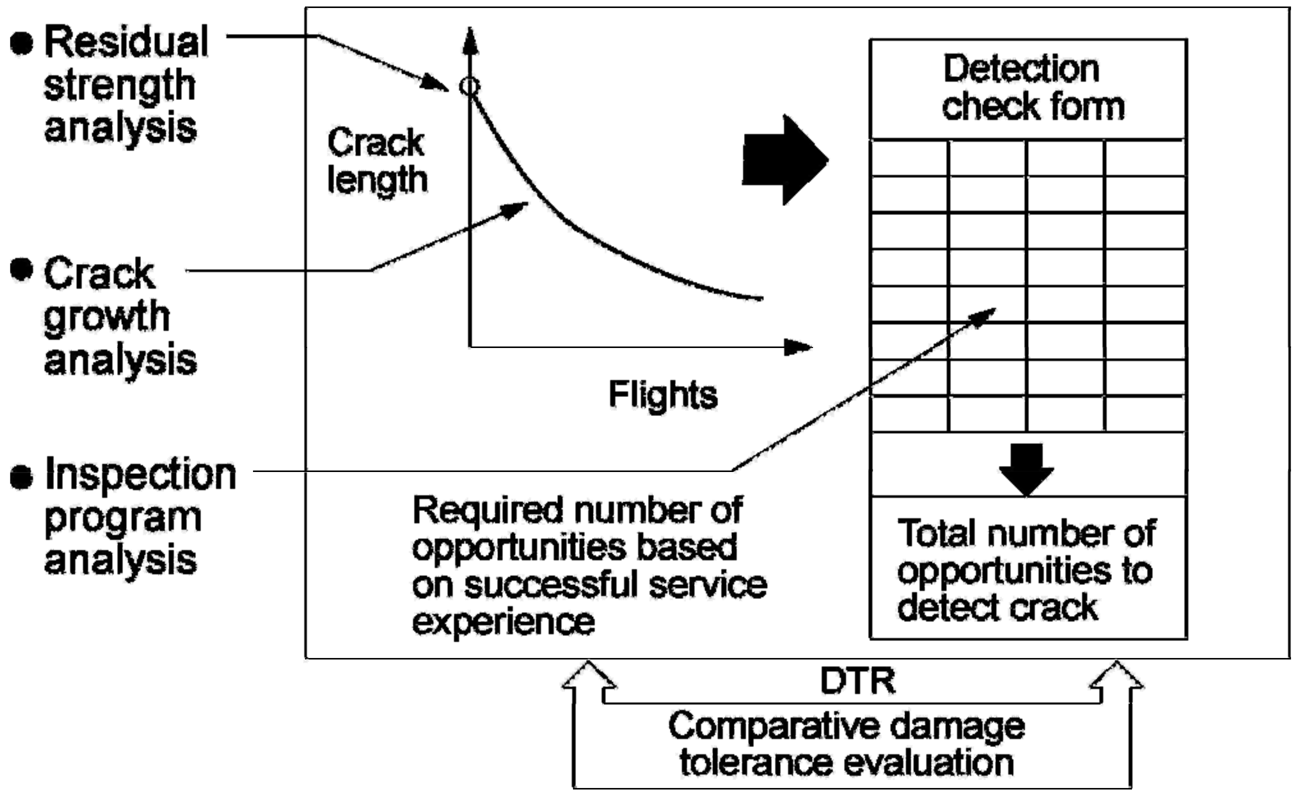
## Analytical approach

- **Damage tolerance is verified by analytical assessment of damage growth, residual strength, and surveillance.**

## Validation

- **Damage tolerance is validated by panel and component tests.**
  - **Residual strength**
  - **Crack growth**
  - **Qualification**
  - **Inspection program**

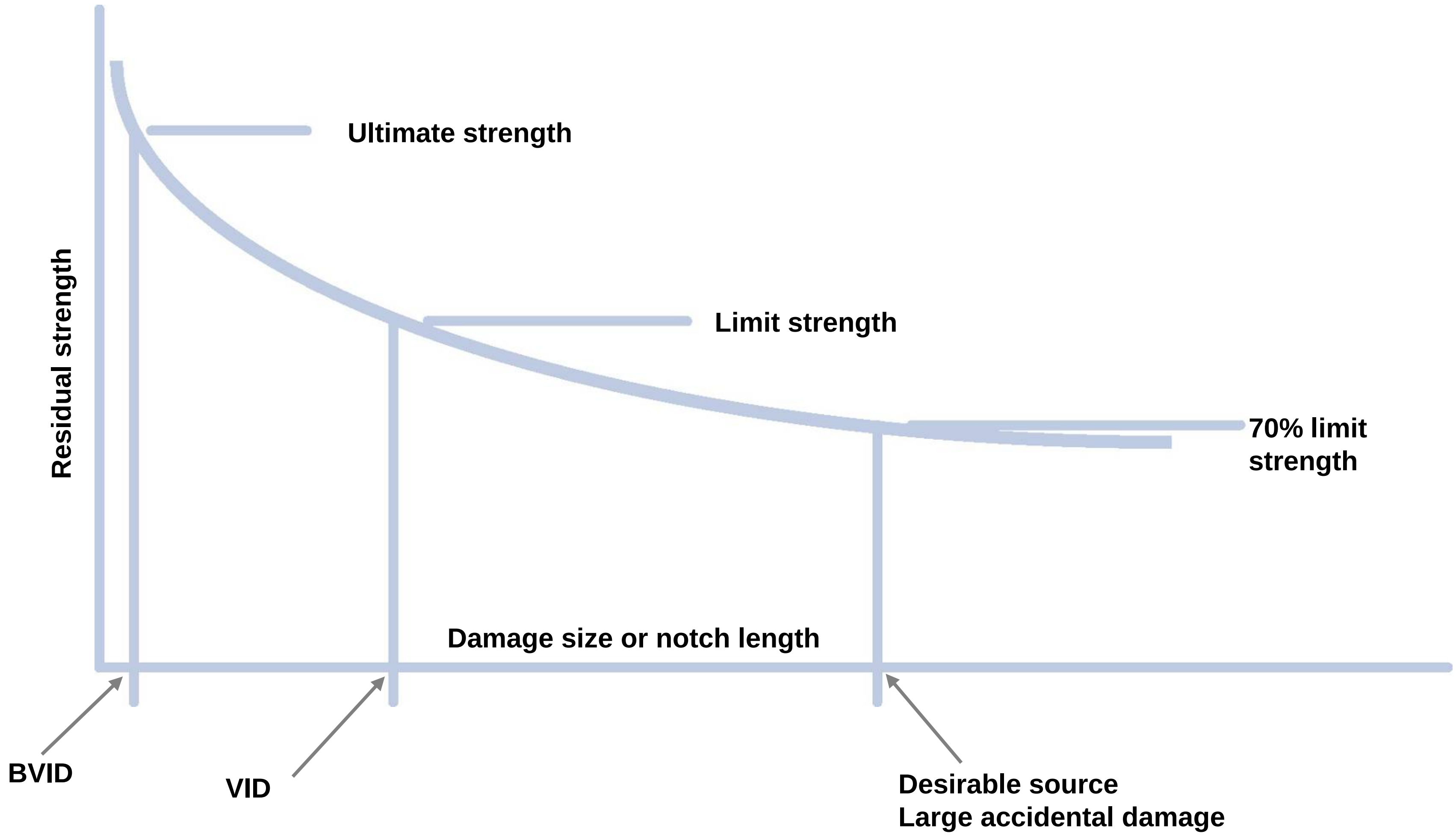
# Damage Detection Evaluation



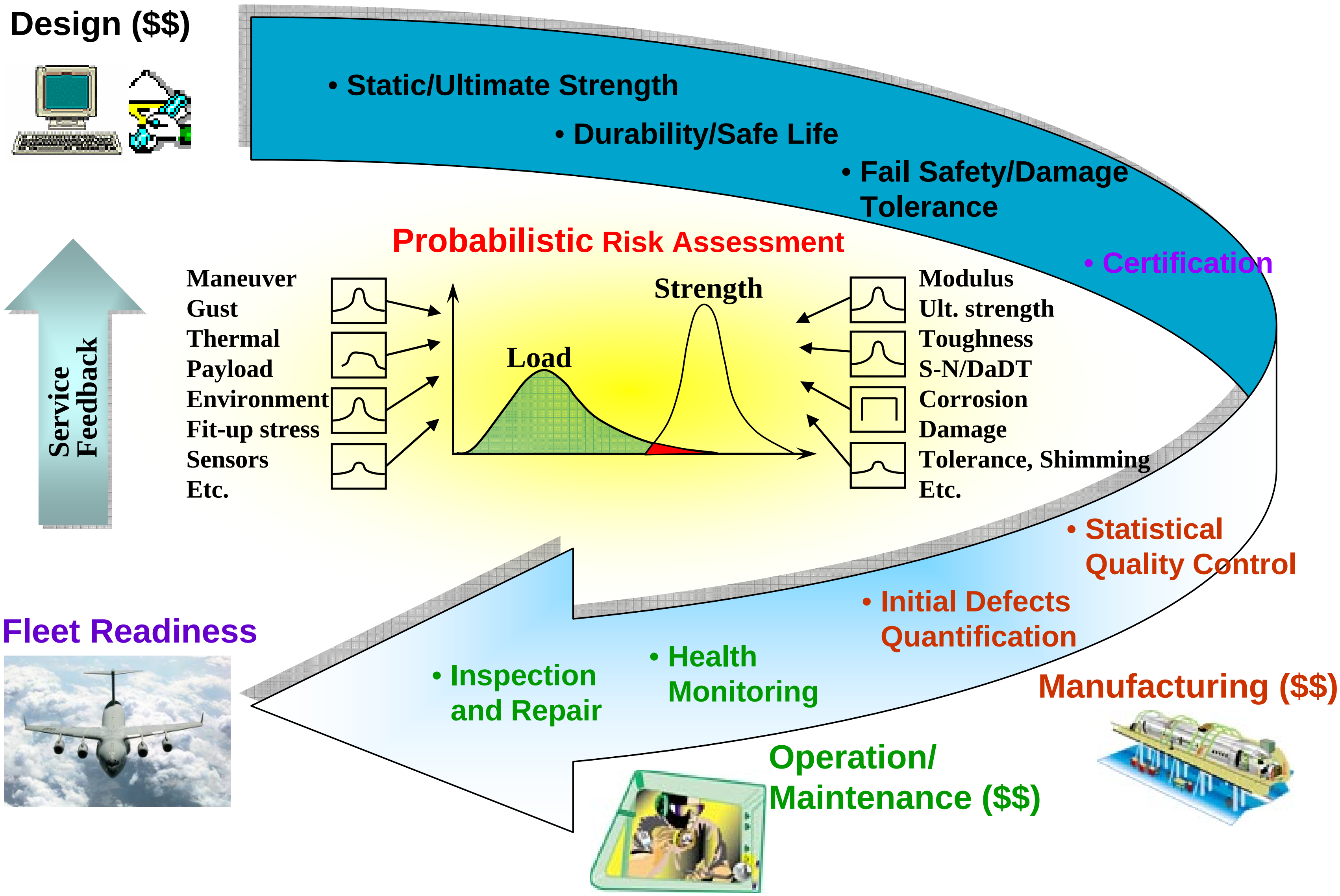
# Structural Classification and Damage Tolerance Requirements

| **Structural category** | | **Required design attributes** | **Analysis requirements** | **Structural classification examples** |
|---|---|---|---|---|
| Other structure | Secondary structure ① | Design for loss of component or safe separation | Continued safe flight | Flap track canoe fairings (safe separation or safe loss or segment) |
| | Damage obvious or malfunction evident ② | Design for faioure or partial failure of a principal structural element with continued structural integrity | • Residual strength | Wing fuel leaks |
| Primary structure (Structurally significant items or principal structural elements) | Damage detection by plannd inspection ③ | Inspection program matched to structural characteristics | • Residual strength<br>• Crack growth<br>• Inspection program | All primary structure not included in categories and |
| | Safe life design ④ | Design for conservative ratigue life (damage tolerant design is impractical) | Fatigue analysis verified by test | Landing gear structure |

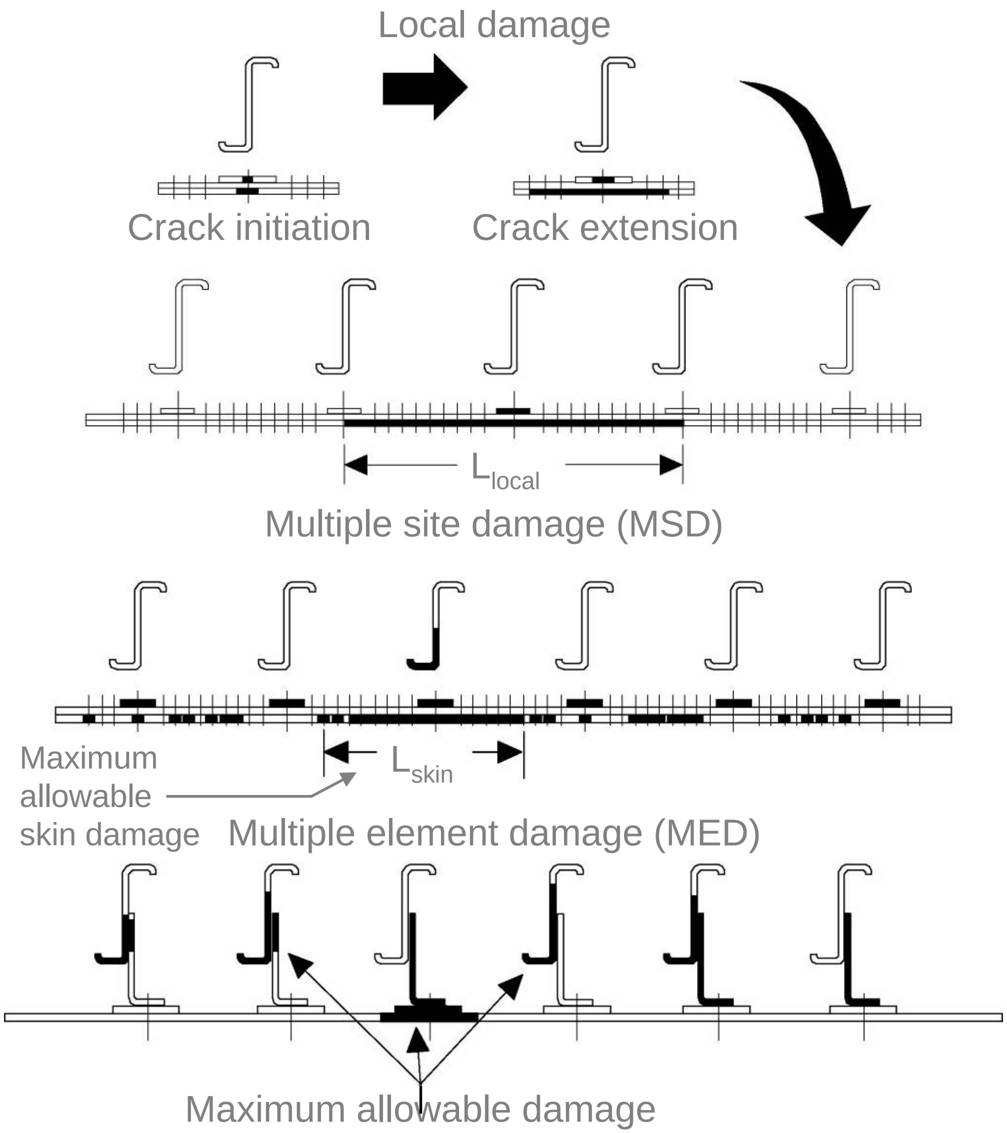
# Residual Strength Versus Damage Size or Notch Length



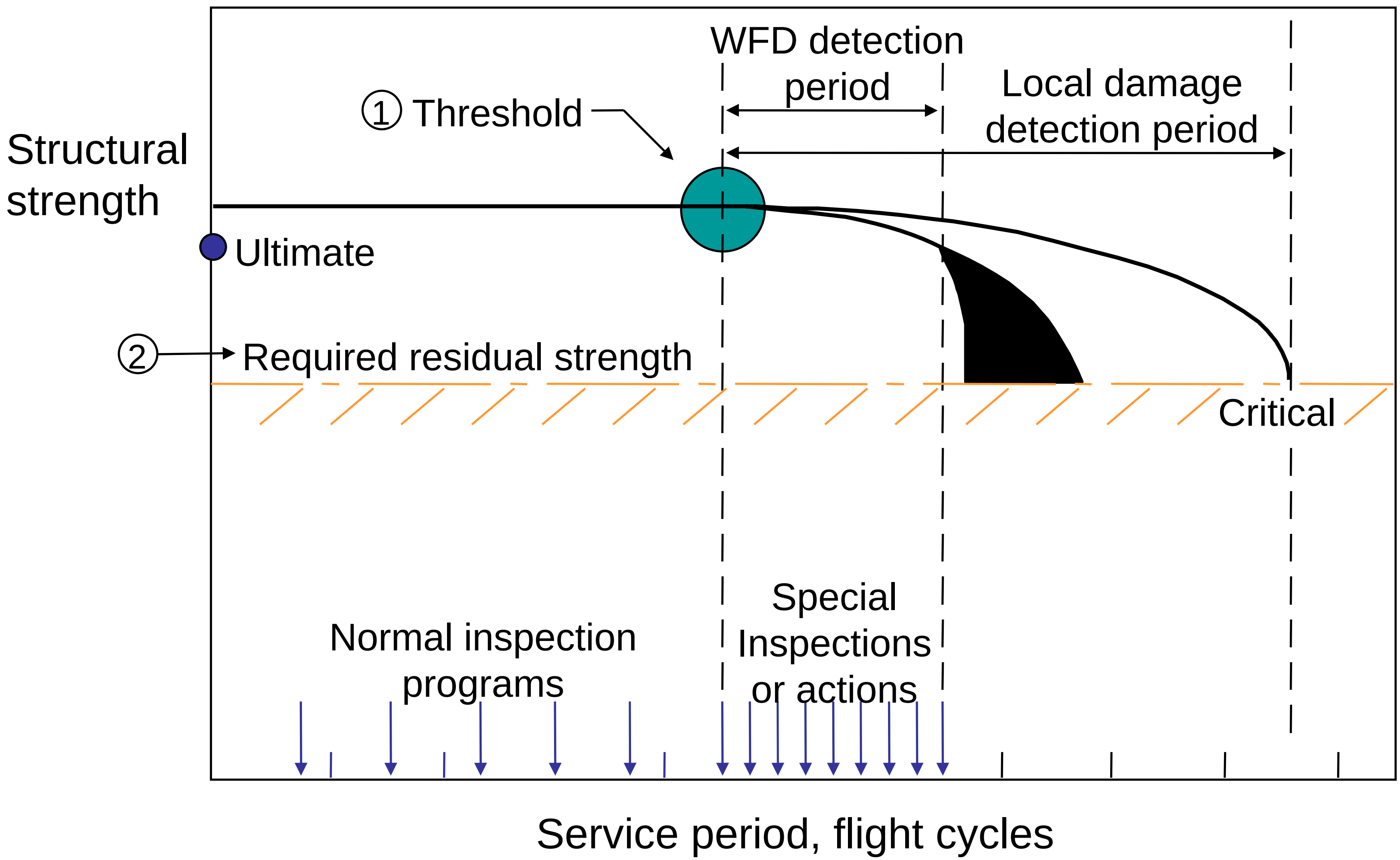
# Probabilistic Life Cycle



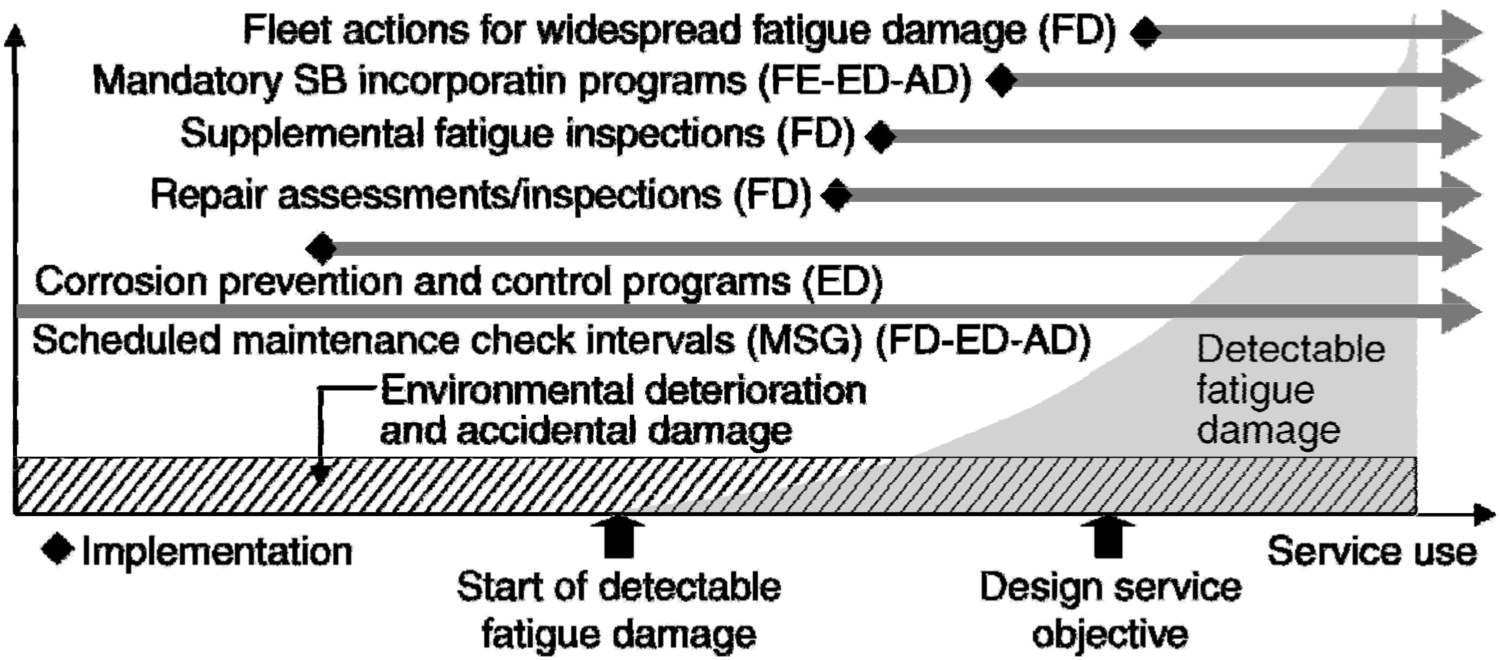
# Local Versus Widespread MSD or MED



# Widespread Fatigue Damage Detection

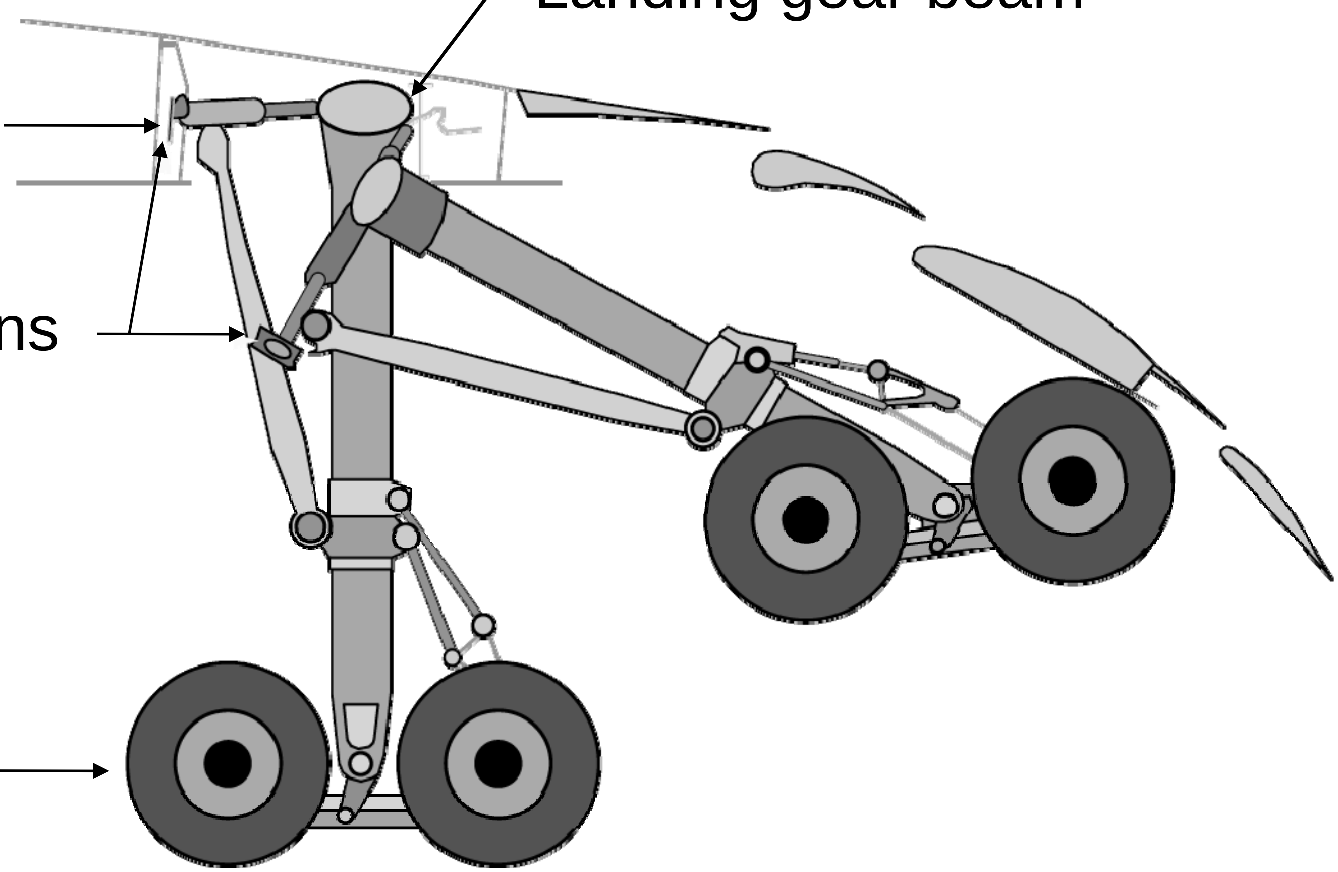


# Aging Fleet Programs

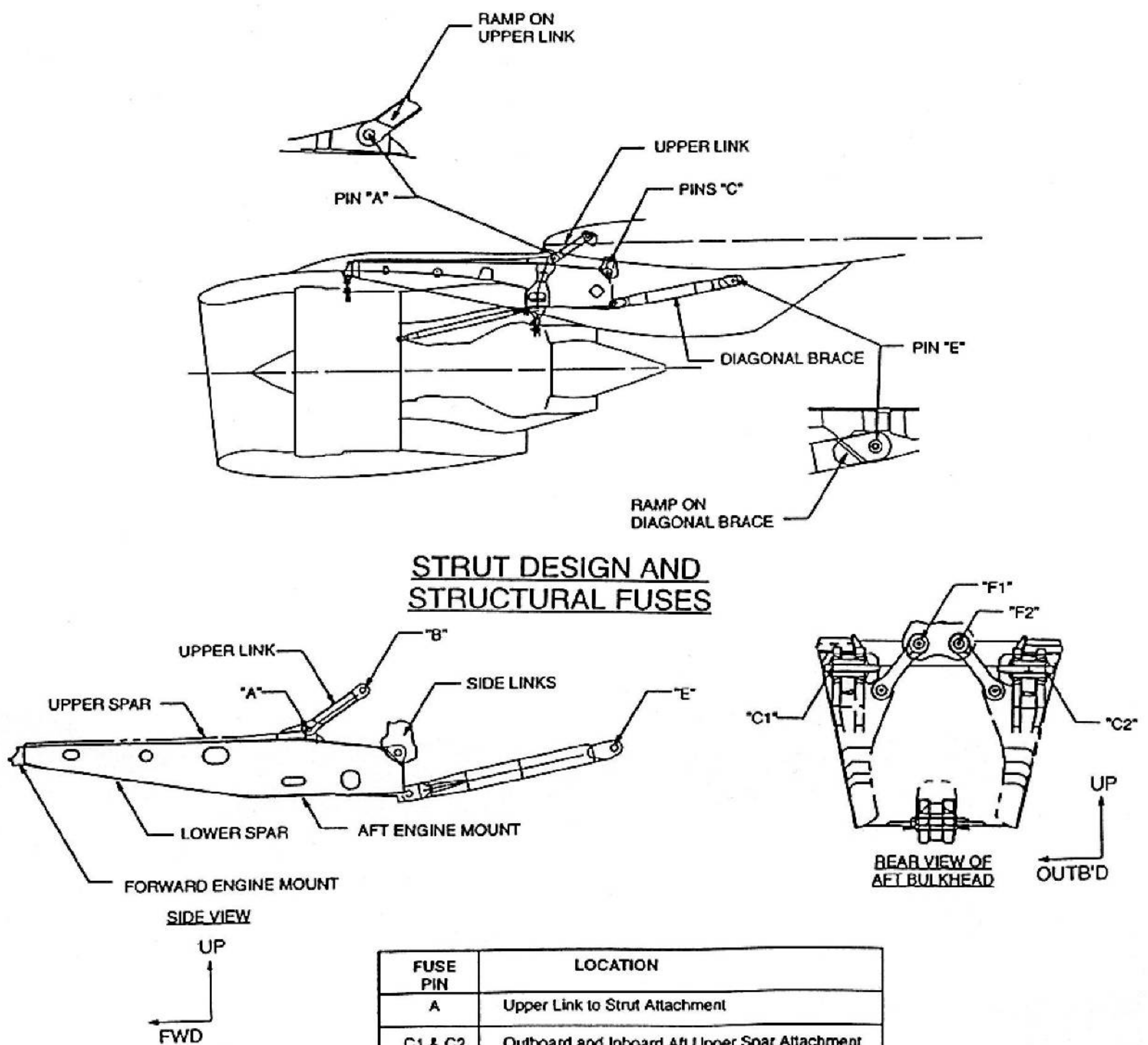


# Landing Gear is an Example of Safe-Life Structure

# Airplane Designed to Survive Minor Crashes

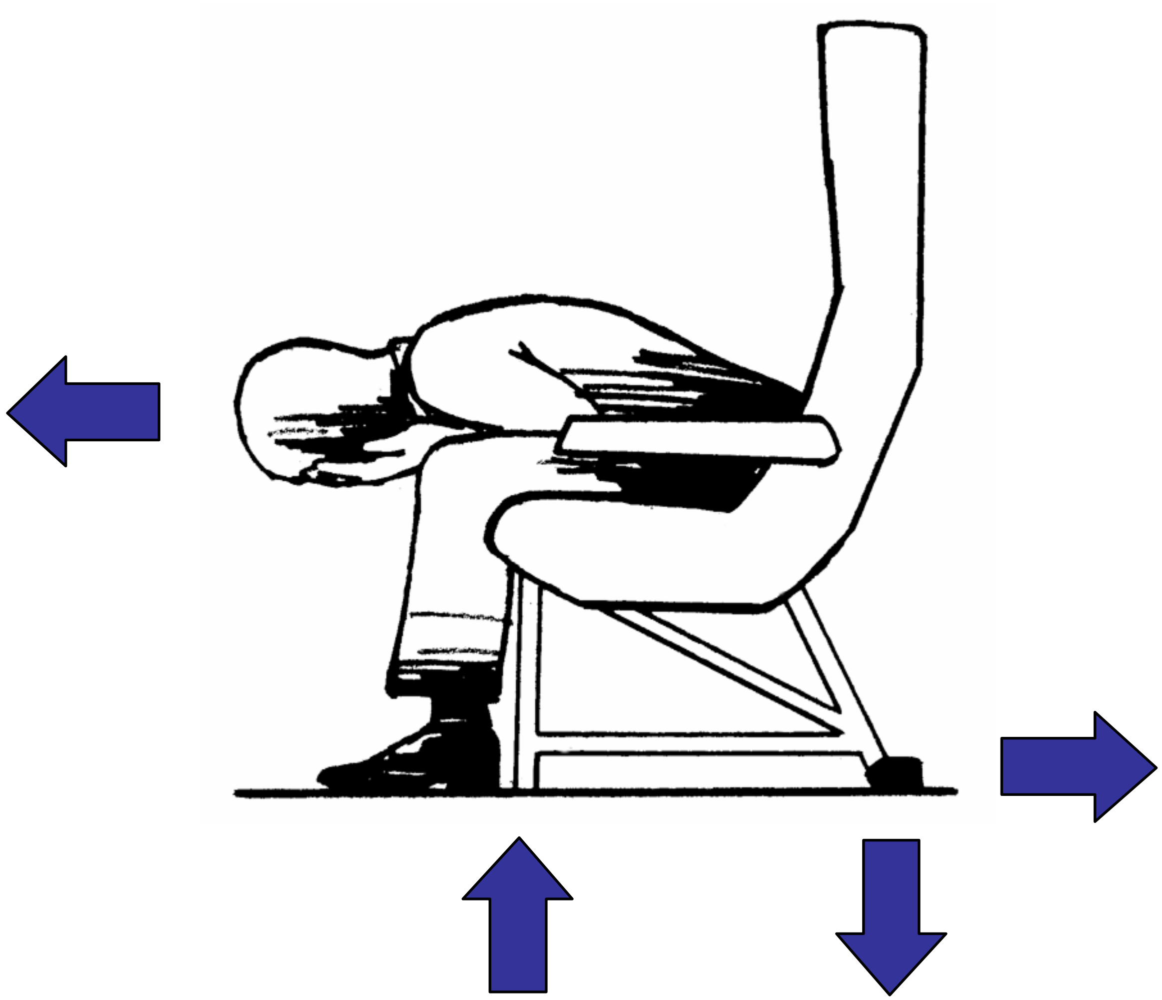


# Strut Design and Structural Fuses

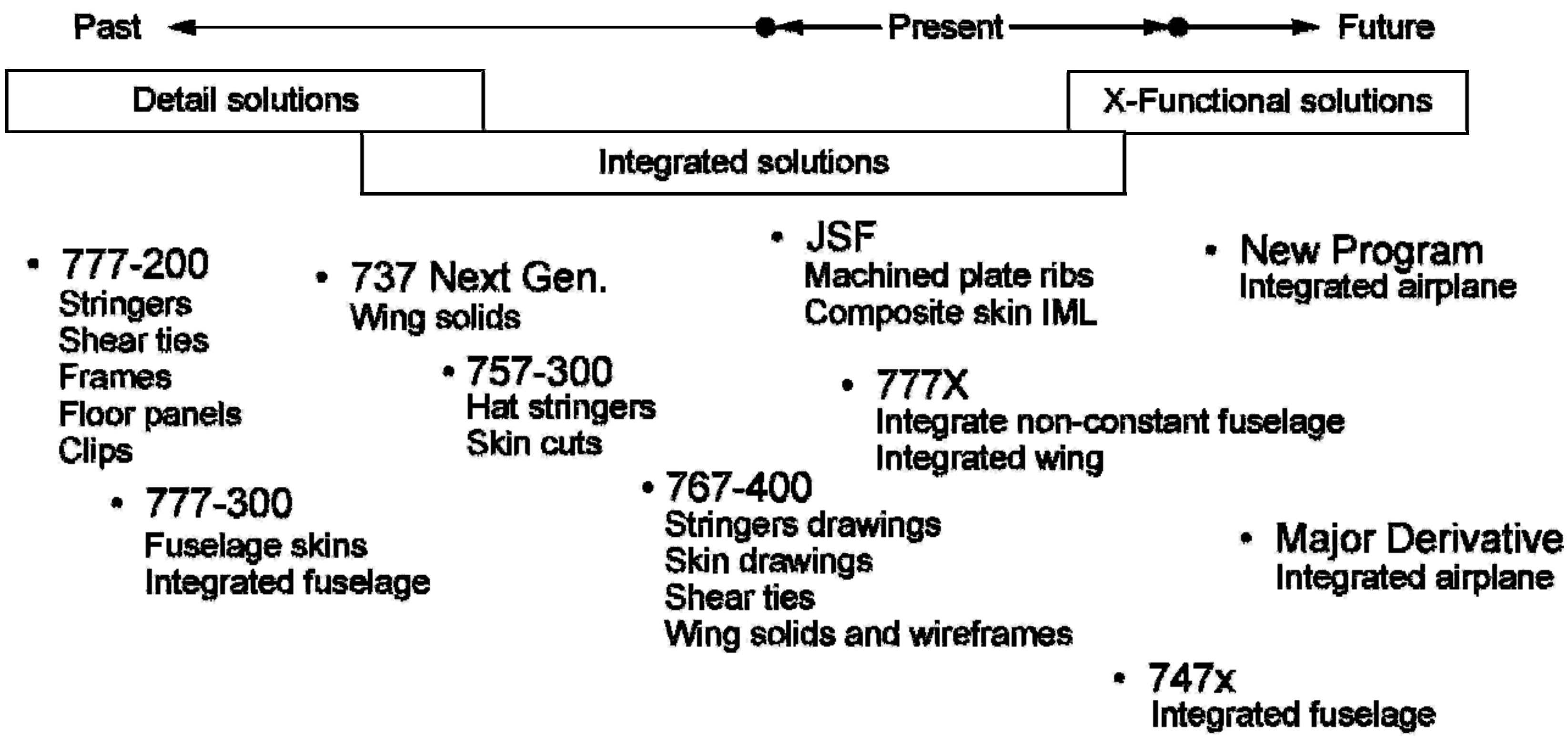



| FUSE PIN | LOCATION |
|---|---|
| A | Upper Link to Strut Attachment |
| C1 & C2 | Outboard and Inboard Aft Upper Spar Attachment |
| E | Diagonal Brace to Wing Attachment |
| F1 & F2 | Side Links to Wing Attachment |

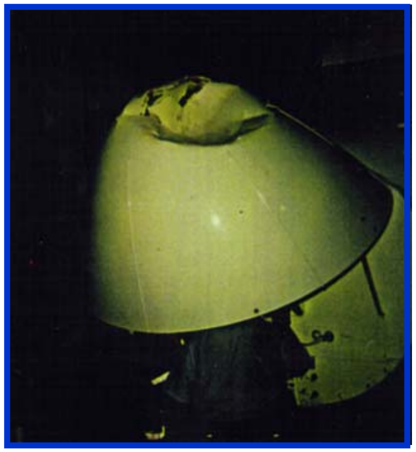
# Floor Structure is Often Designed by Crash Conditions



# KBE Evolution and Implementation History

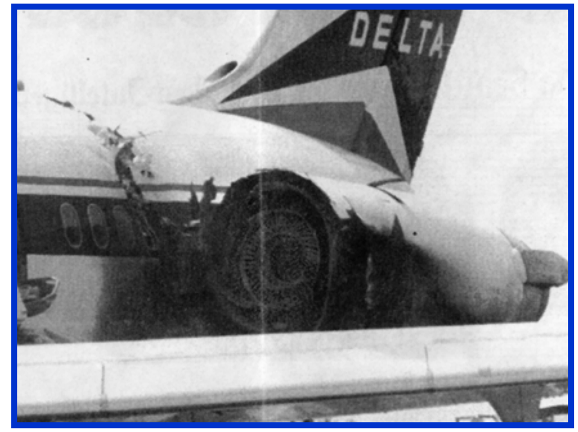


# External Criteria That Affect the Design of the Structure



Bird strike

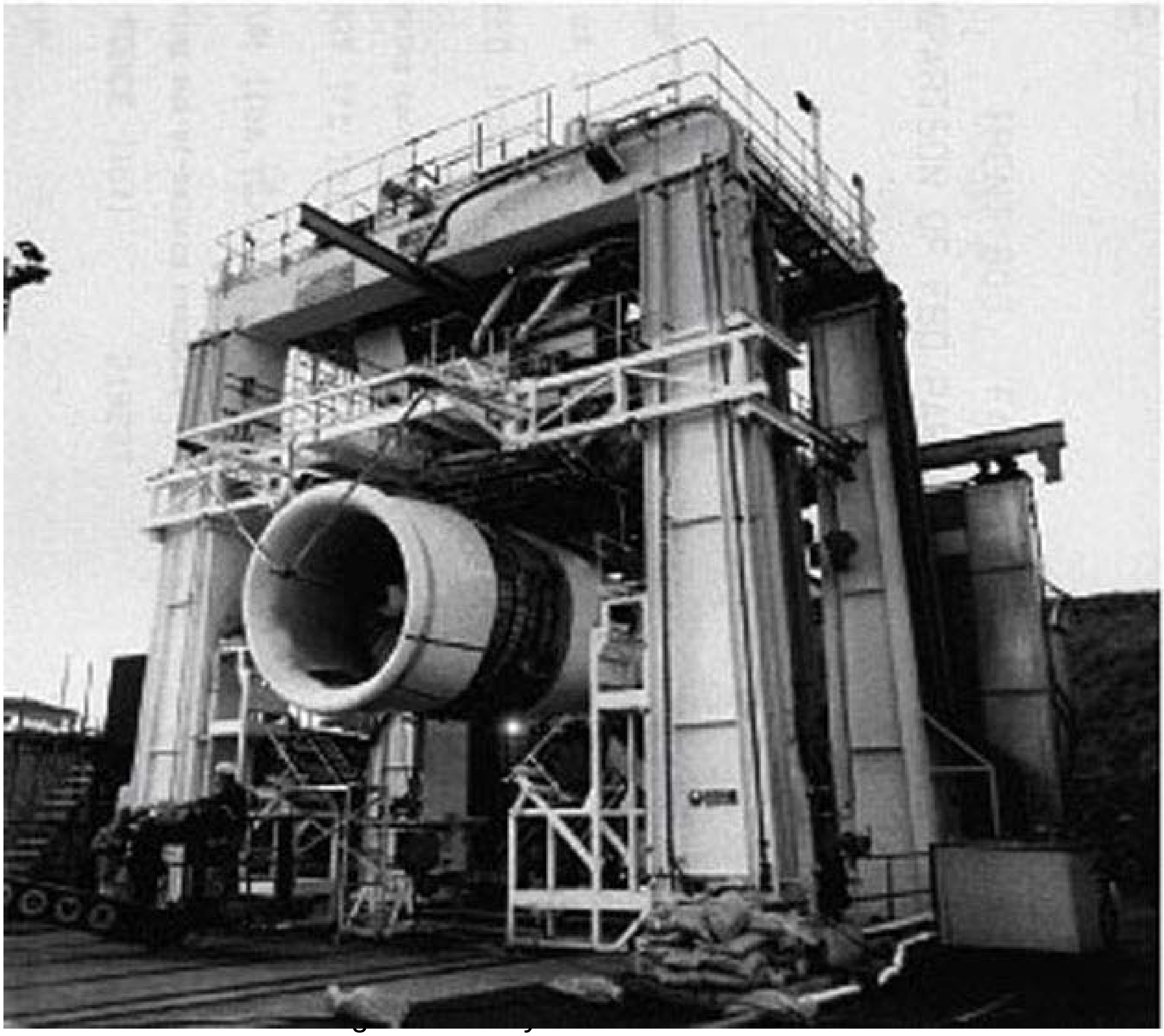
Engine blade loss




Tire burst

Tire tread

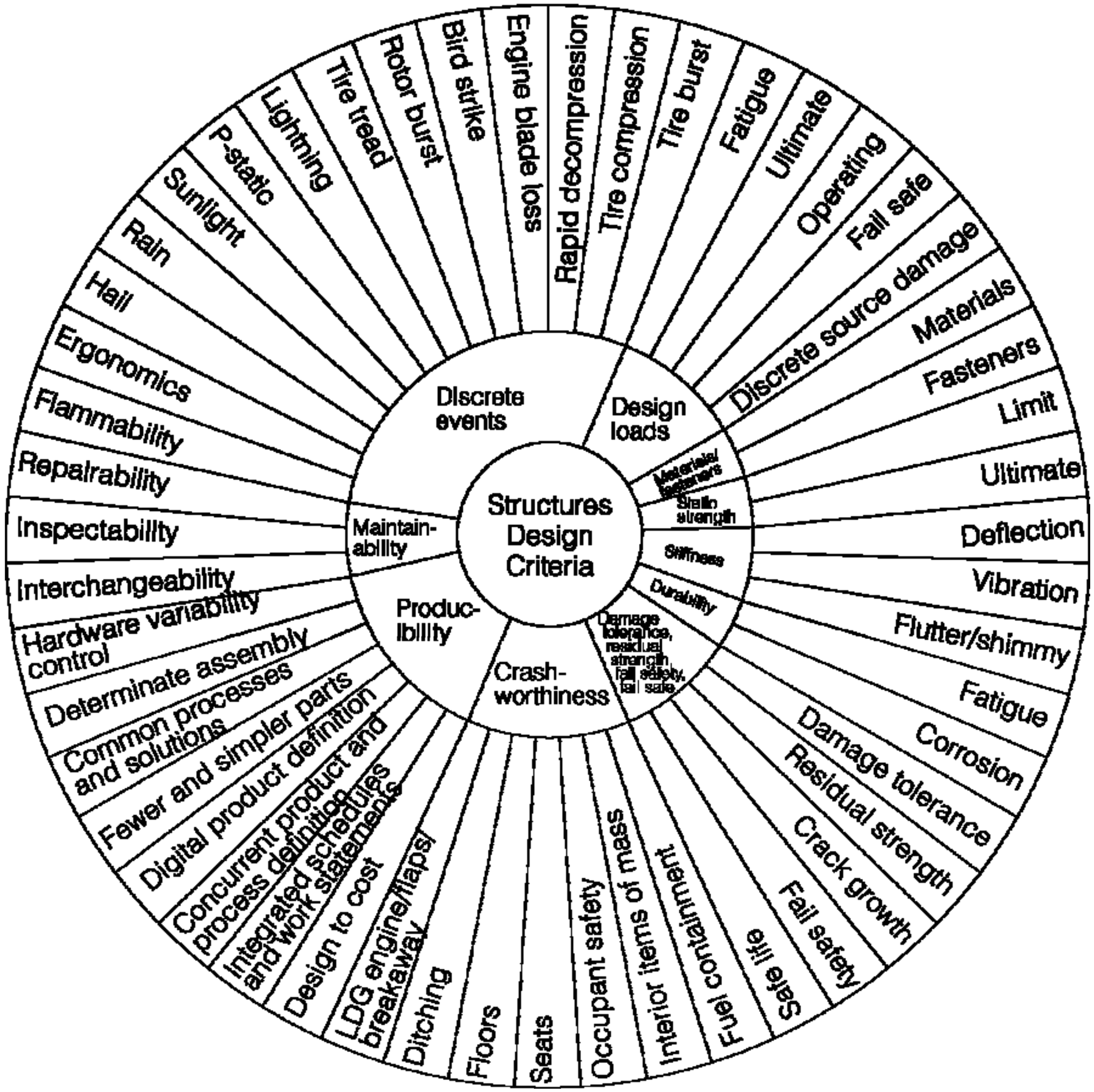
# Fan Bladeout Test



# Summary

- Regulatory requirements have evolved over the years based on significant service and test experience
- Validation and certification approach is primarily analytical supported by test evidence
- Supporting evidence includes testing through a "building block" approach
- The environmental effects are characterised by test and are accounted for in the analysis
- Process and tools are continually improved to enhance accuracy and reduce design cost and cycle time

# Appendix



Structures Design Criteria
Discrete events
loads
Stiffness
Durability
Damage tolerance, residual strength, fail safety, fail safe
Crash-worthiness
Produc-ibility
Maintain-ability
Engine blade loss
Bird strike
Rotor burst
Tire tread
Lightning
P-static
Sunlight
Rain
Hail
Ergonomics
Flammability
Repairability
Inspectability
Interchangeability
Hardware variability control
Determinate assembly
Common processes and solutions
Fewer and simpler parts
Digital product definition
Concurrent product and process definition
Integrated schedules and work statements
Design to cost
LDG engine/flaps/ breakaway
Ditching
Floors
Seats
Occupant safety
Interior items of mass
Fuel containment
Safe life
Fail safety
Crack growth
Residual strength
Damage tolerance
Corrosion
Fatigue
Flutter/shimmy
Vibration
Deflection
Ultimate
Limit
Fasteners
Materials
Discrete source damage
Fail safe
Operating
Ultimate
Fatigue
Tire burst
Tire compression
Rapid decompression