Aircraft Structures

Part 1 Full size aircraft

Part 2 Miniature aircraft

Bill Kuhlman

Aircraft Structures, Part 1

Full size aircraft

Central Theme

An aircraft structure is a load-management system,
not simply a collection of strong pieces.

What Must the Structure Do?

1. Support aerodynamic loads
2. Accomodate control system loads
3. Resist maneuver and gust loads
4. Maintain aerodynamic shape
5. Resist torsion
6. Survive vibration and fatigue
7. Support concentrated masses
8. Transmit landing loads

And...

Do all of those things at minimum practical mass.

The Four Primary Questions

1. What loads does an aircraft structure have to carry?
2. How are those loads transmitted through the aircraft?
3. How do materials and structural geometry work together?
4. Why have aircraft structures evolved from wood and fabric to metal monocoques and composites?

Strength ≠ Stiffness ≠ Durability

A structure can…

- be strong enough but too flexible
- be stiff enough but fail from fatigue
- have adequate static strength but buckle under a dynamic load
- survive one flight but have inadequate fatigue life

Primary Question #1

What loads does an aircraft structure have to carry?

Loads Acting on an Aircraft

FORCES

- Lift
- Weight
- Drag
- Thrust
- Aerodynamic moments
- Inertial moments

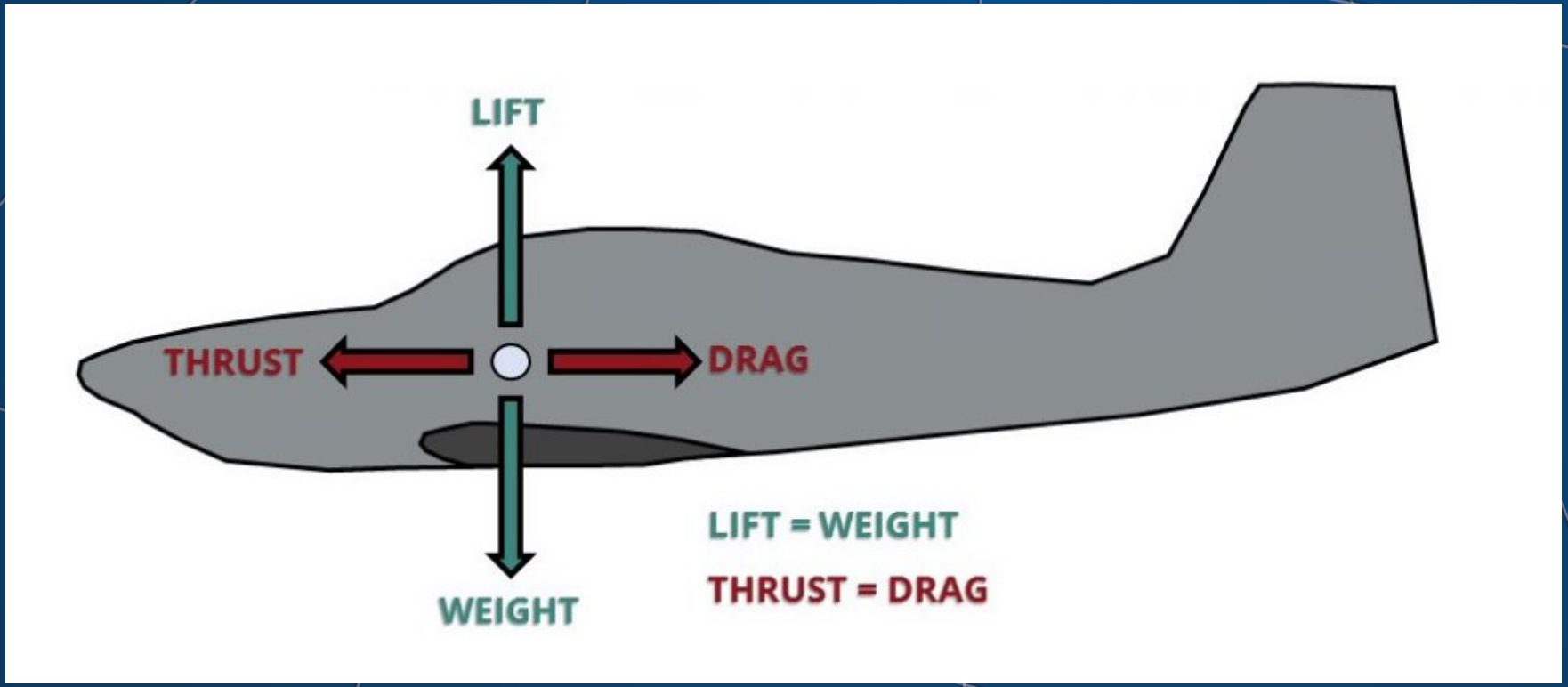
STRESSES

- Tension
- Compression
- Bending
- Shear
- Torsion

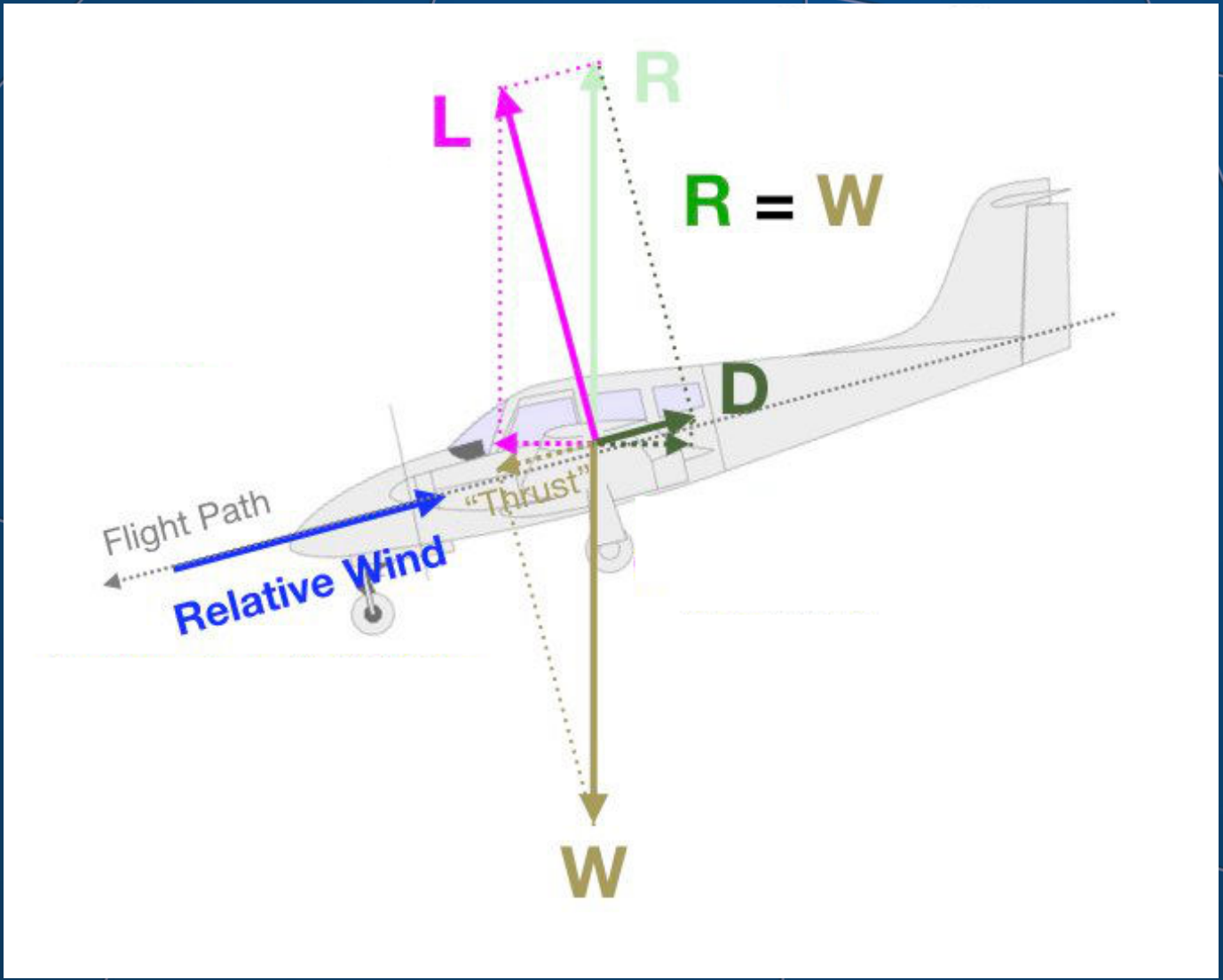
Loads Acting on an Aircraft

FORCES

- Lift
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- Thrust
- Aerodynamic moments
- Inertial moments



Straight and level flight at constant speed

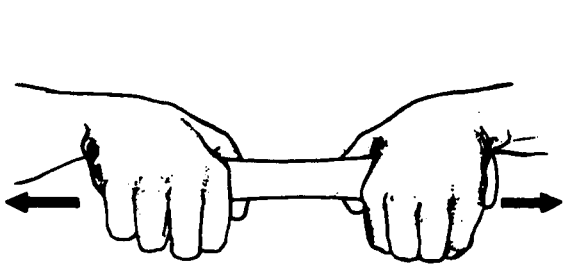


Gliding flight at constant speed

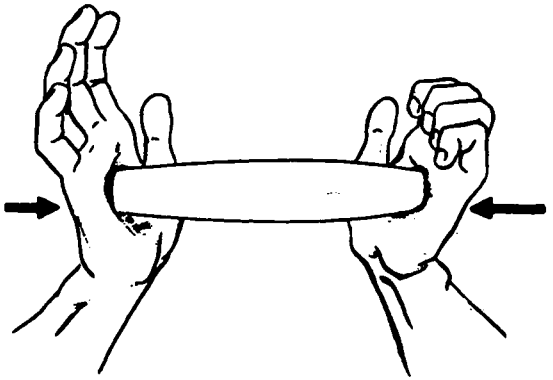
Loads Acting on an Aircraft

STRESSES

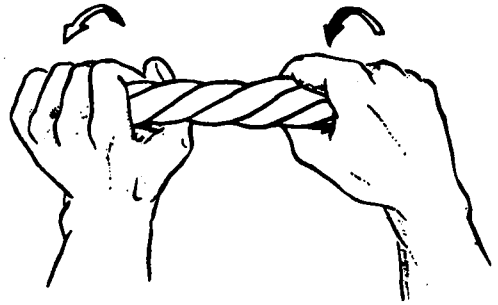
- Tension
- Compression
- Bending
- Shear
- Torsion



(a) Tension



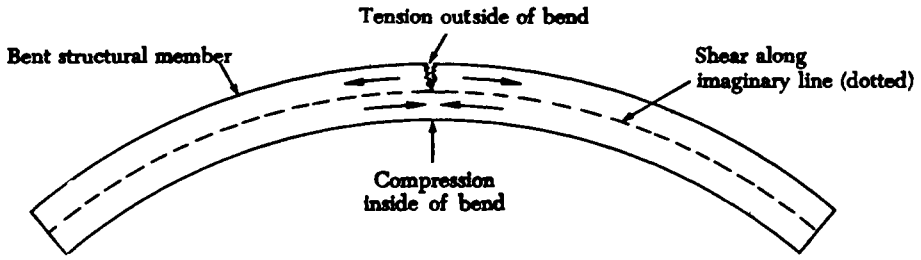
(b) Compression



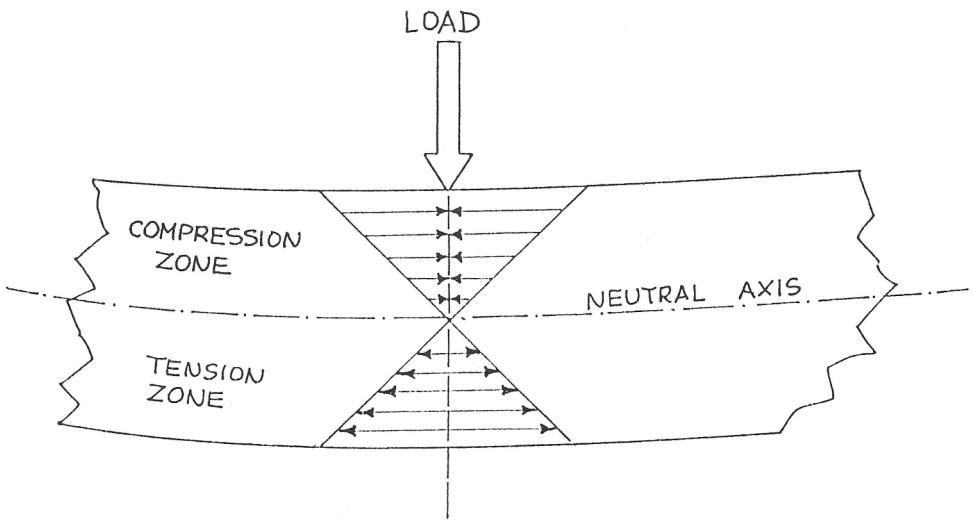
(c) Torsional



(d) Shear

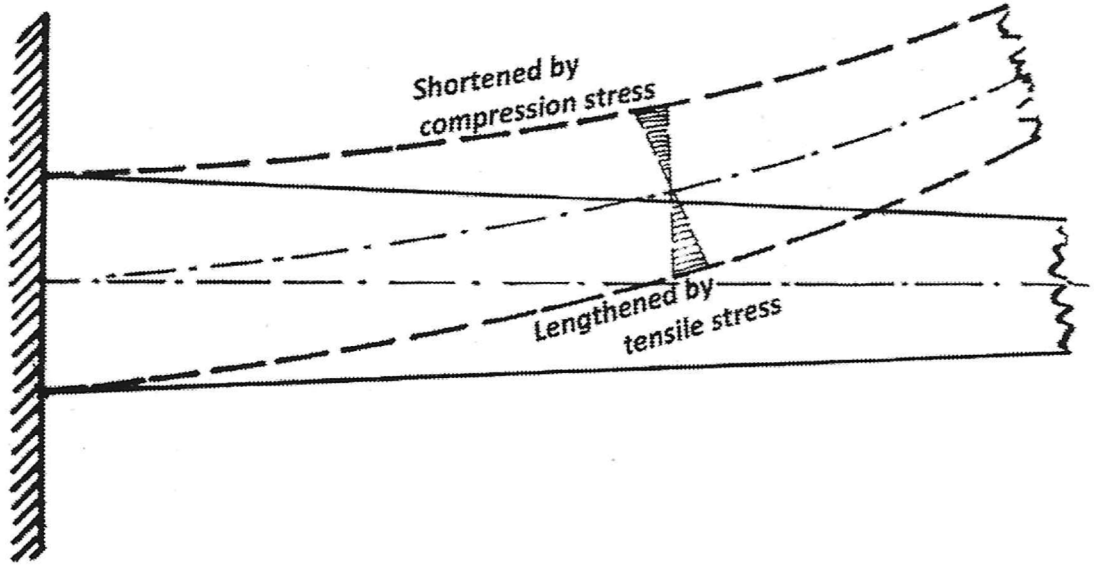


(e) Bending (the combination stress)



Beam bending under load

Wing bending due to lift

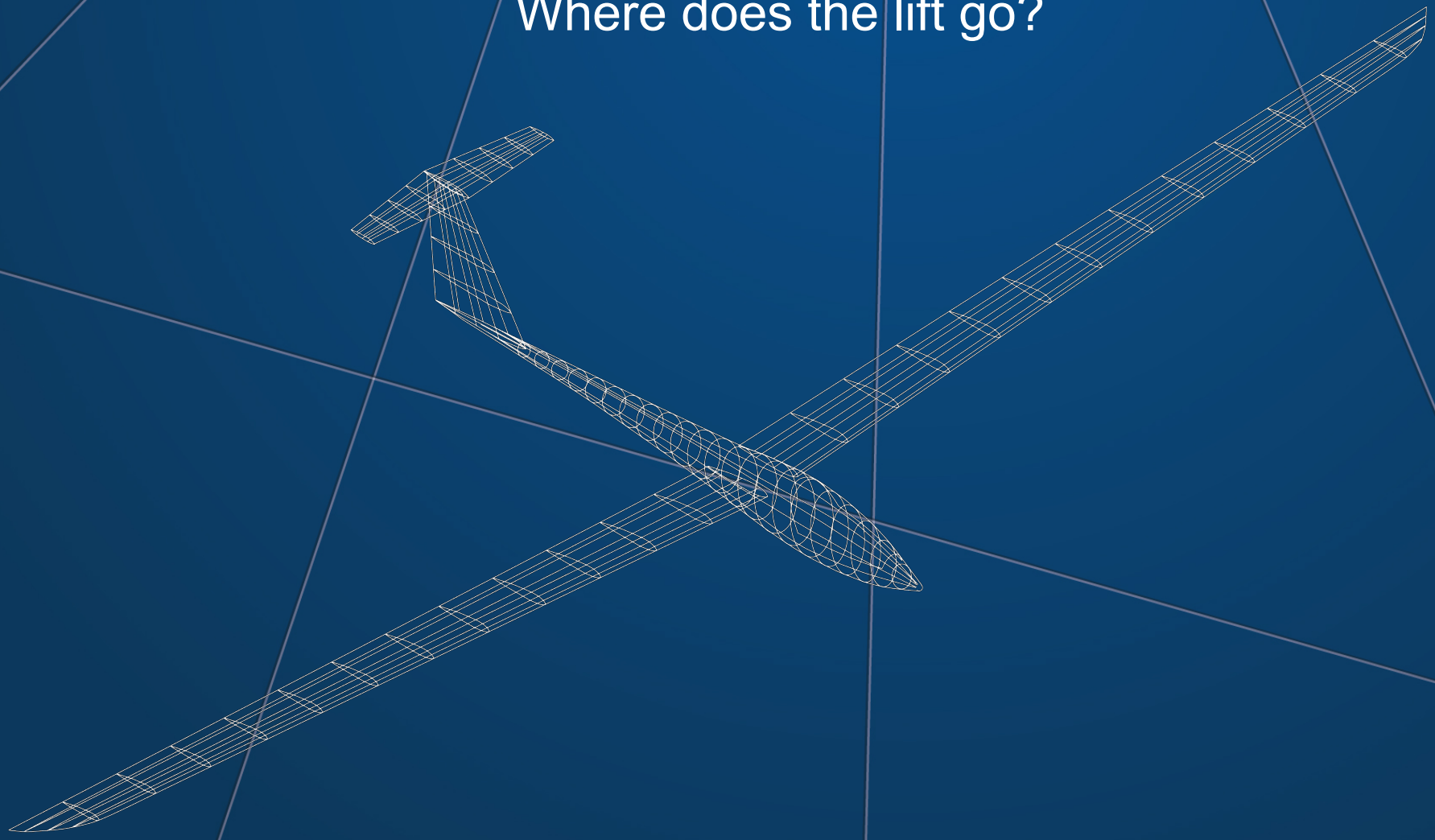


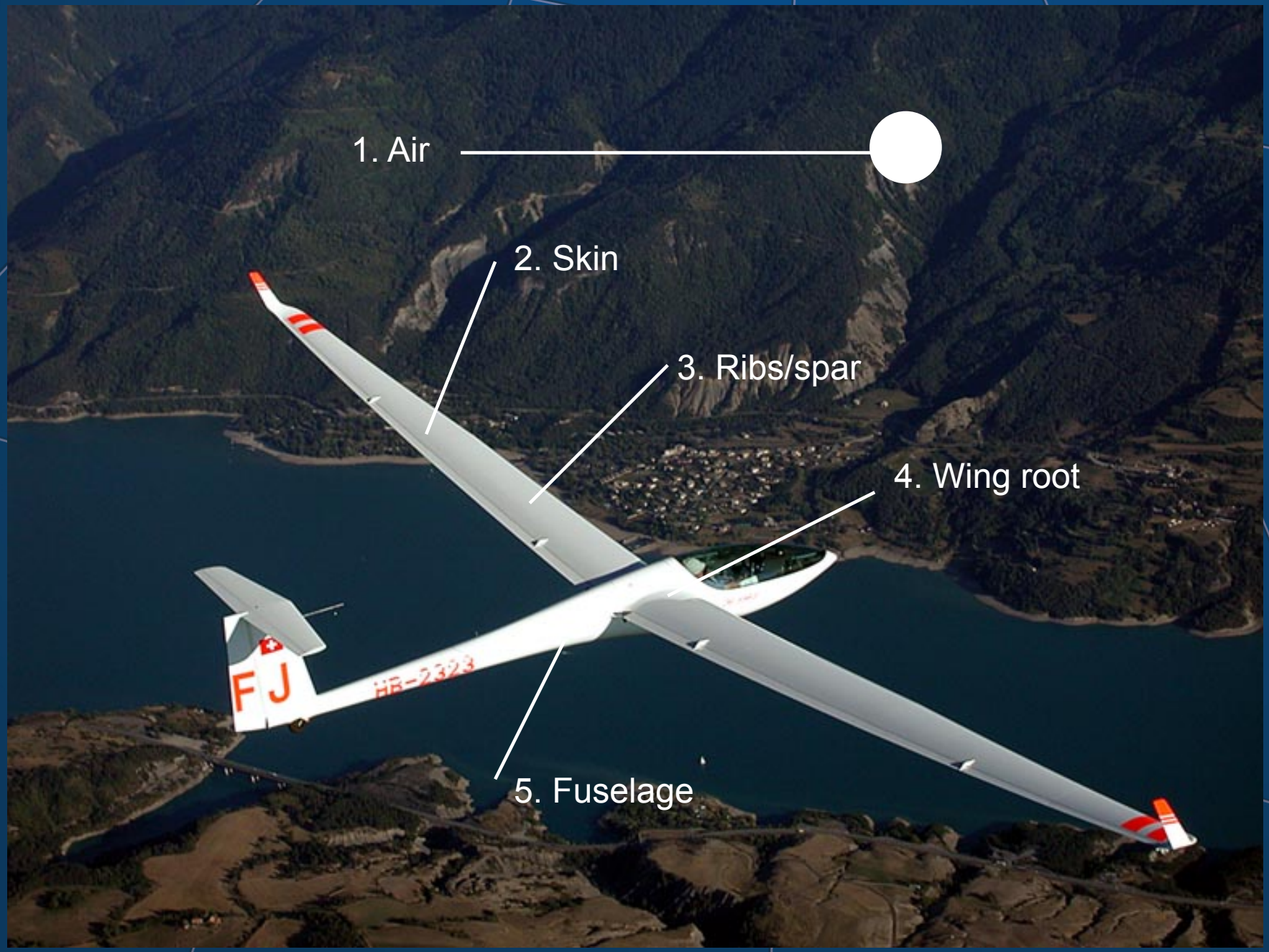
Primary Question #2

How are those loads transmitted through the aircraft?

The Concept of the Load Path

Where does the lift go?




1. Air
2. Skin
3. Ribs/spar
4. Wing root
5. Fuselage
FJ
HB-2323

PRIMARY STRUCTURES

Wing
- Ribs and/or skin
- Spar(s)
- Carry-through

Fuselage
- Bulkheads
- Stringers and/or shell

Stabilizer(s)
- Ribs and/or skin
- Spar(s)

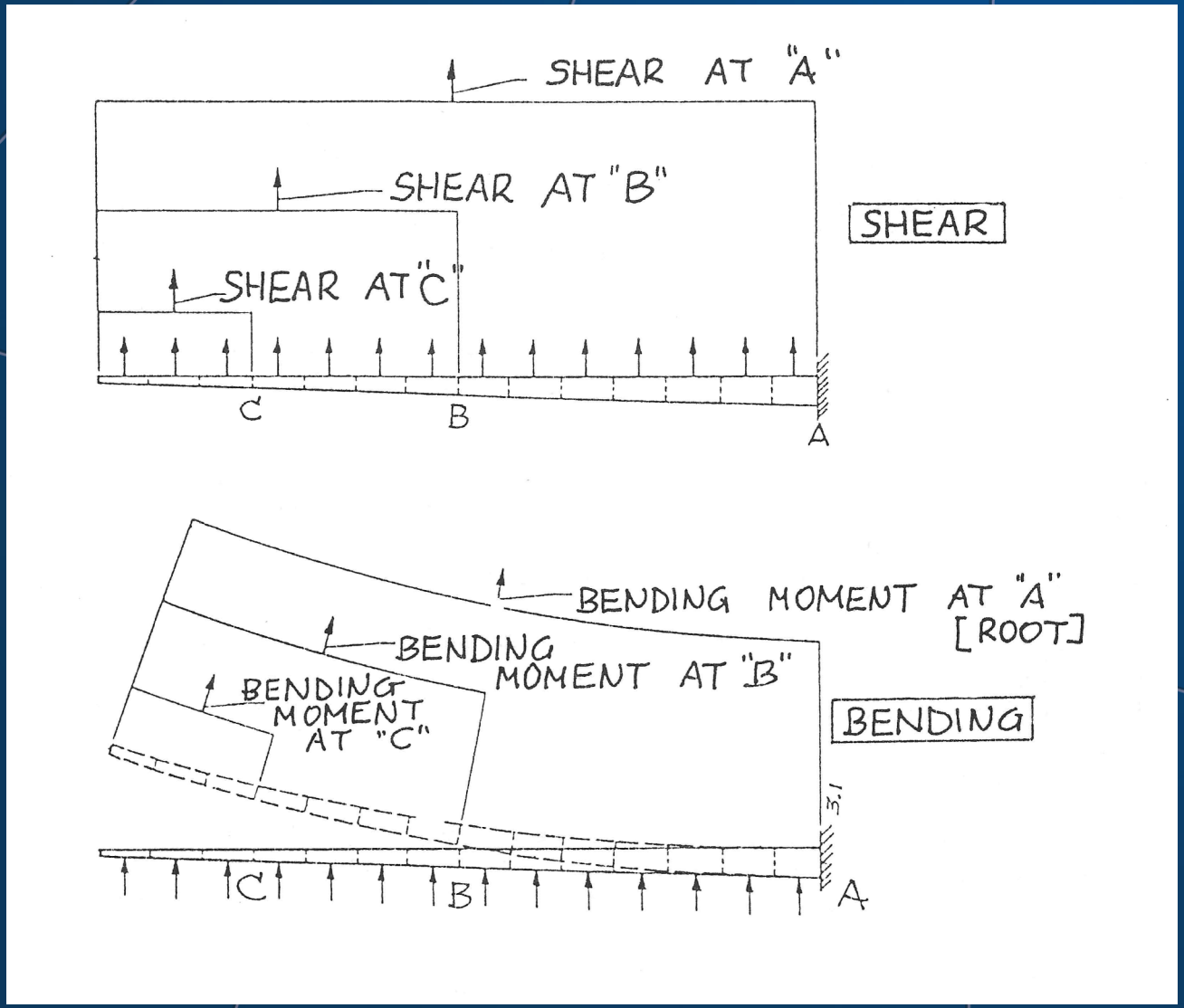
SECONDARY STRUCTURES

- Supporting systems
- Fairings
- Access panels

NON-STRUCTURAL COMPONENTS

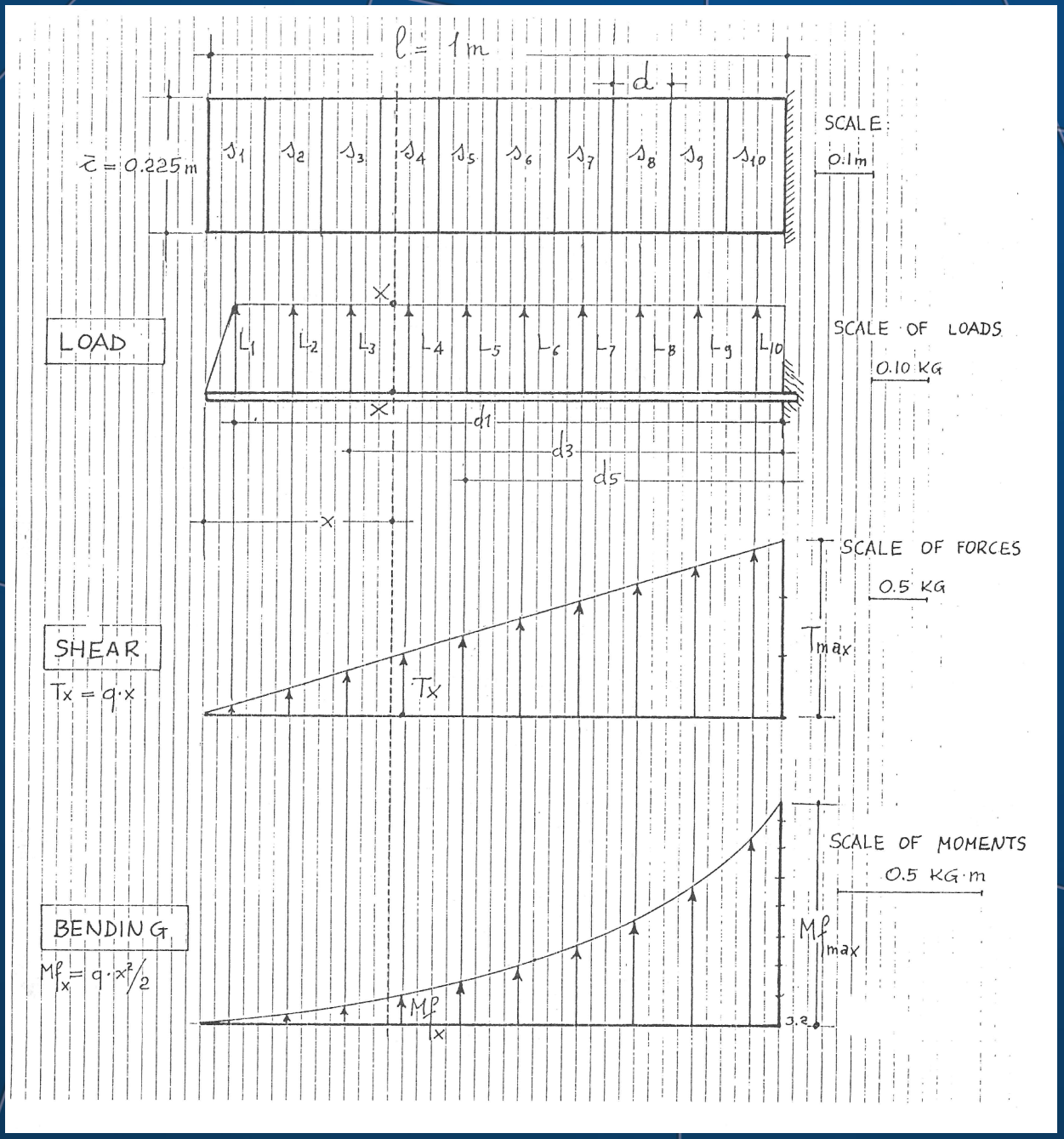
- Aerodynamic or cosmetic components

Shear & Bending Moment

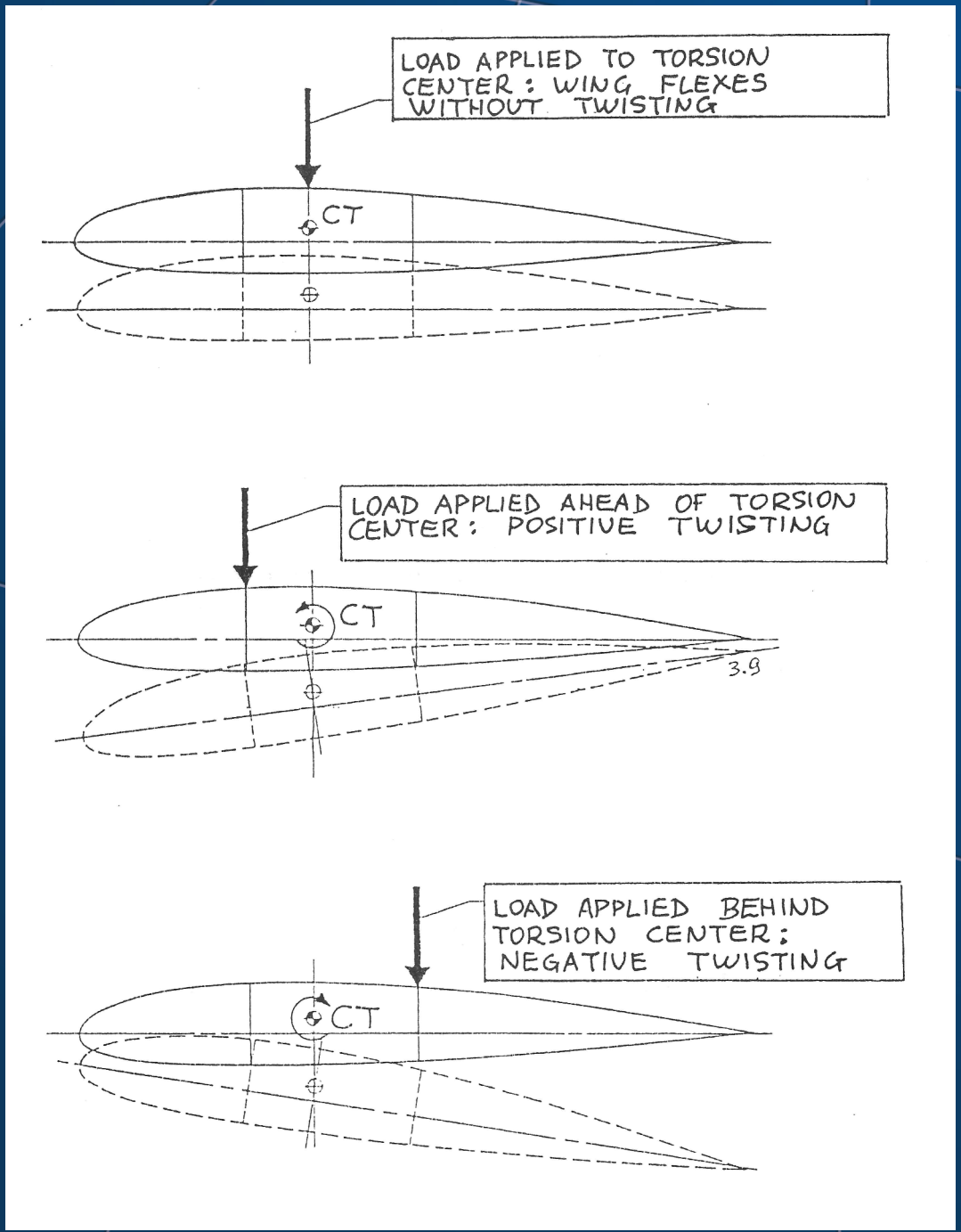




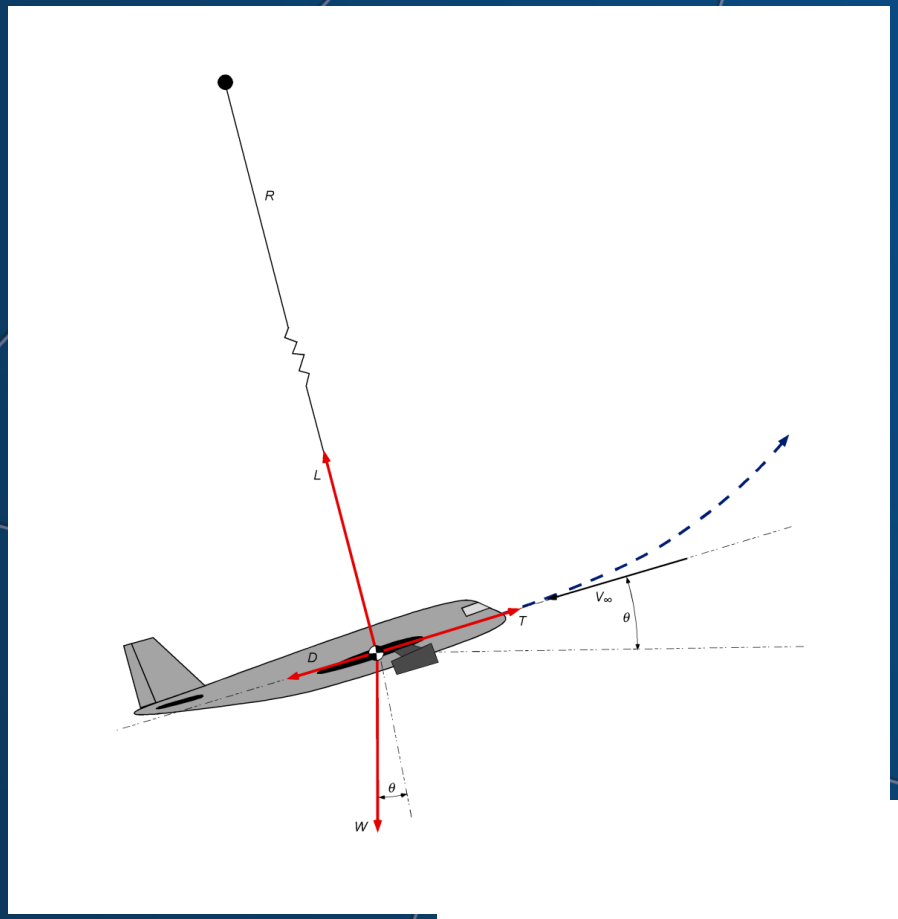
Fixed


l = 1 m
d
z = 0.225 m
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10
SCALE:
0.1 m
LOAD
L1 L2 L3 L4 L5 L6 L7 L8 L9 L10
SCALE OF LOADS
0.10 KG
x
d1
d3
d5
SHEAR
Tx = q·x
Tx
Tmax
SCALE OF FORCES
0.5 KG
BENDING
Mf x = q·x²/2
Mf x
Mf max
SCALE OF MOMENTS
0.5 KG·m

Torsion

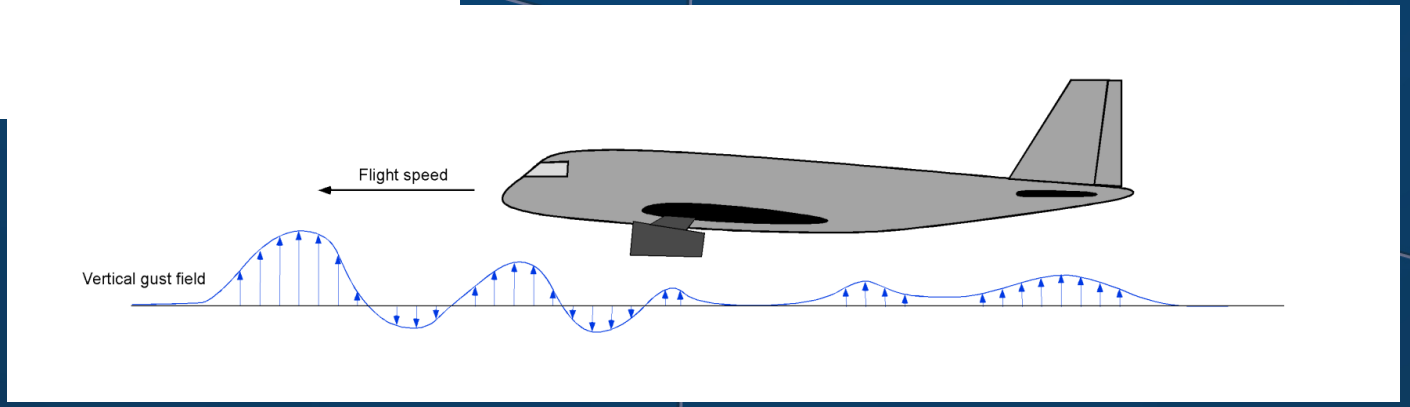

LOAD APPLIED TO TORSION CENTER : WING FLEXES WITHOUT TWISTING
CT
LOAD APPLIED AHEAD OF TORSION CENTER : POSITIVE TWISTING
CT
3.9
LOAD APPLIED BEHIND TORSION CENTER : NEGATIVE TWISTING
CT

Dynamic Loads



Pull-up loads

Vertical gust loads



Turning/banking loads

L = Lift

L’ = Apparent lift

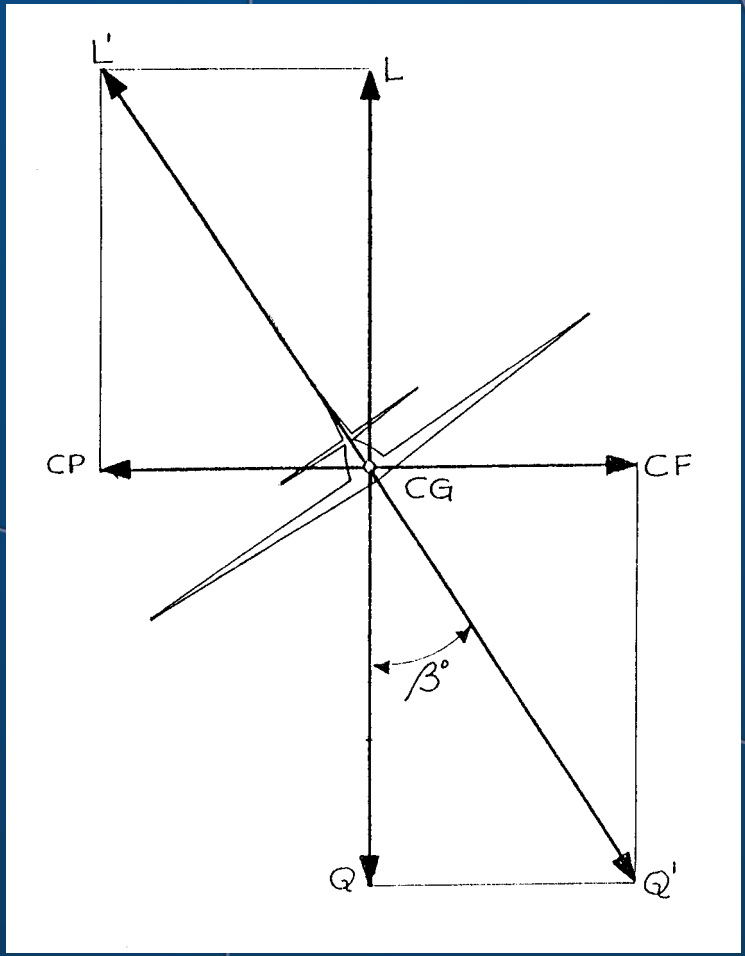
Q = Weight

Q’ = Apparent Weight

β = Turn Angle

CF – Centrifugal Force

CP = Centripetal Force



Moment of Inertia

1. INITIAL BALANCE (Static Equilibrium)

A teeter-totter (massless) is balanced by positioning the fulcrum so that the torques (moments) about the fulcrum are equal.

BALANCE CONDITION:

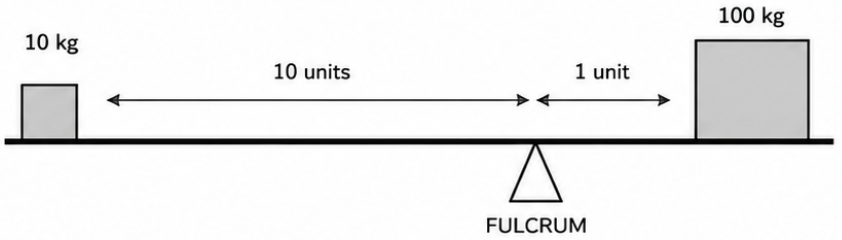
$$m_1 \cdot d_1 = m_2 \cdot d_2$$

where:

m_1, m_2 = masses on each side (kg)

d_1, d_2 = perpendicular distances from fulcrum to each mass (units)

(massless teeter-totter)



Example:

$m_1 = 10$ kg, $d_1 = 10$ units

$m_2 = 100$ kg, $d_2 = 1$ unit

Check:

$m_1 \cdot d_1 = 10 \cdot 10 = 100$

$m_2 \cdot d_2 = 100 \cdot 1 = 100$

$\Rightarrow$ Balanced

Aircraft balance (location of center of gravity) is similar to a teeter-totter

Simply...

$\text{mass}_1 \bullet \text{distance}_1 = \text{mass}_2 \bullet \text{distance}_2$

1. INITIAL BALANCE (Static Equilibrium)

A teeter-totter (massless) is balanced by positioning the fulcrum so that the torques (moments) about the fulcrum are equal.

BALANCE CONDITION:

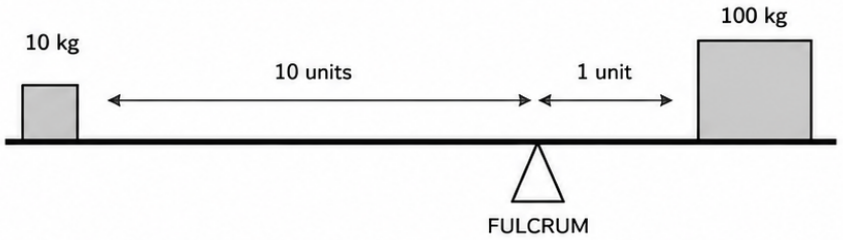
$$m_1 \cdot d_1 = m_2 \cdot d_2$$

where:

m_1, m_2 = masses on each side (kg)

d_1, d_2 = perpendicular distances from fulcrum to each mass (units)

(massless teeter-totter)



Example:	Check:	
$m_1 = 10$ kg, $d_1 = 10$ units	$m_1 \cdot d_1 = 10 \cdot 10 = 100$	⇒ Balanced
$m_2 = 100$ kg, $d_2 = 1$ unit	$m_2 \cdot d_2 = 100 \cdot 1 = 100$	

2. MOMENTS OF INERTIA about the Fulcrum

The moment of inertia of a point mass about a pivot (fulcrum) is:

POINT MASS MOMENT OF INERTIA:

$$I = m \cdot r^2$$

where:

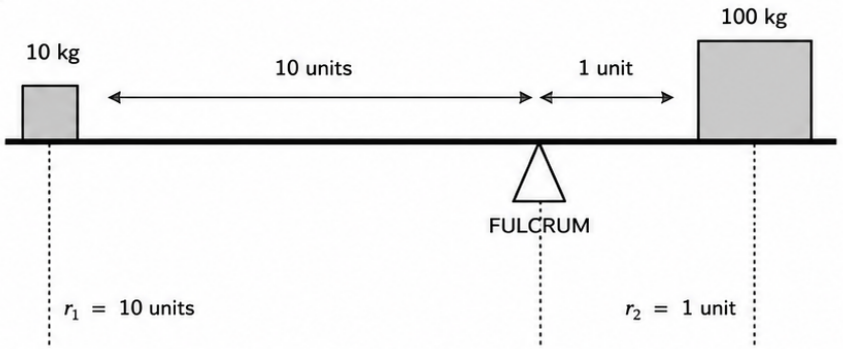
I = moment of inertia (kg·units^2)

m = mass (kg)

r = perpendicular distance from fulcrum to the mass (units)

Total moment of inertia (two masses):

$$I_{total} = m_1 d_1^{\,2} + m_2 d_2^{\,2}$$



Moment of inertia of 10 kg mass:	Moment of inertia of 100 kg mass:	Total moment of inertia:
$I_1 = m_1 r_1^2 = 10 \cdot (10)^2 = 1000$ kg·units^2	$I_2 = m_2 r_2^2 = 100 \cdot (1)^2 = 100$ kg·units^2	$I_{total} = I_1 + I_2 = 1000 + 100 = 1100$ kg·units^2

Moment of inertia for a balanced teeter-totter

Simply...

$$\text{mass}_1 \bullet \text{distance}_1^{\,2} = \text{mass}_2 \bullet \text{distance}_2^{\,2}$$

Flutter

Flutter is a dynamic instability
of an elastic structure in a fluid flow,
caused by positive feedback
between the deflection of the body
and the force exerted by the fluid flow.


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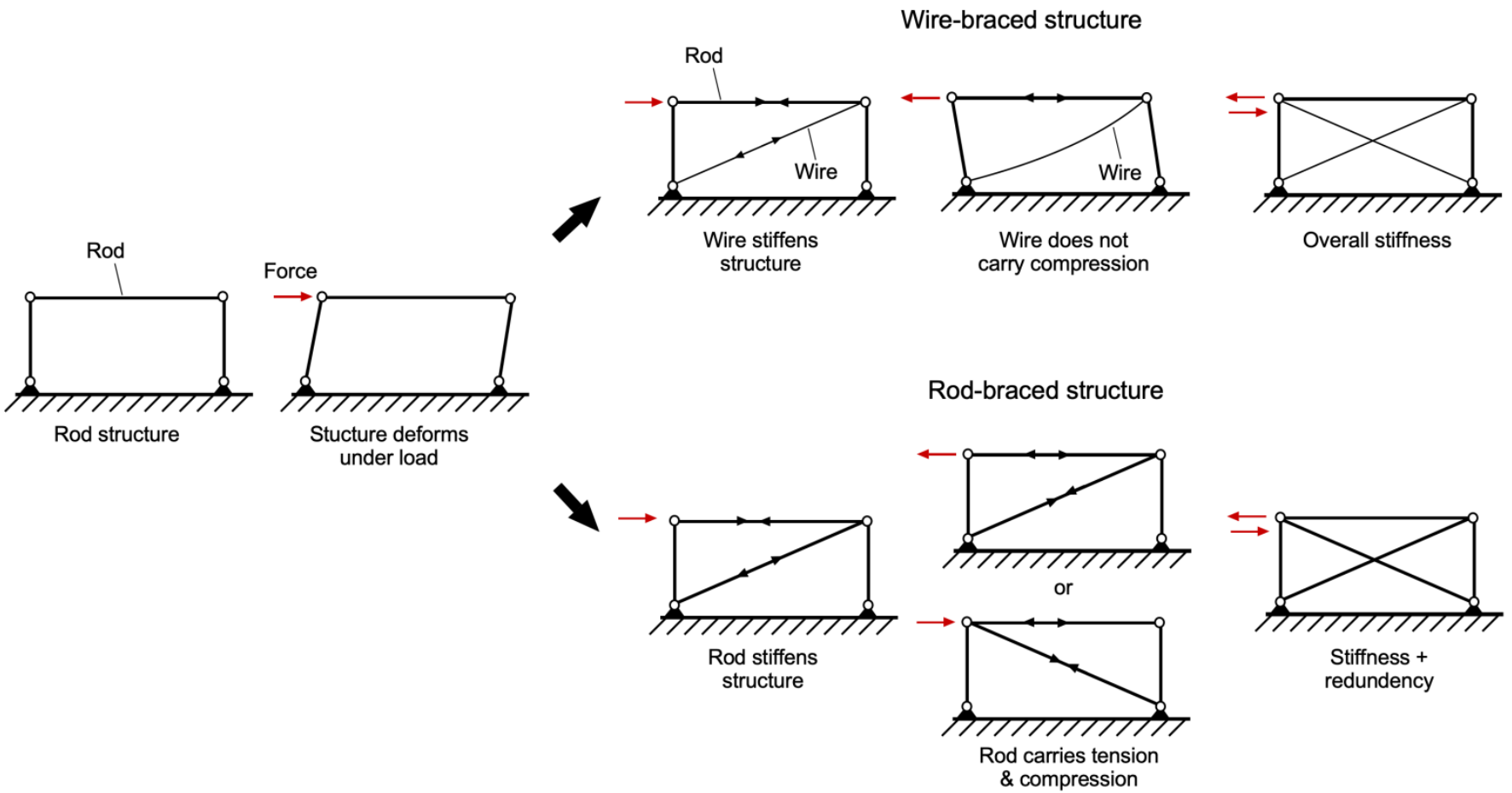
Primary Question #3

How do materials and structural geometry work together?

There are three basic structural types

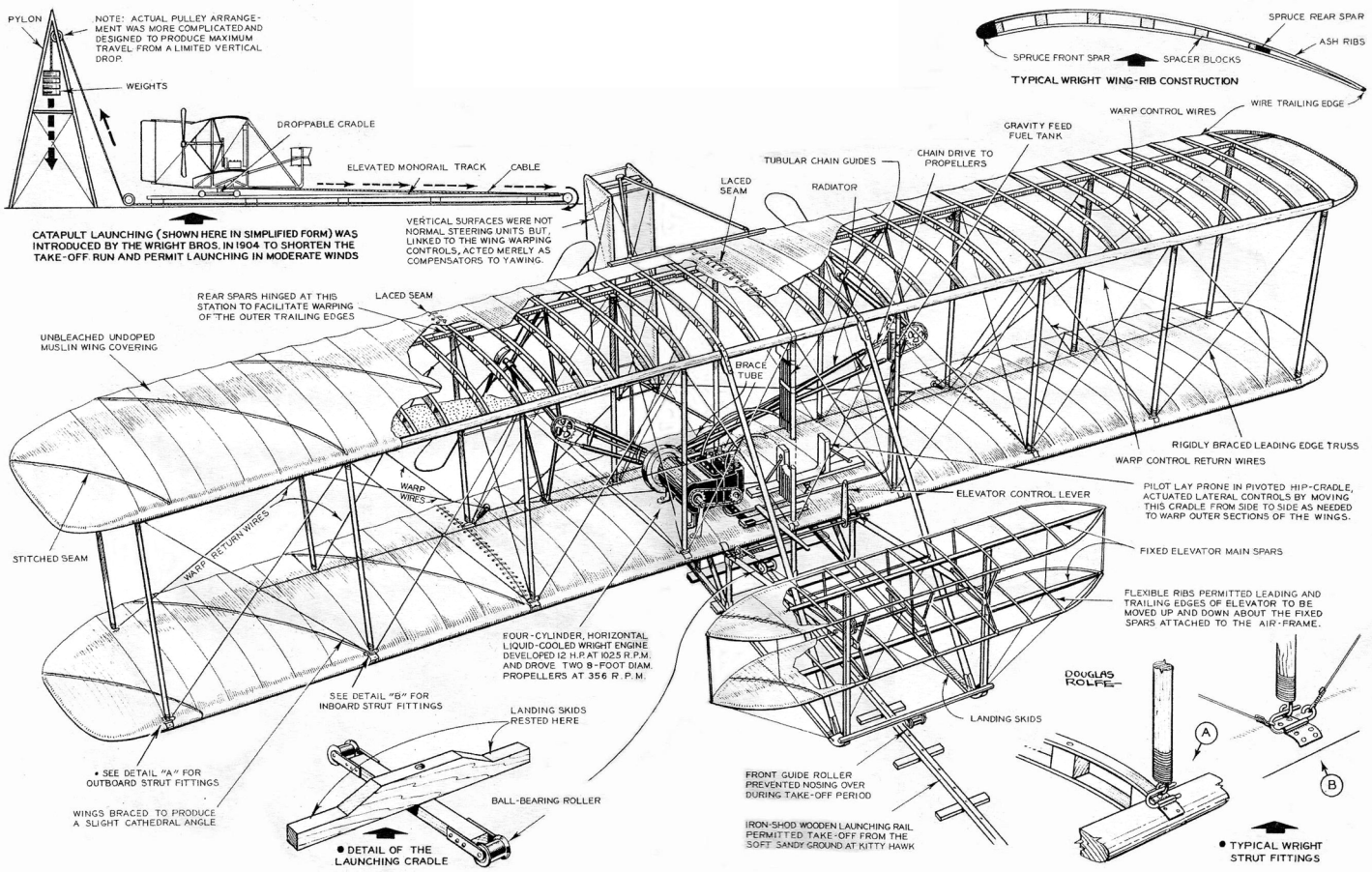
- Truss
- Monocoque
- Semi-monocoque

Trusses


Wire-braced structure
Rod
Wire
Wire
Rod
Force
Wire stiffens structure
Wire does not carry compression
Overall stiffness
Rod structure
Stucture deforms under load
Rod-braced structure
or
Rod stiffens structure
Rod carries tension & compression
Stiffness + redundency

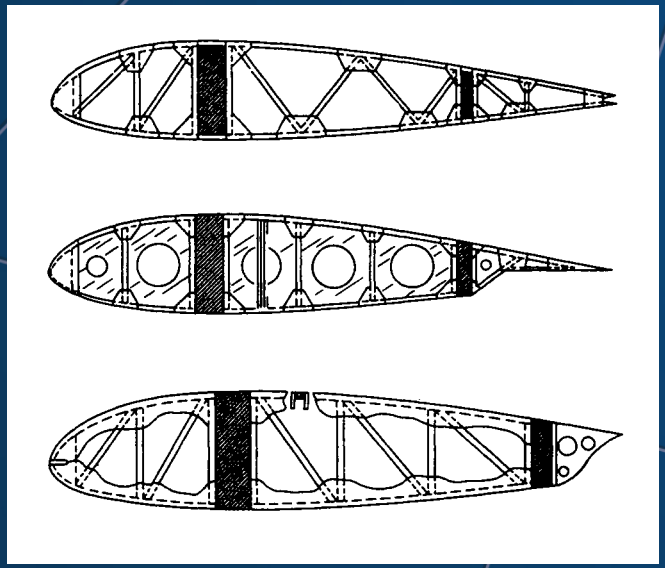


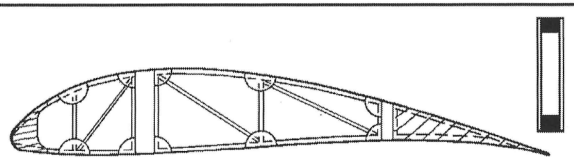
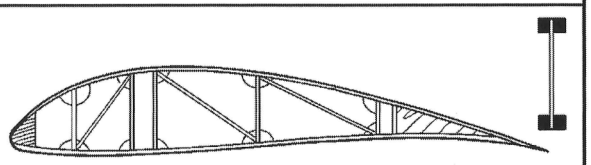
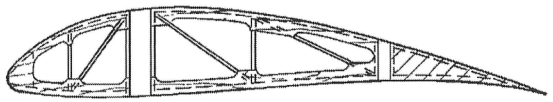
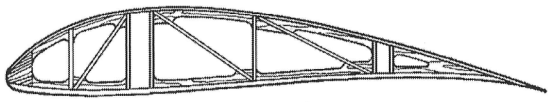
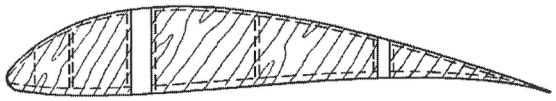
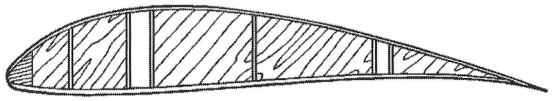
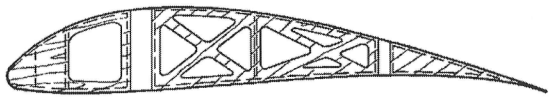
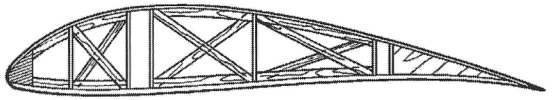
Wright Flyer (1903) at the National Air & Space Museum

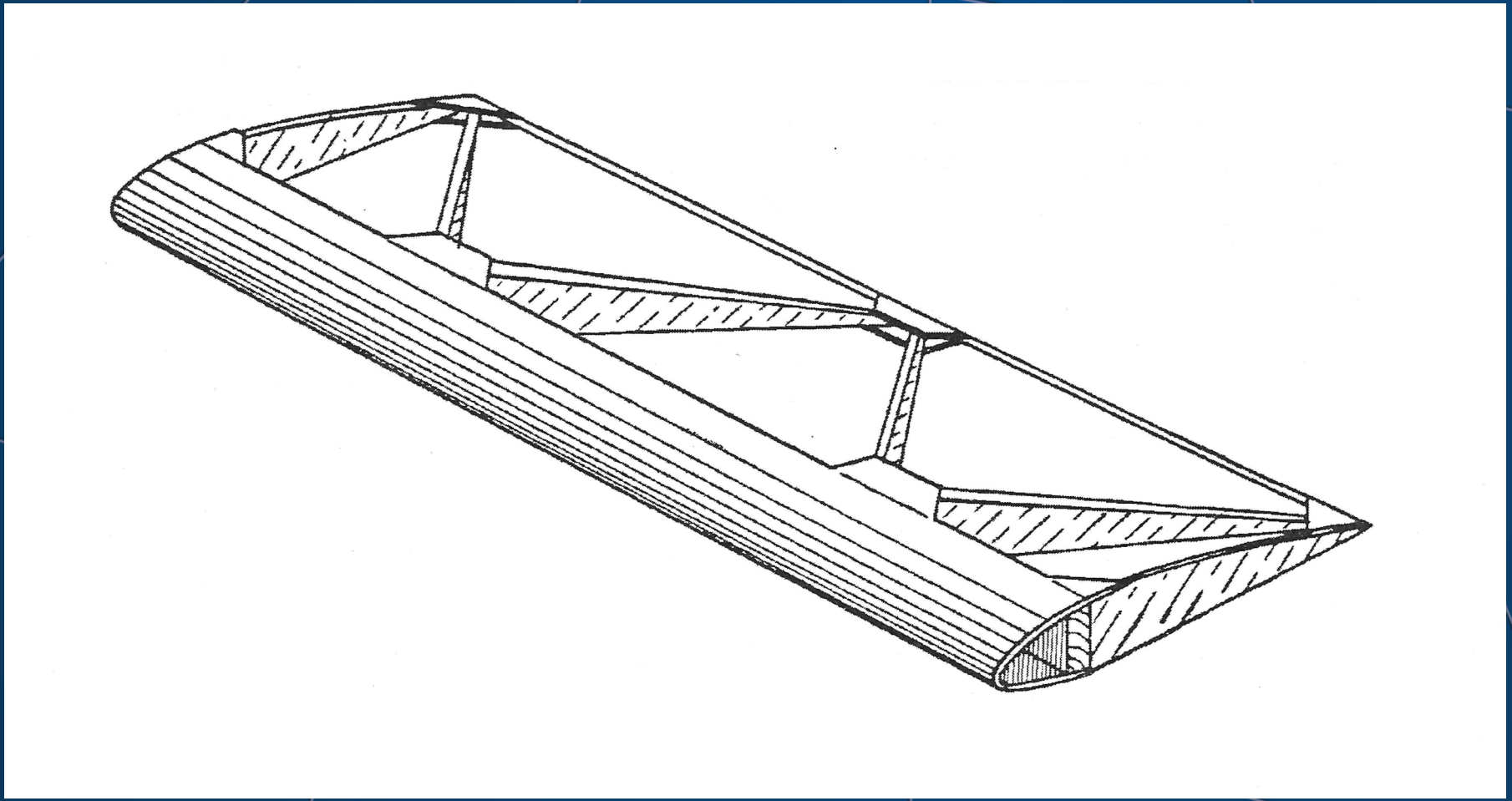


Wright Flyer (1903) cutaway

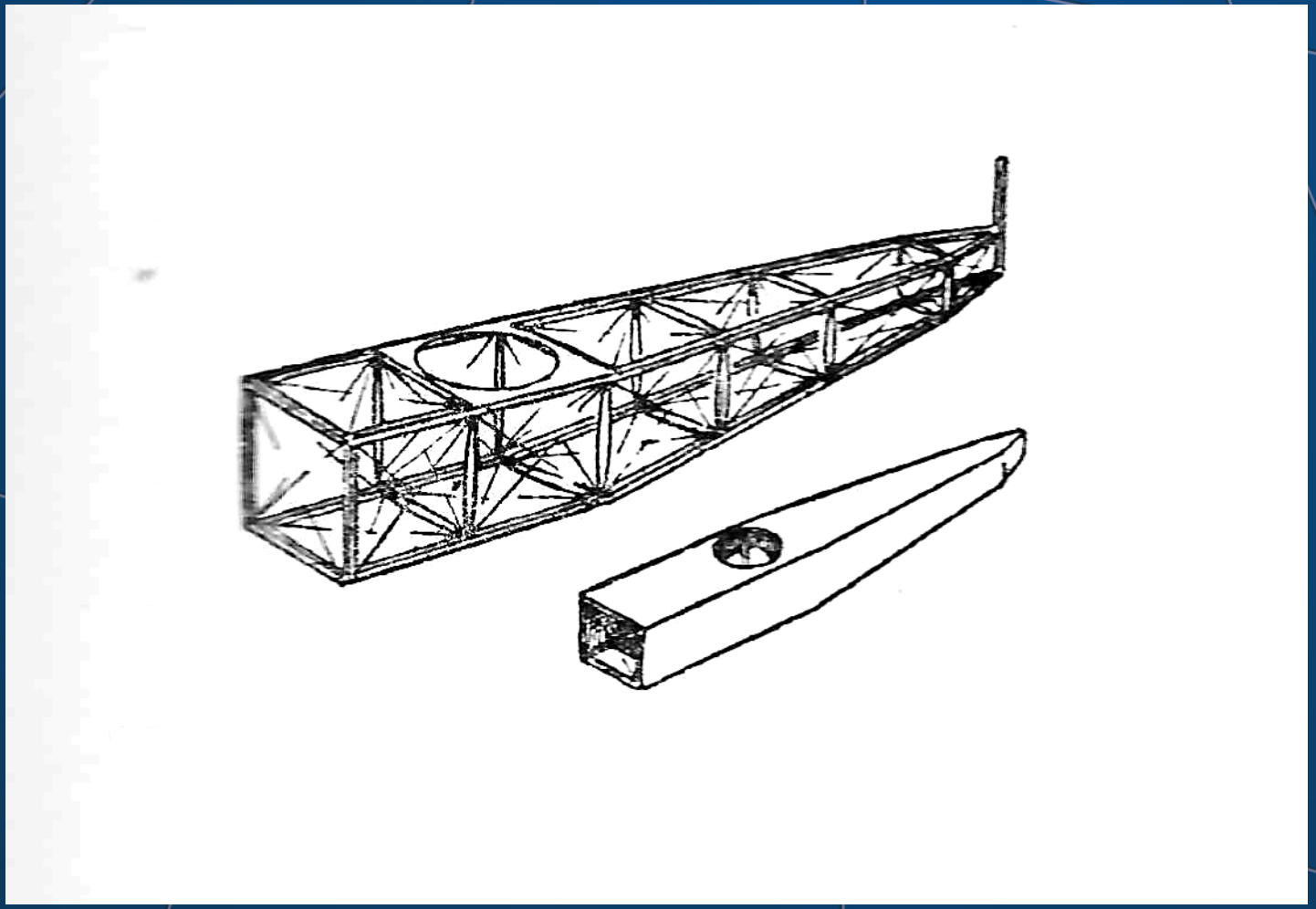
Wood Ribs



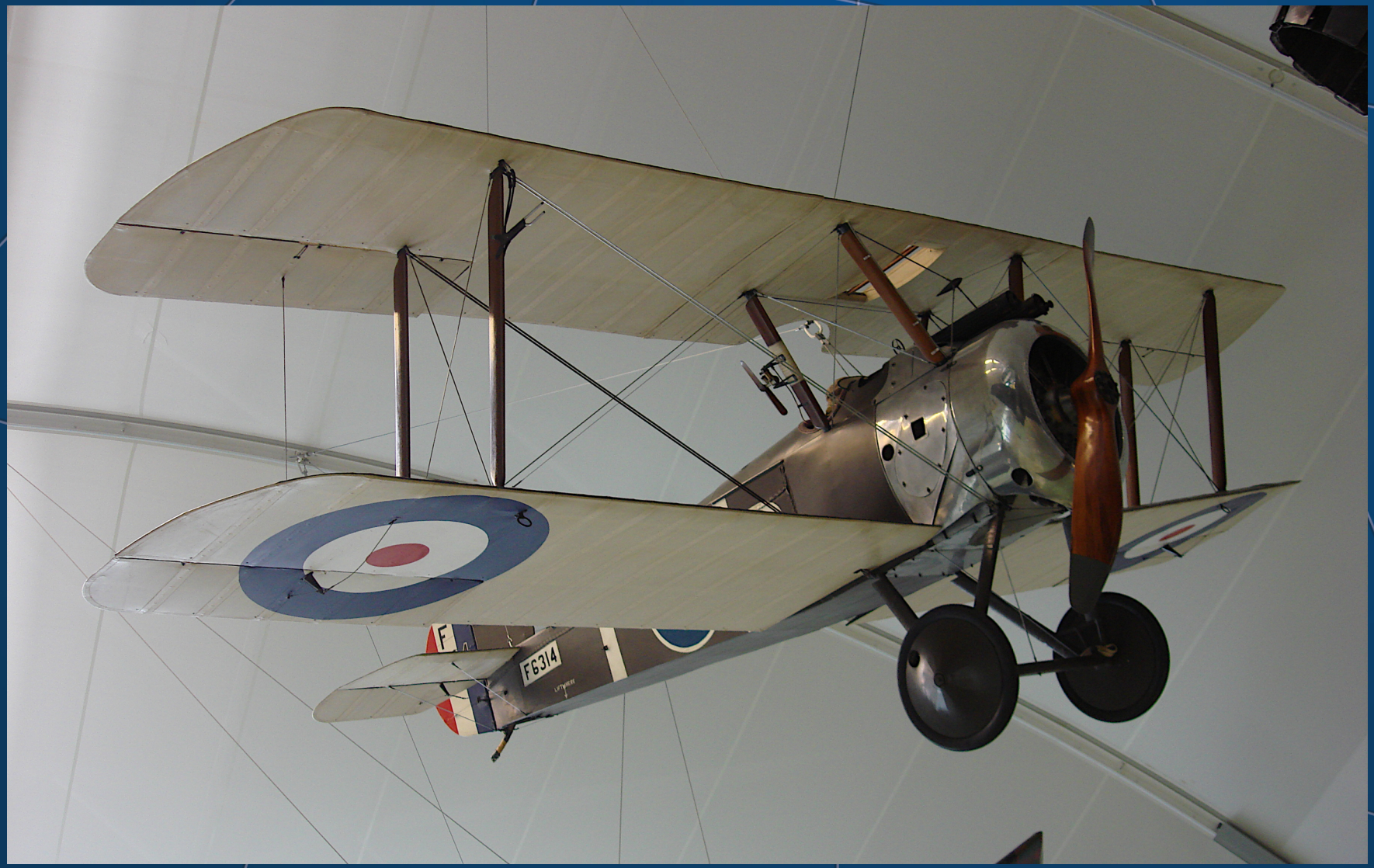
Box Section Ribs	'I' Section Ribs (Double 'T')
	
	
	
	



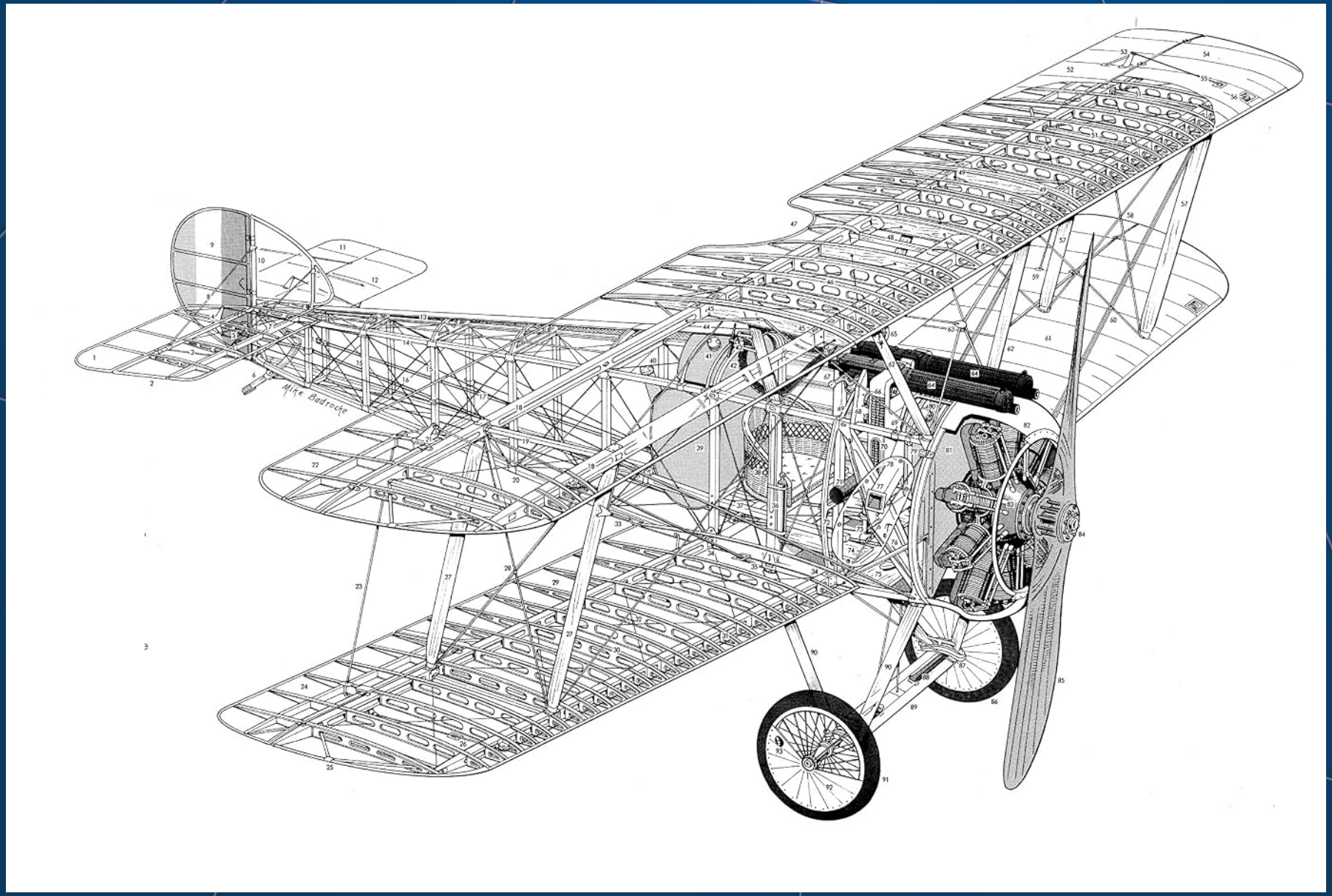
Control surface with diagonal ribs



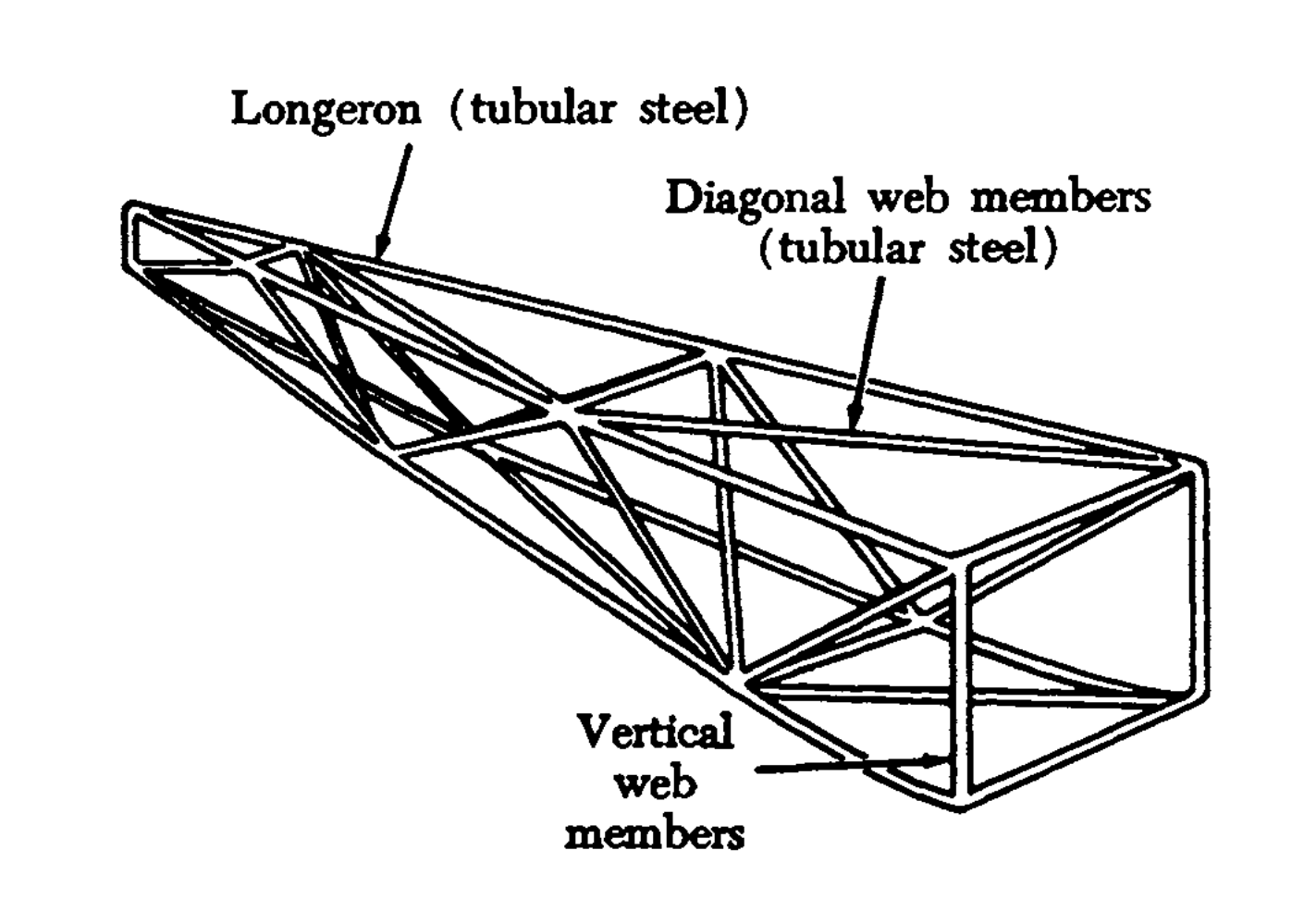
Simple wooden truss fuselage with wire diagonals



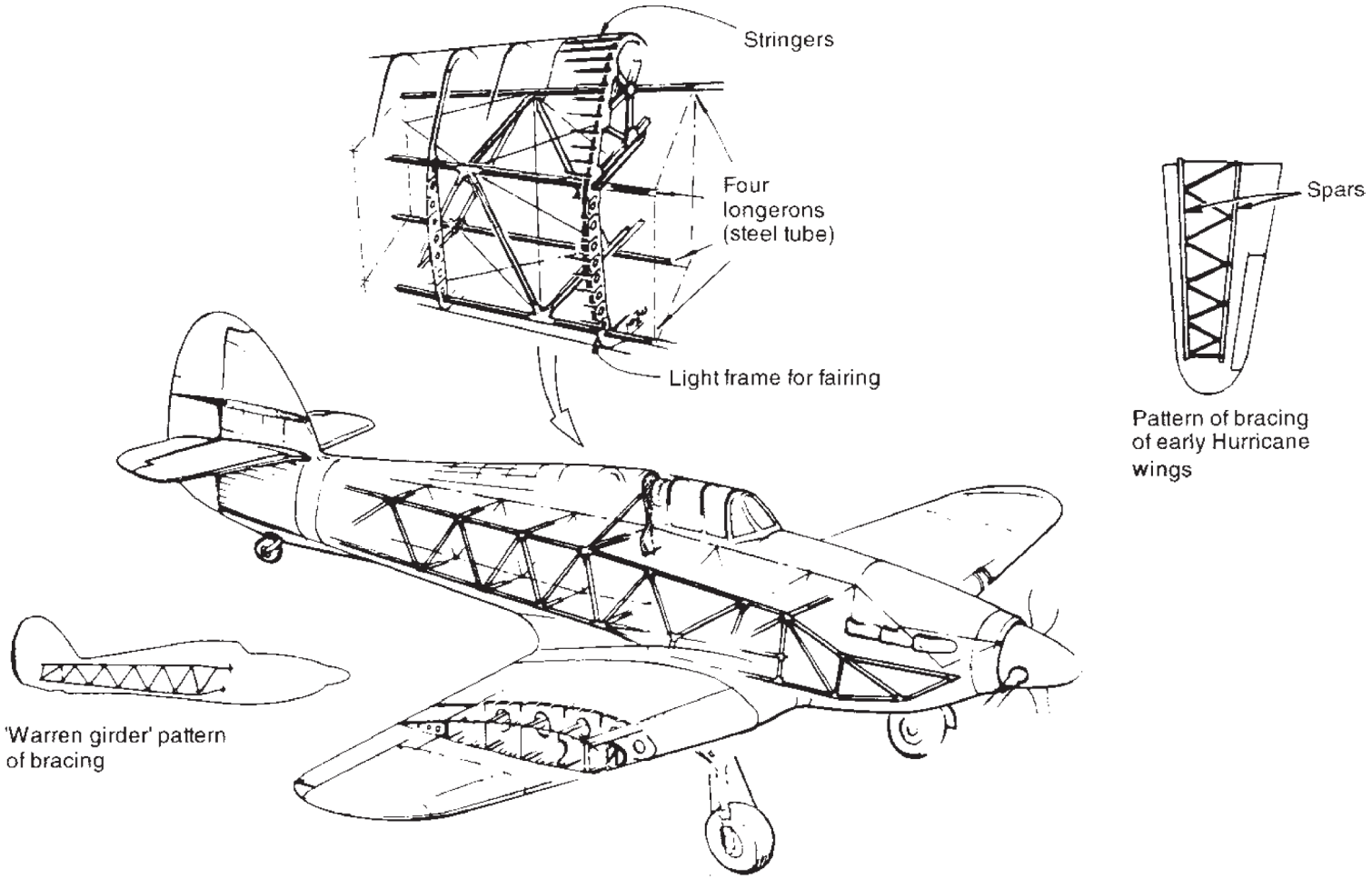
Sopwith Camel at the Royal Air Force Museum



Sopwith Camel cutaway



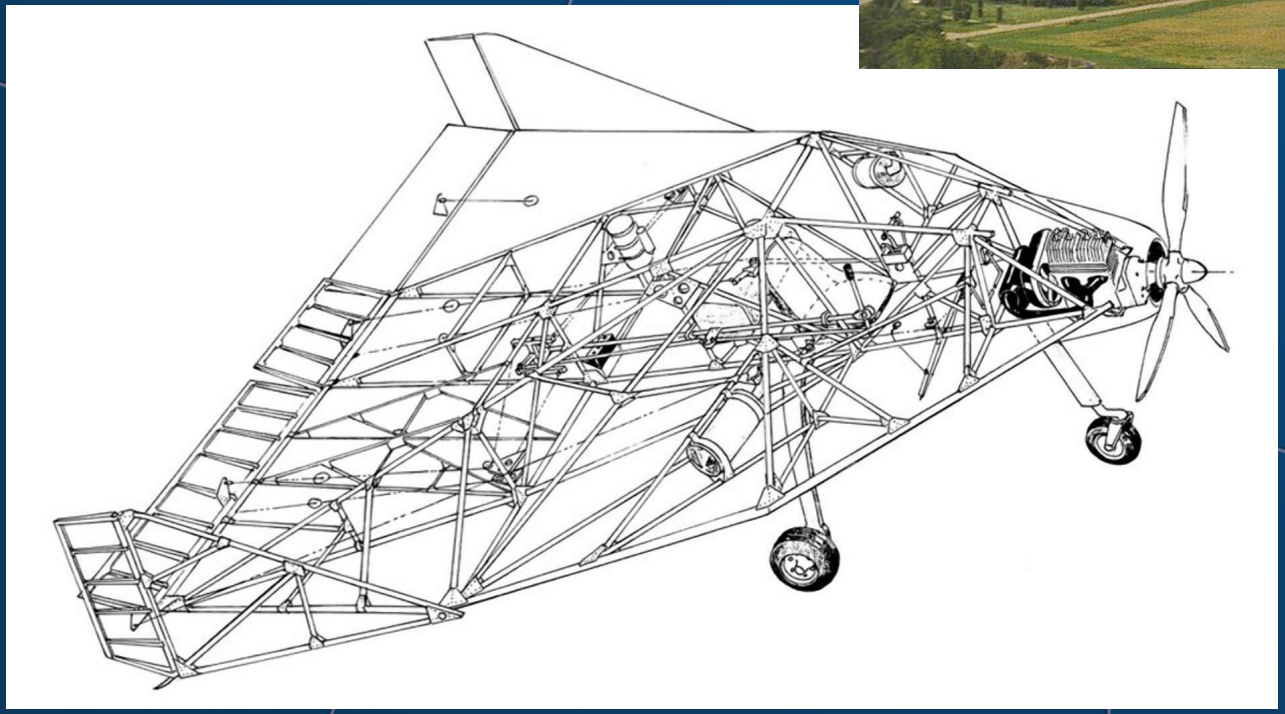
Simple all-metal truss fuselage



Hawker Hurricane (1935)

Barnaby Wainfan
FMX-4 Facetmobile

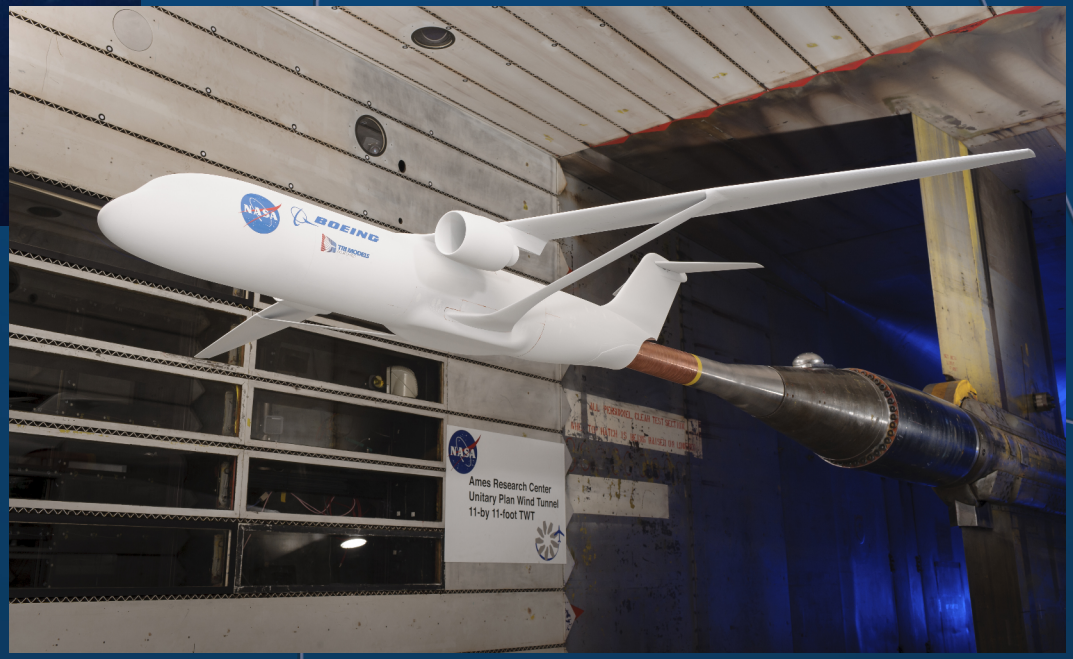




Truss-braced Wings

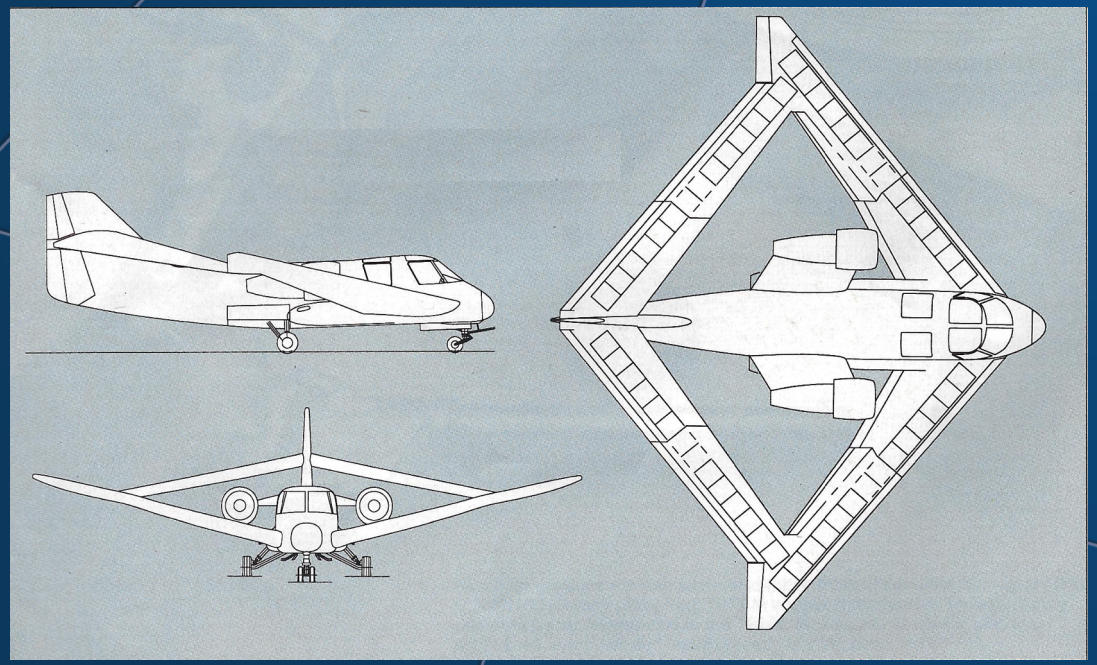


Boeing SUGAR Volt
concept aircraft (2010)



NASA Ames SUGAR
wind tunnel testing

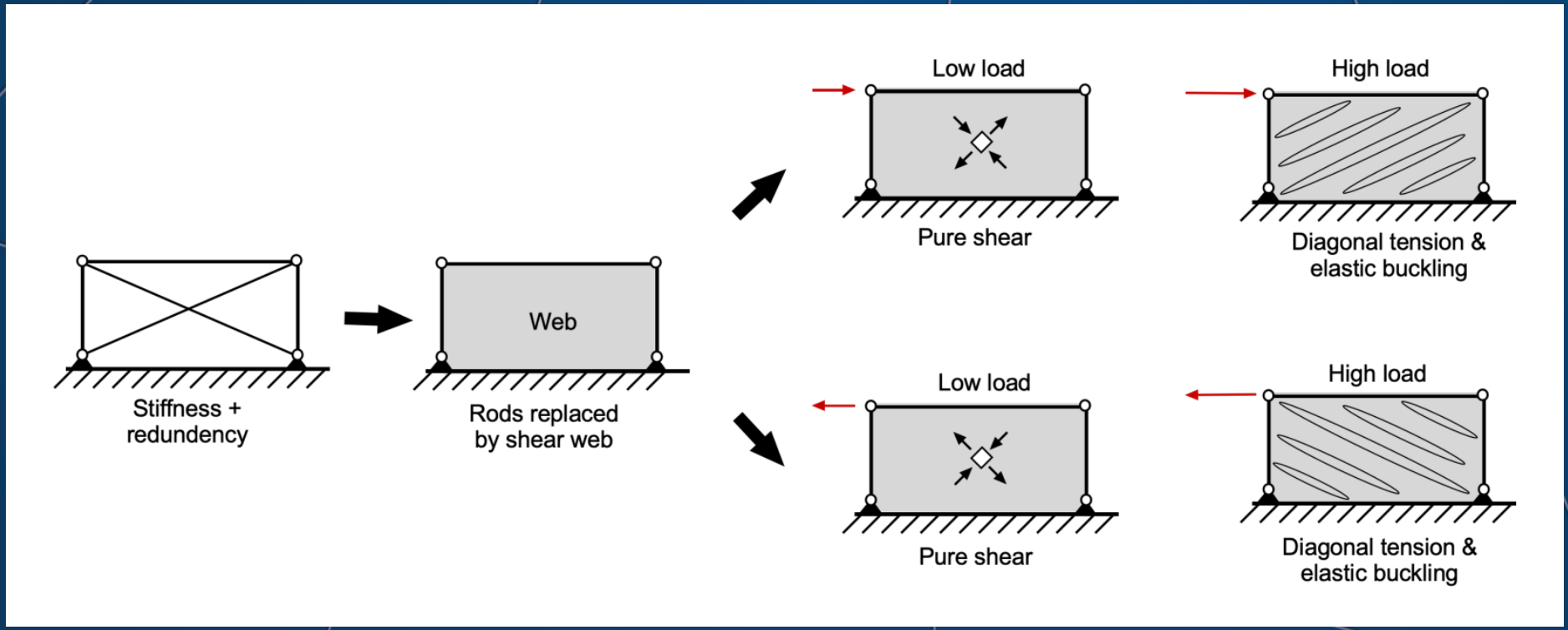
Diamond Wing

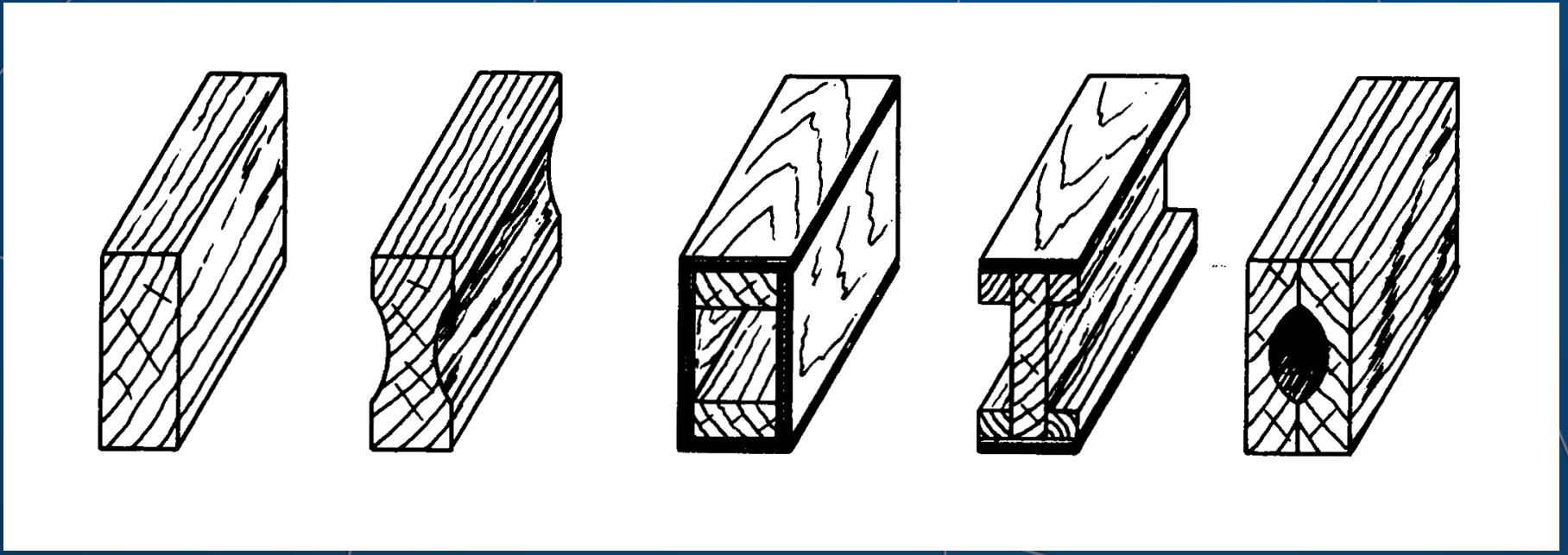




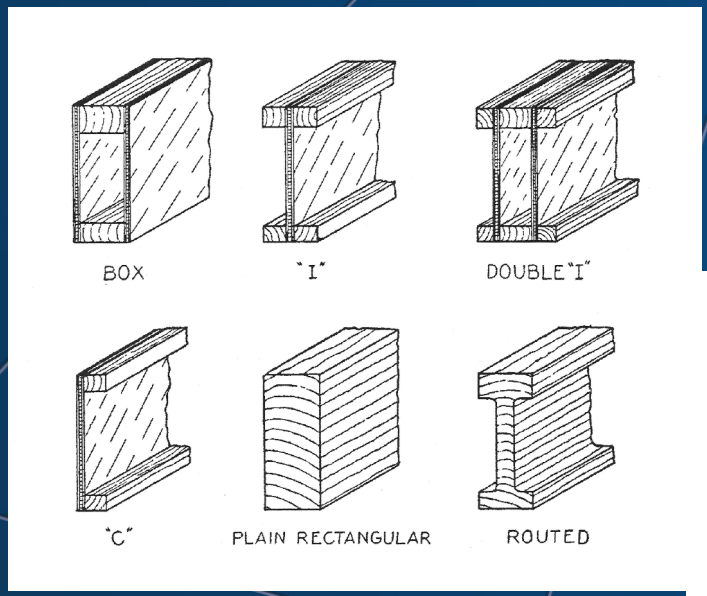
Boeing EX “Diamond Wing” (AWACS)

The Shear Web

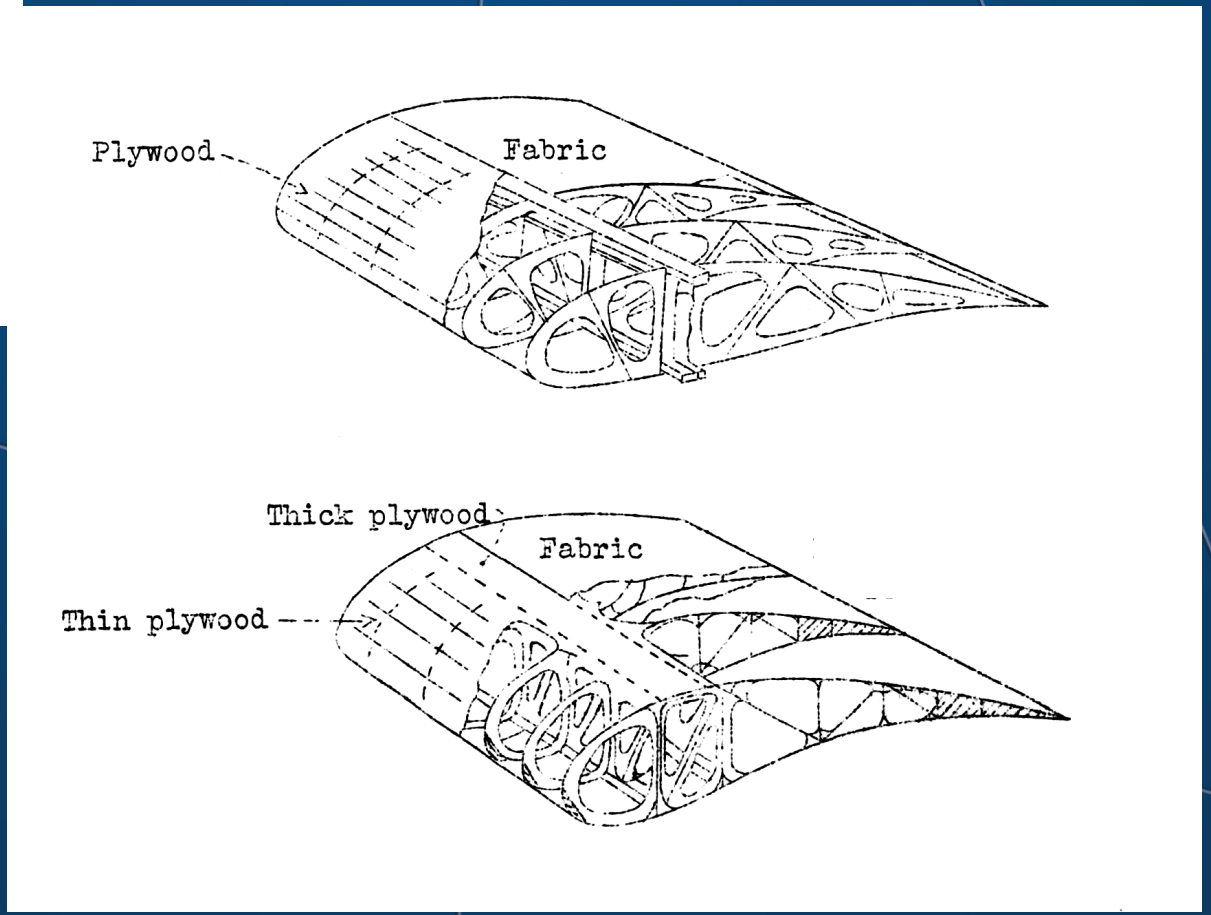




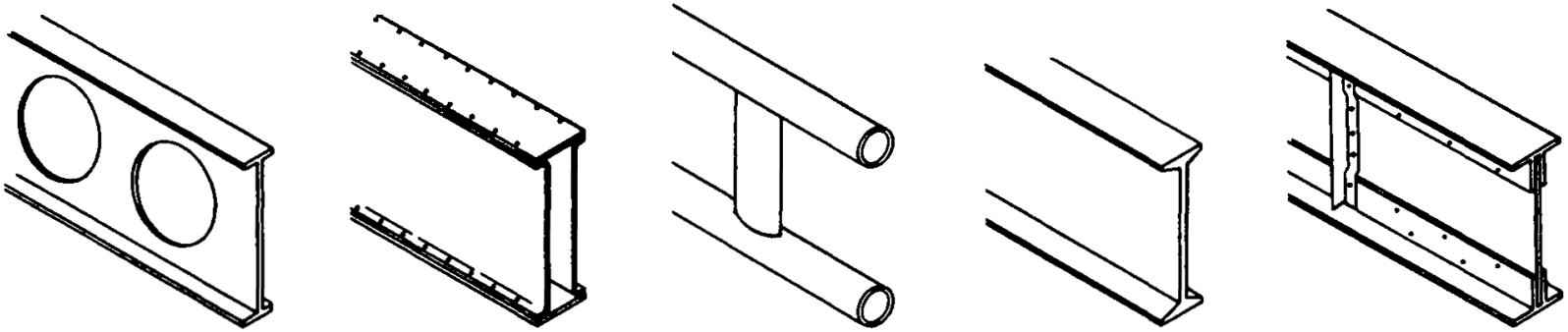
Wooden spars with shear web construction



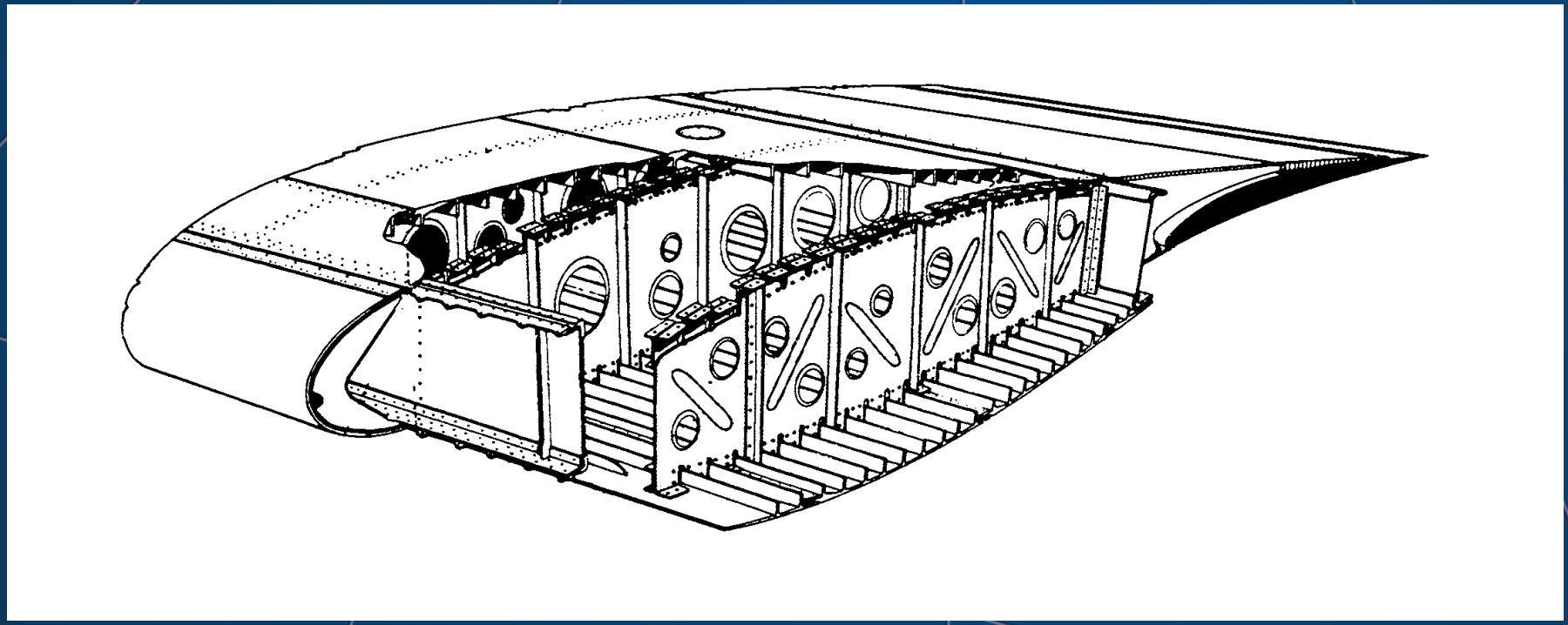
"I" spar wing



Box spar wing

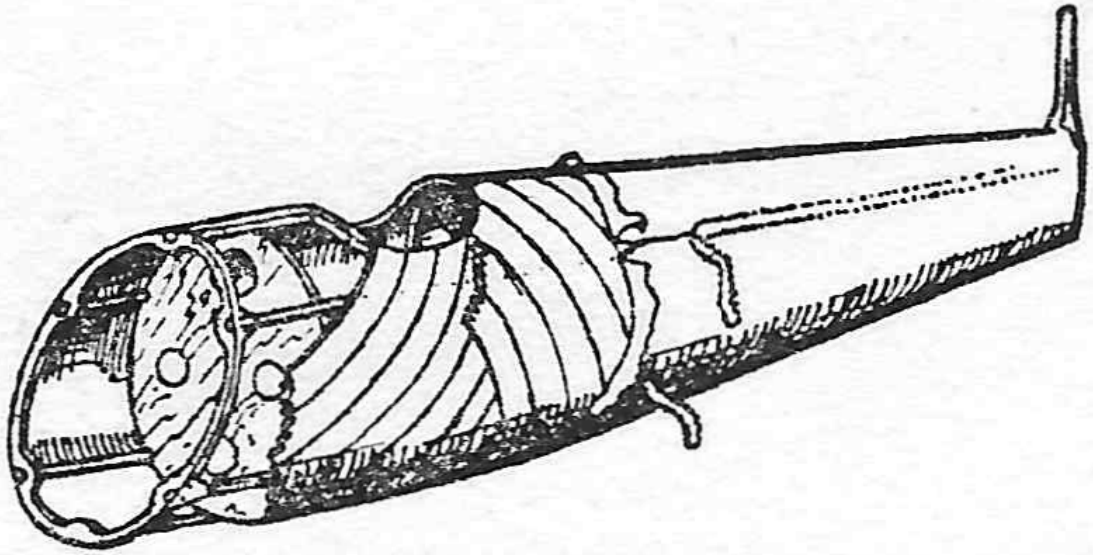


Metal spars with shear web construction



Metal wing with shear web construction

Monocoque

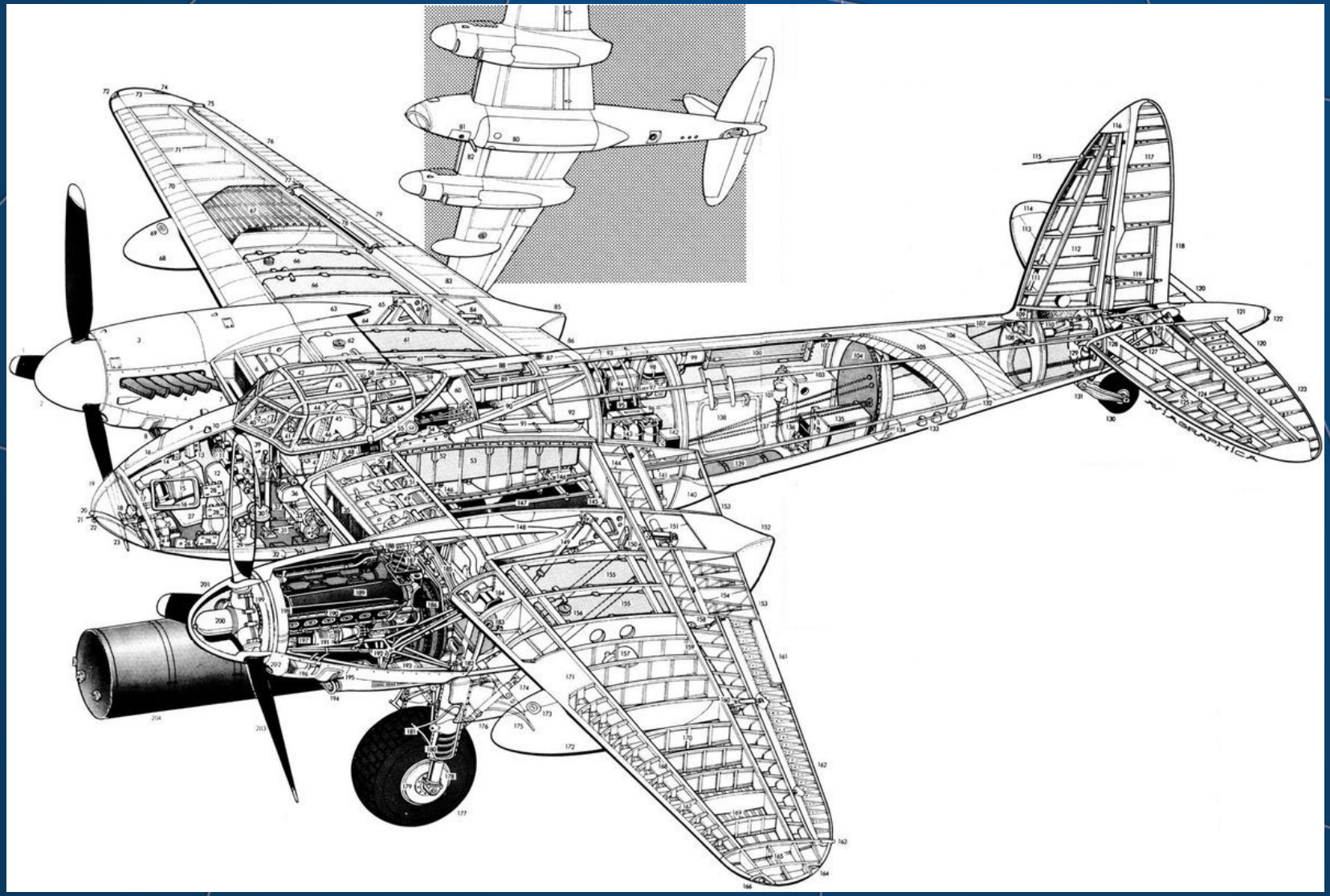




LFG Roland D.I “Shark” (1916)

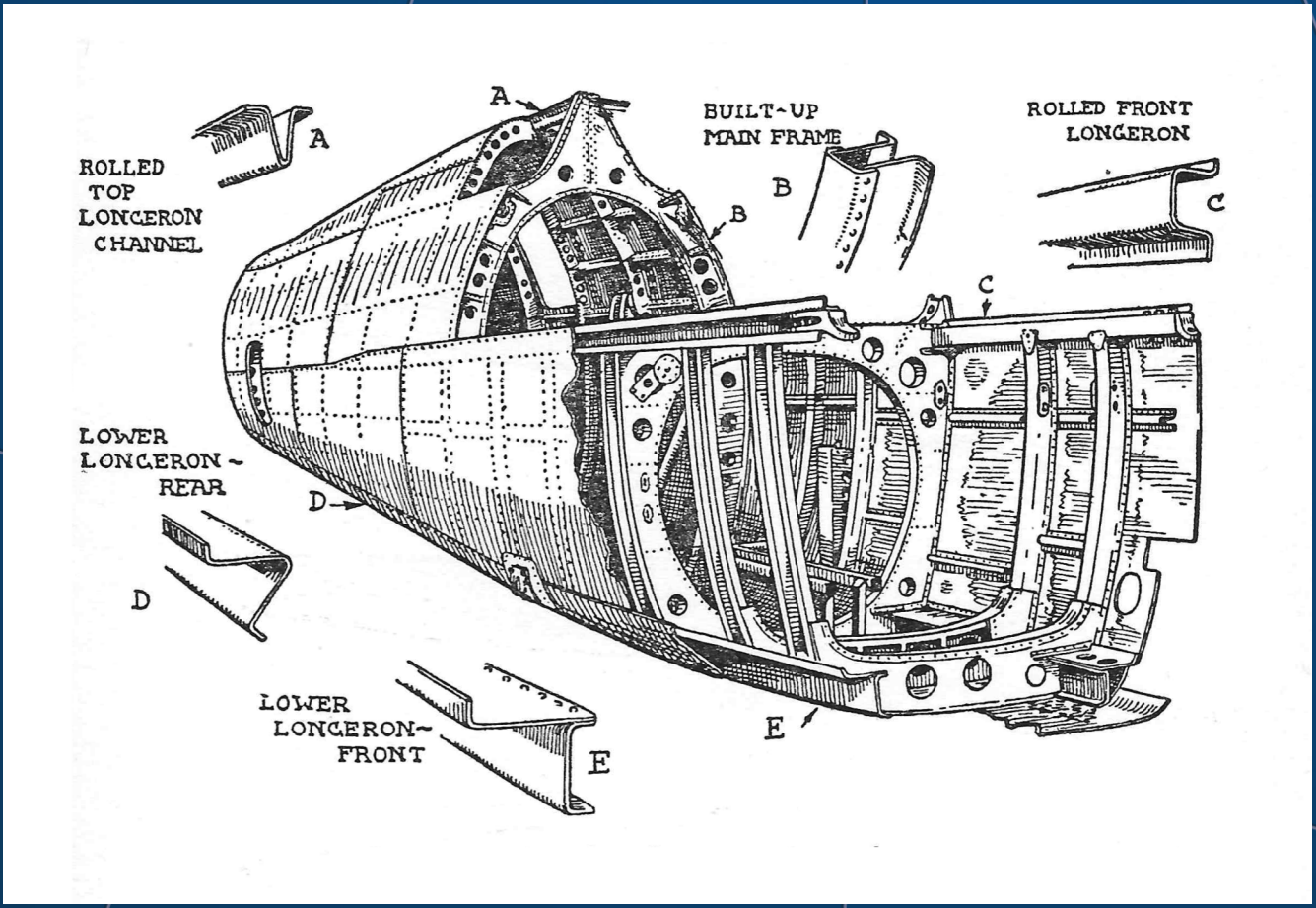


De Havilland DH.98 “Mosquito” (1941)

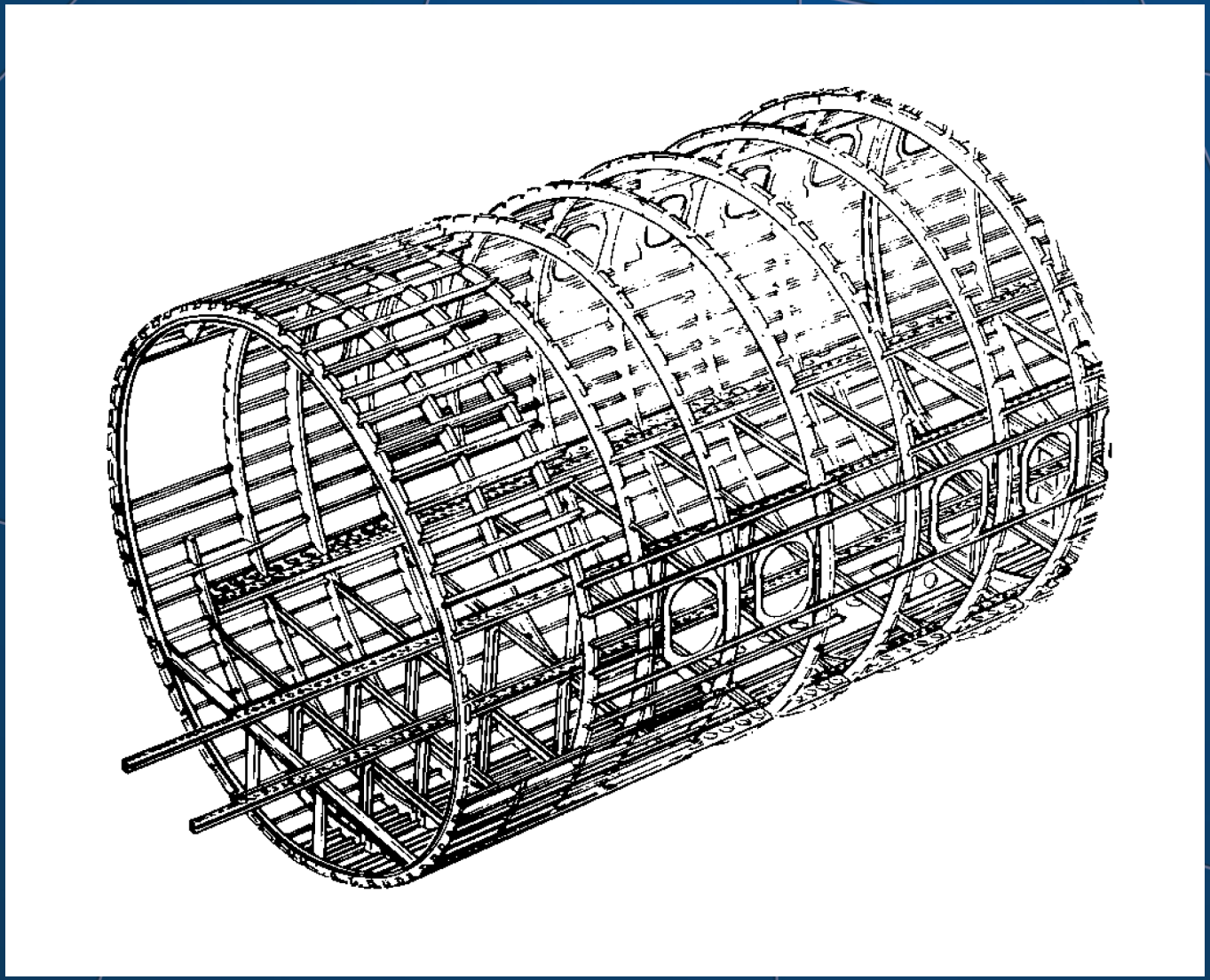


De Havilland DH.98 “Mosquito” cutaway

Semi-monocoque



Supermarine Spitfire fuselage cutaway



Semi-monocoque commercial airliner fuselage

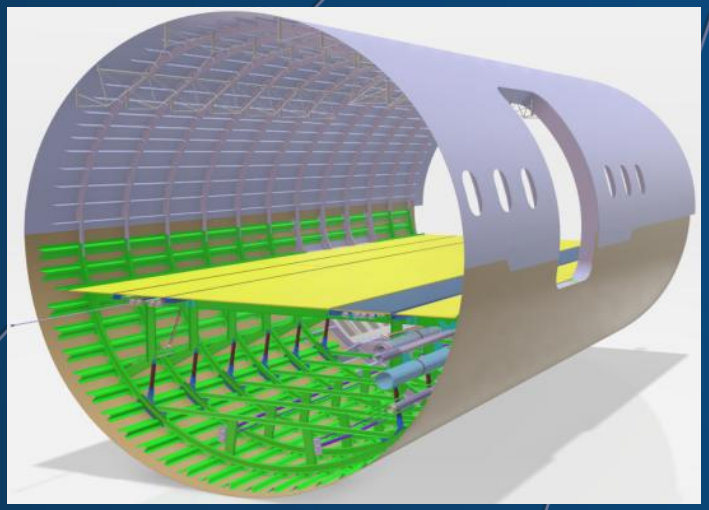
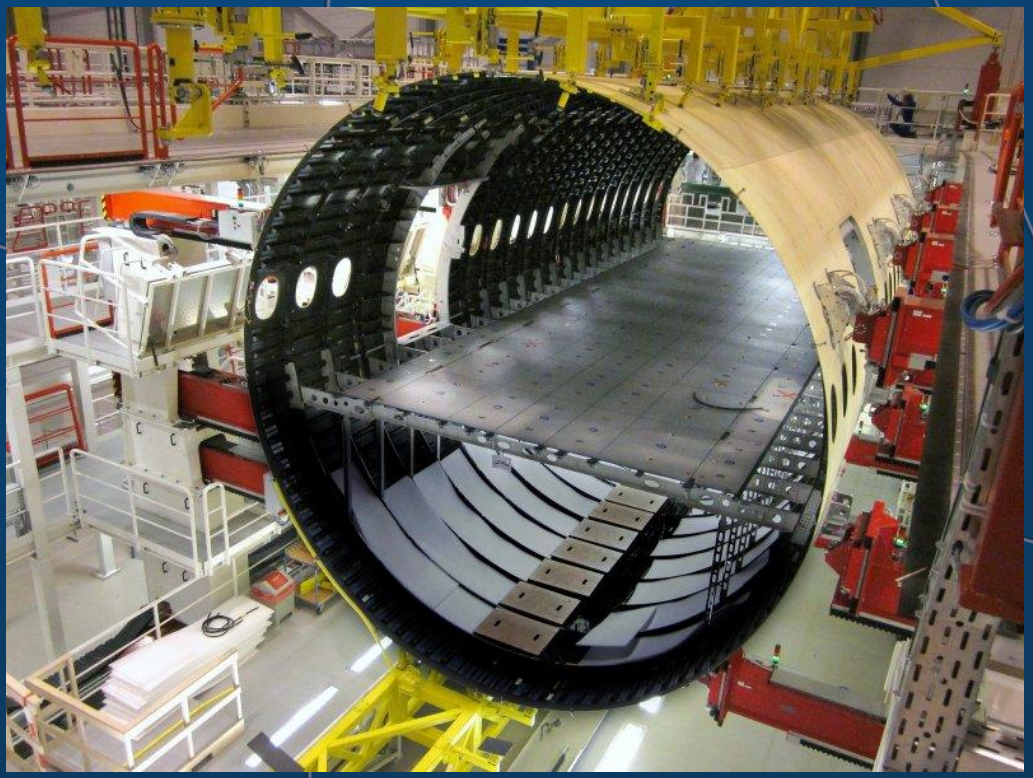


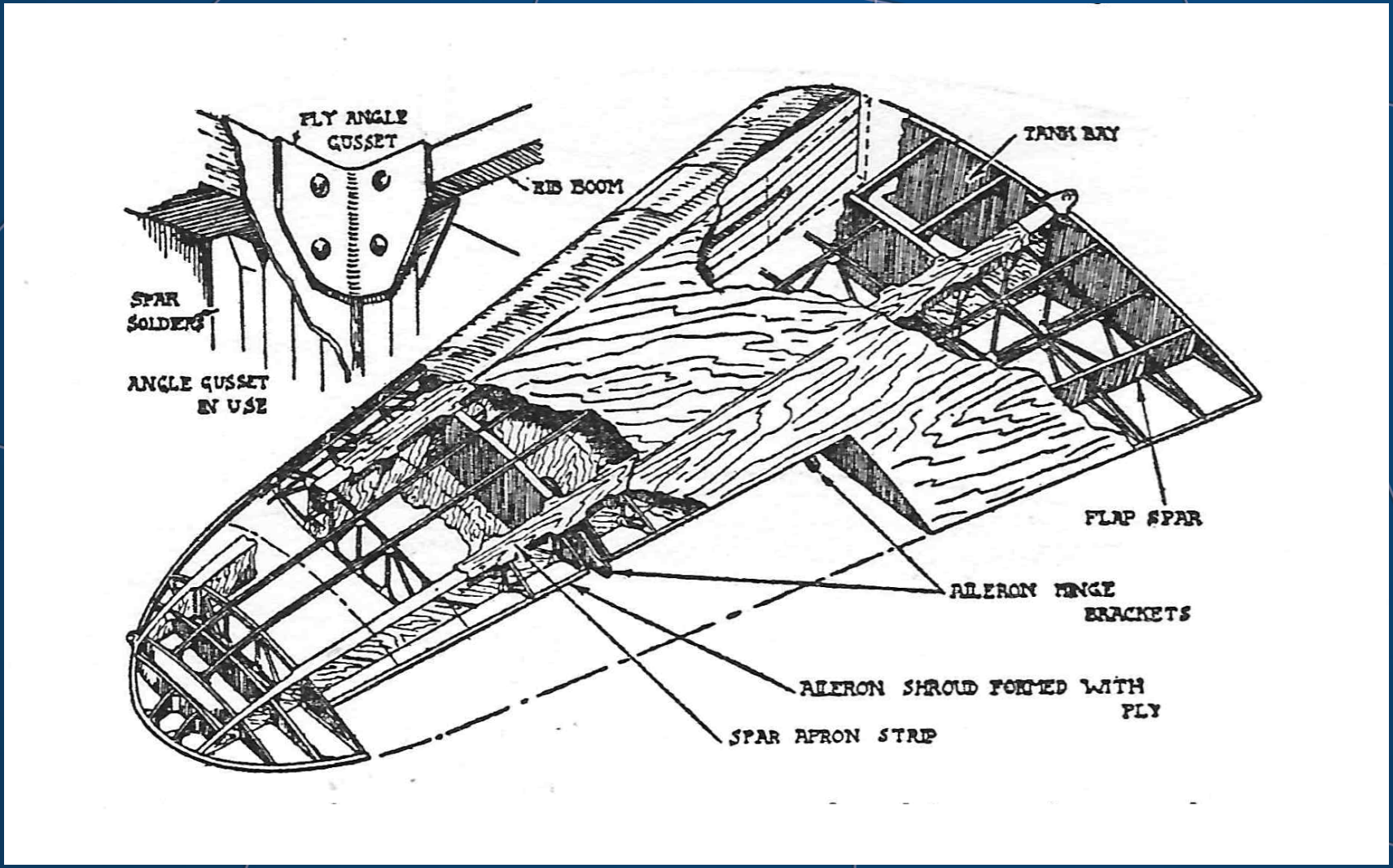
Illustration of commercial airliner fuselage showing formers, stringers and floor



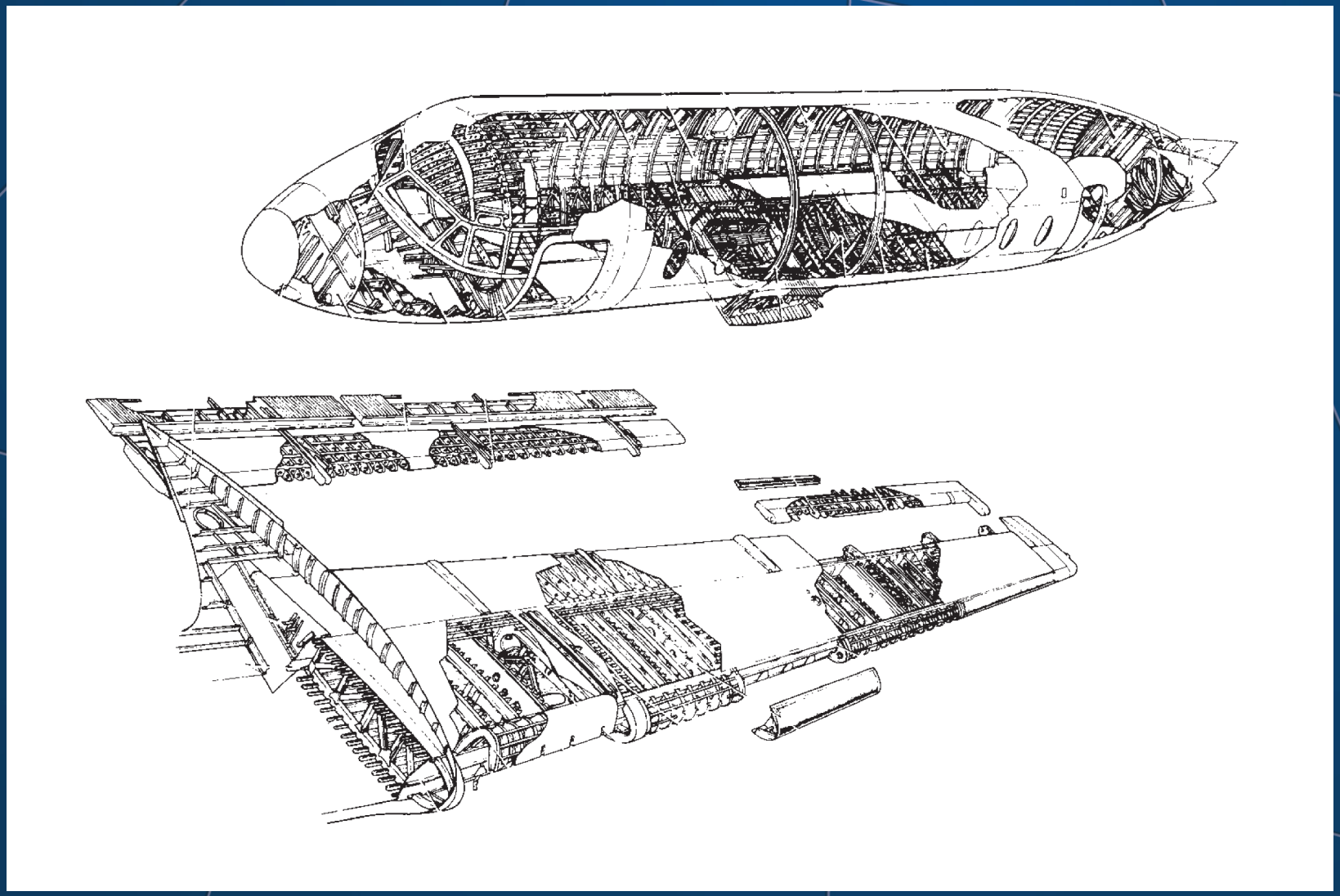
Basic semi-monocoque fuselage panel



Semi-monocoque composite fuselage under construction

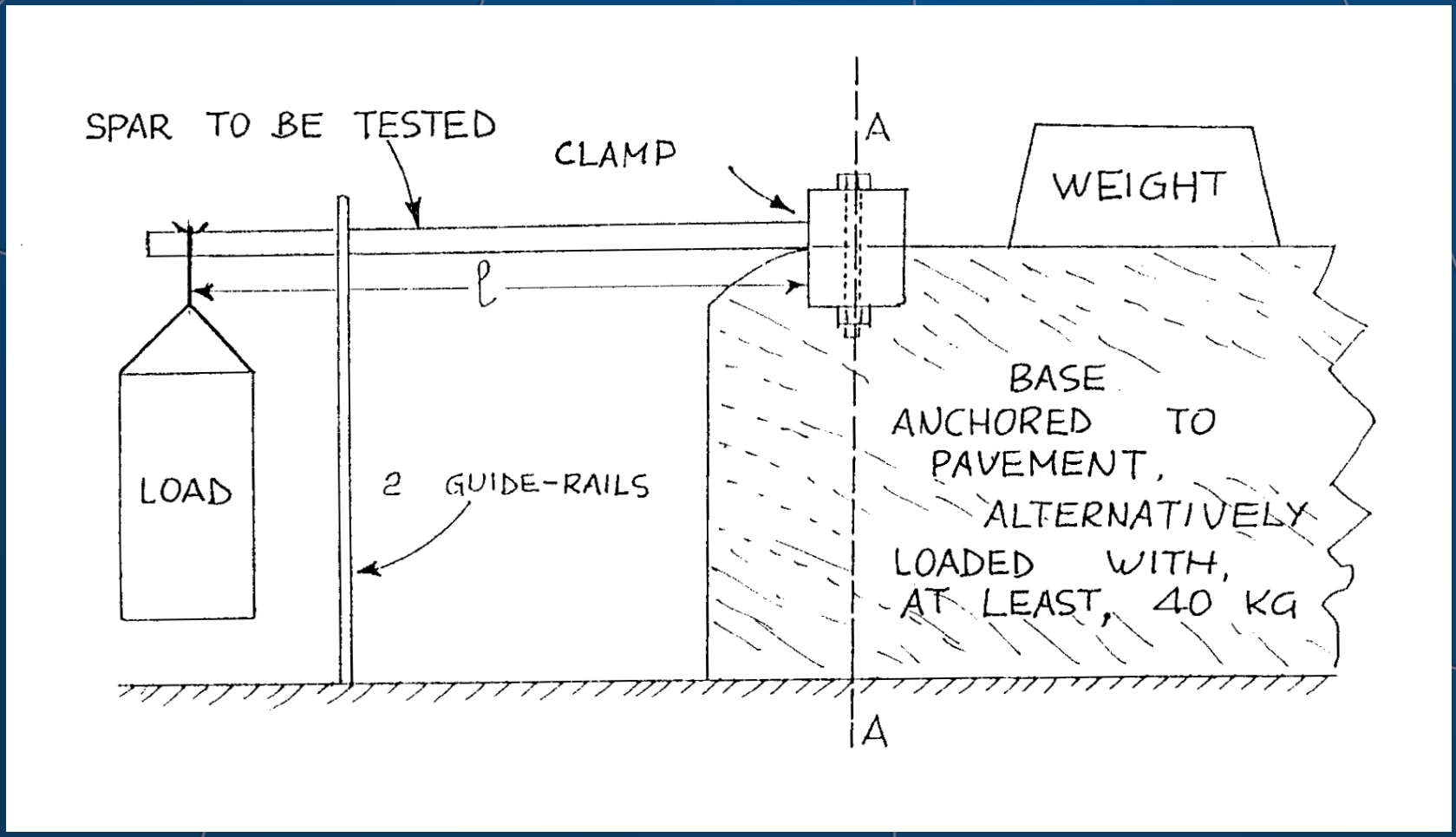


Airspeed Oxford stressed-skin wing cutaway

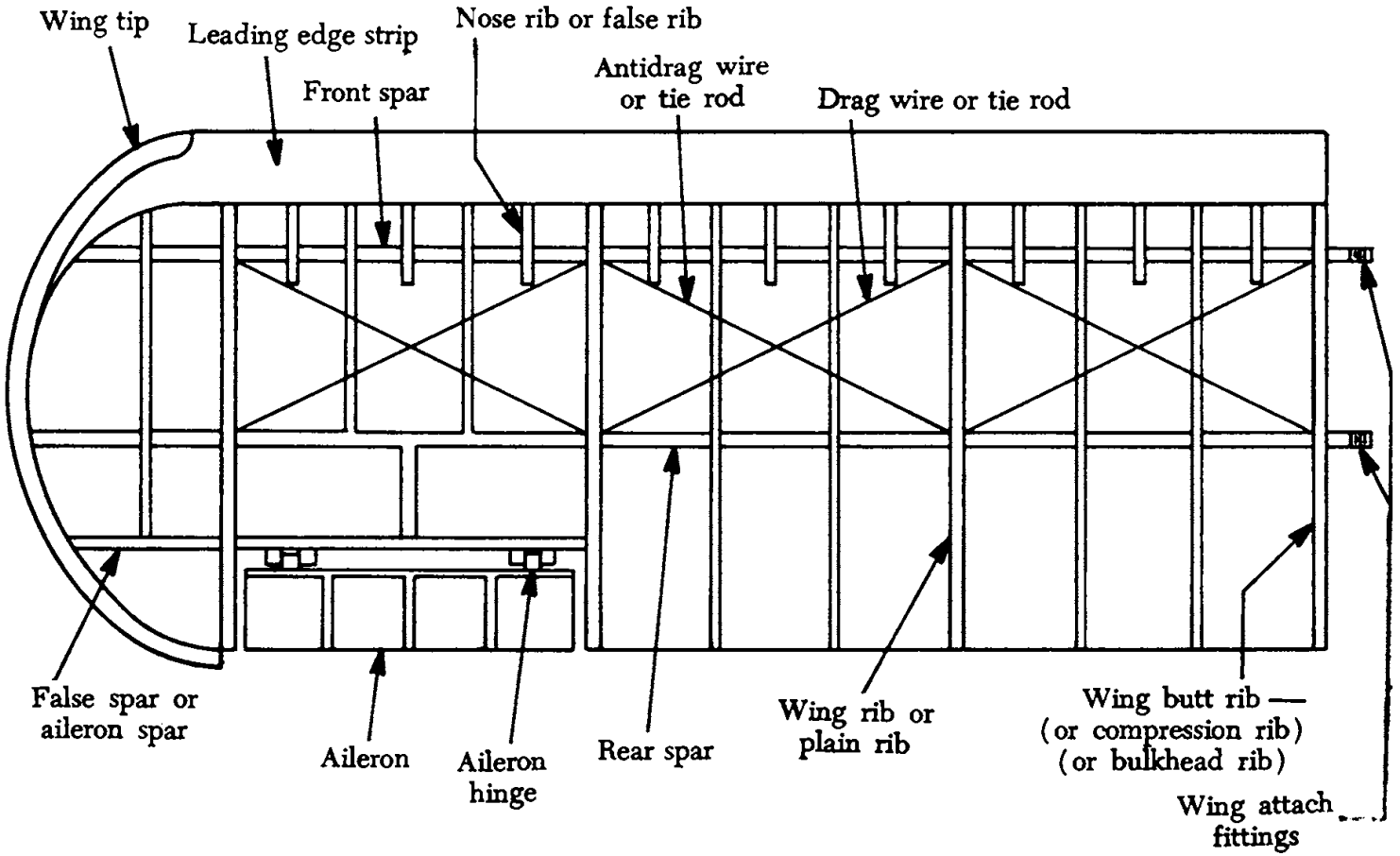


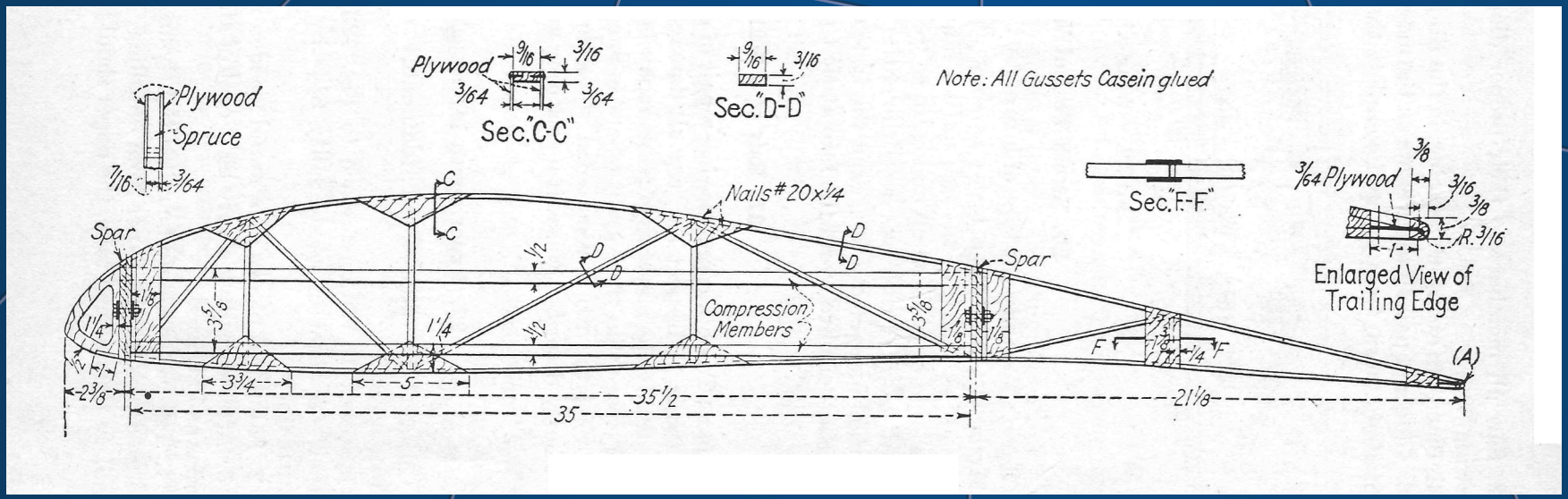
Hawker Siddeley HS 748 cutaway

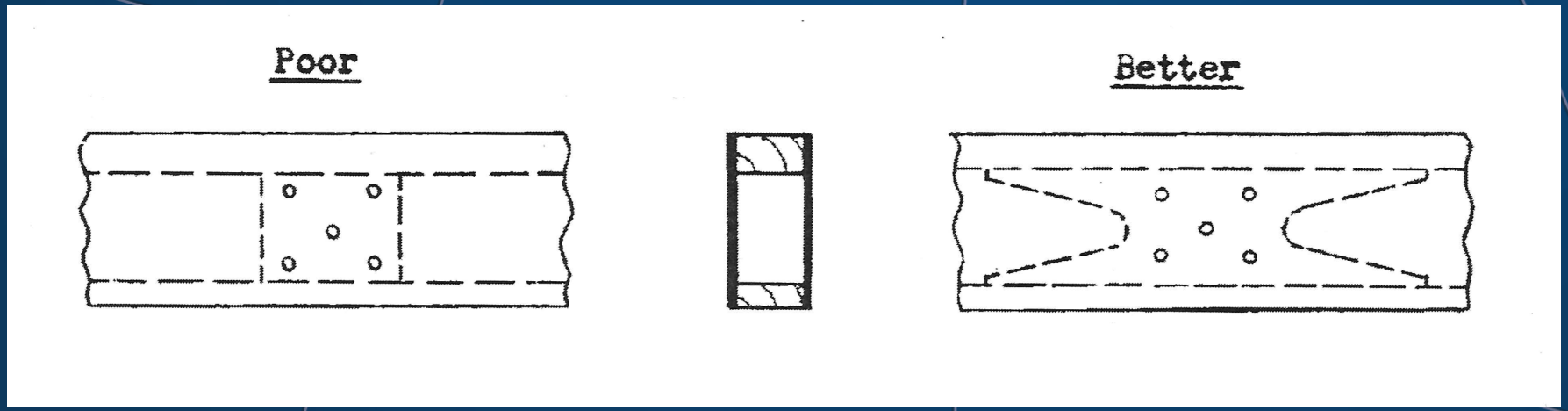
Eliminating stress risers

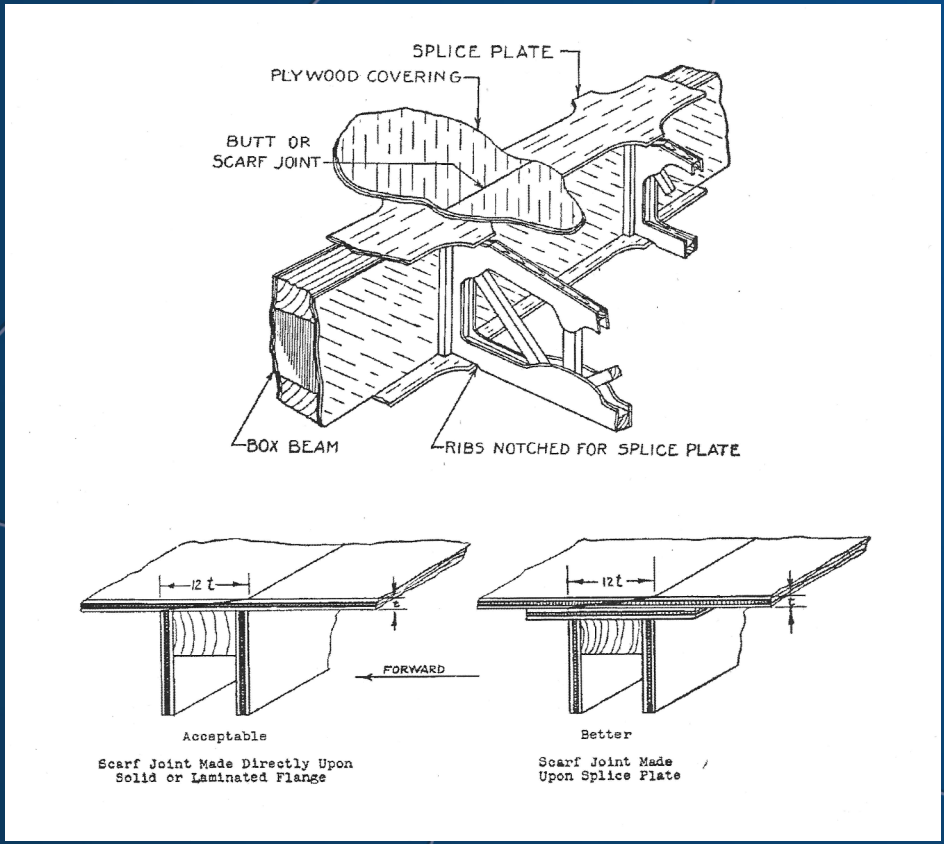


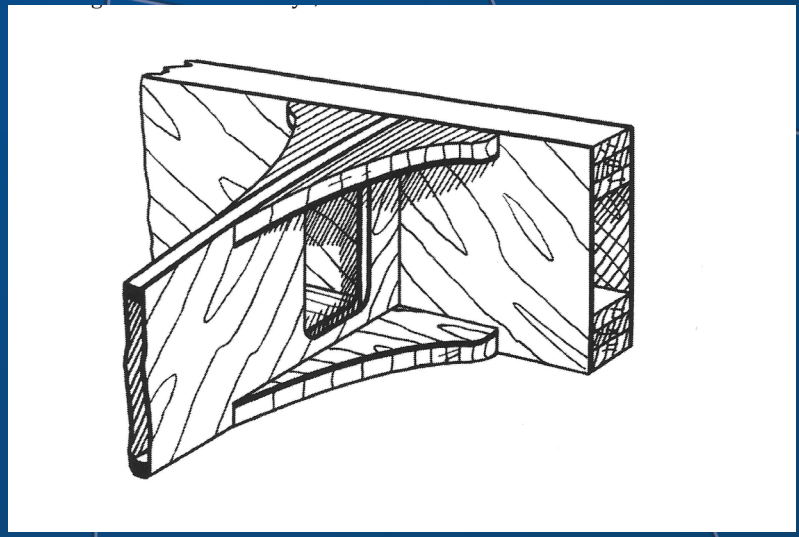
Details of wooden wing construction

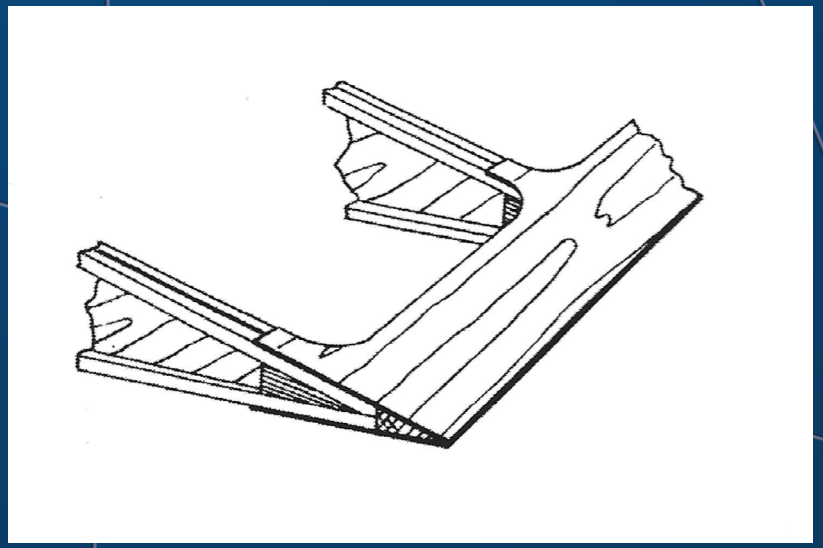



Plywood
Spruce
7/16
3/64
Plywood
9/16
3/16
3/64
3/64
Sec."C-C"
9/16
3/16
Sec."D-D"
Note: All Gussets Casein glued
Sec."F-F"
3/8
3/64 Plywood
3/16
3/8
R. 3/16
1"
Enlarged View of Trailing Edge
Spar
C
C
Nails #20x1/4
D
D
1/2
D
D
1/2
Compression Members
Spar
3-5/16
3-5/16
1 1/4
1/8
1/8
1 1/4
F
1/4
F
(A)
2
1
2-3/8
3-3/4
5
35 1/2
21 1/8
35


Poor
Better





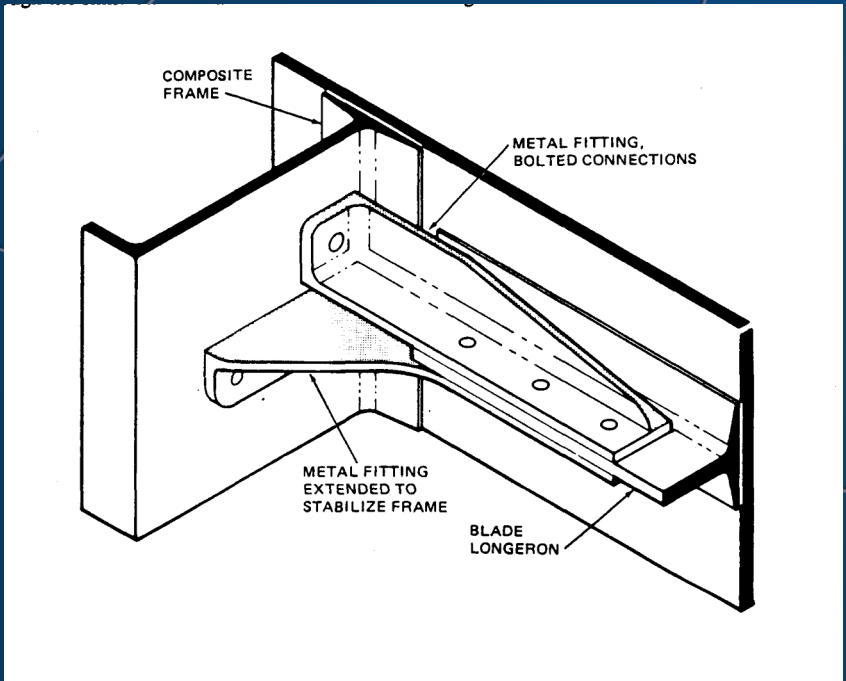


Butt splice and scarf joints

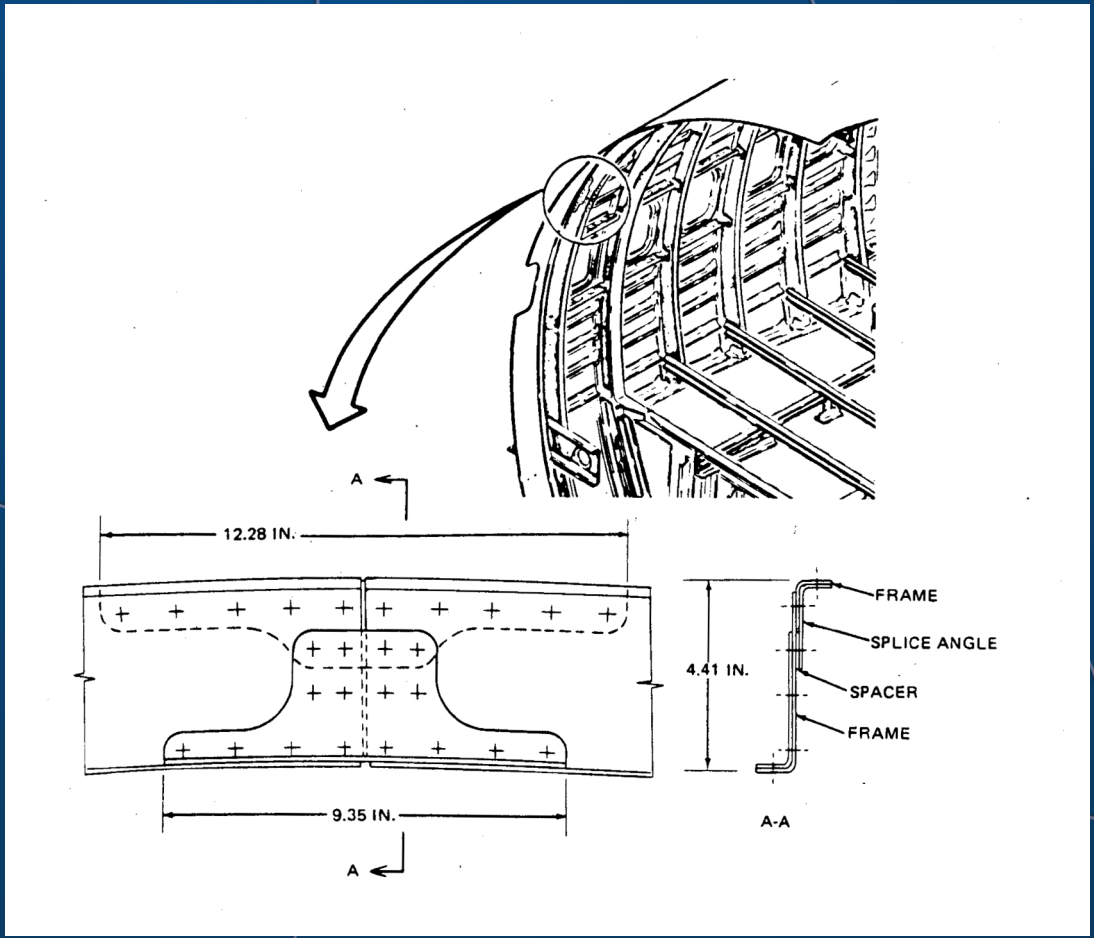
Gussets

Sharp trailing edge

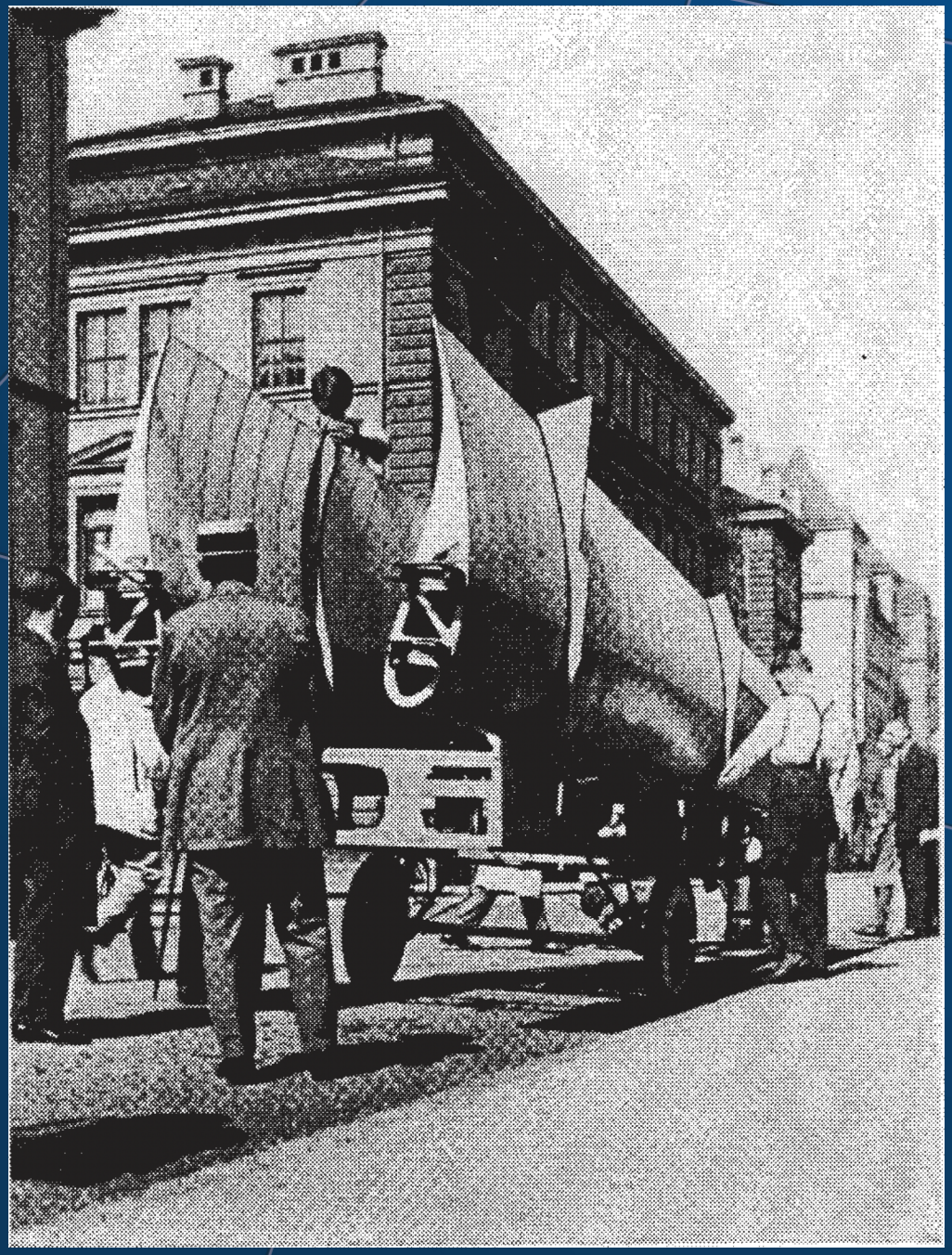
Details of composite construction



Frame & interrupted longeron



Frame splice

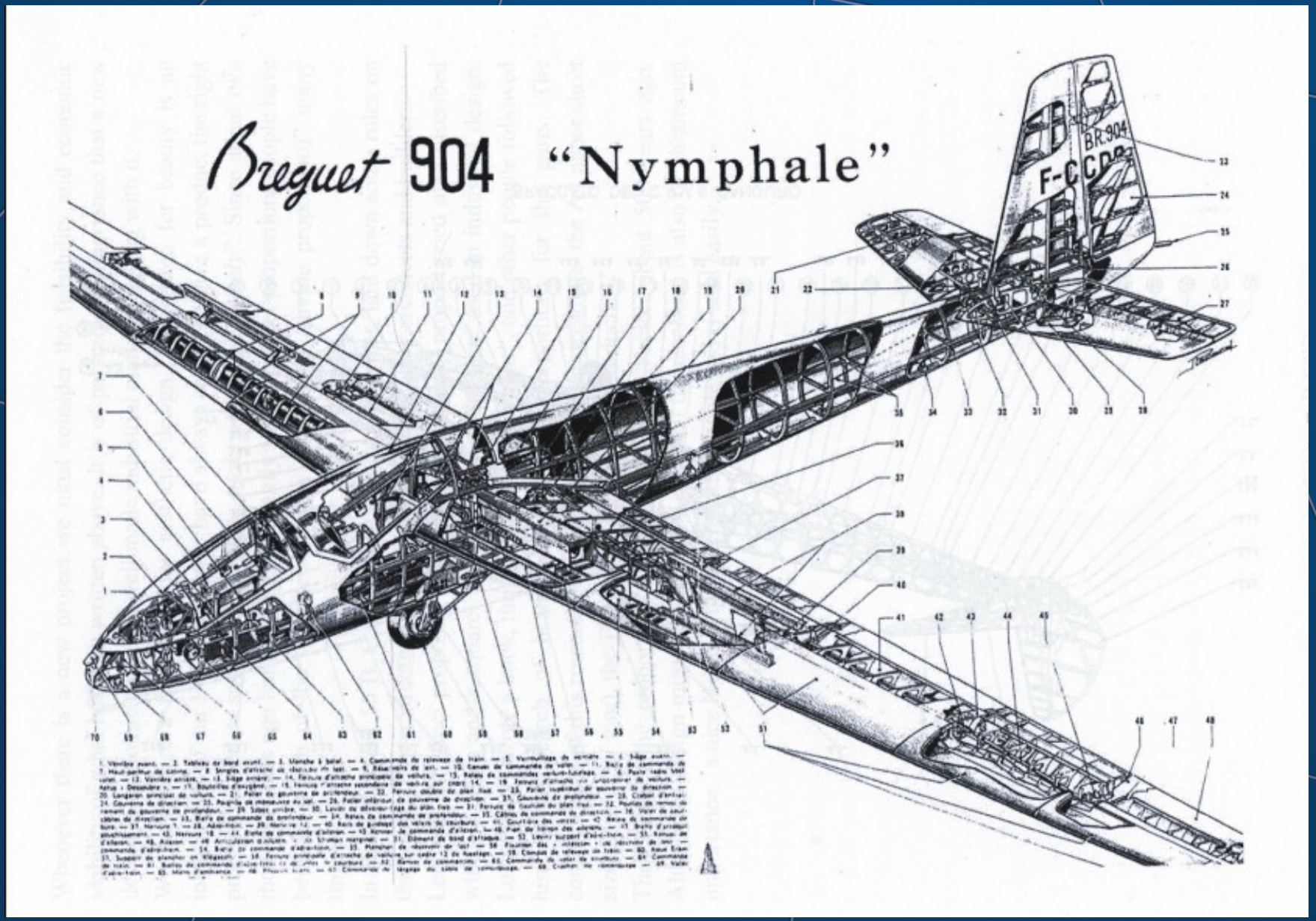


A glider built by Munich college students being made ready for shipment to the Wasserkuppe flying site.

National Geographic, June 1929

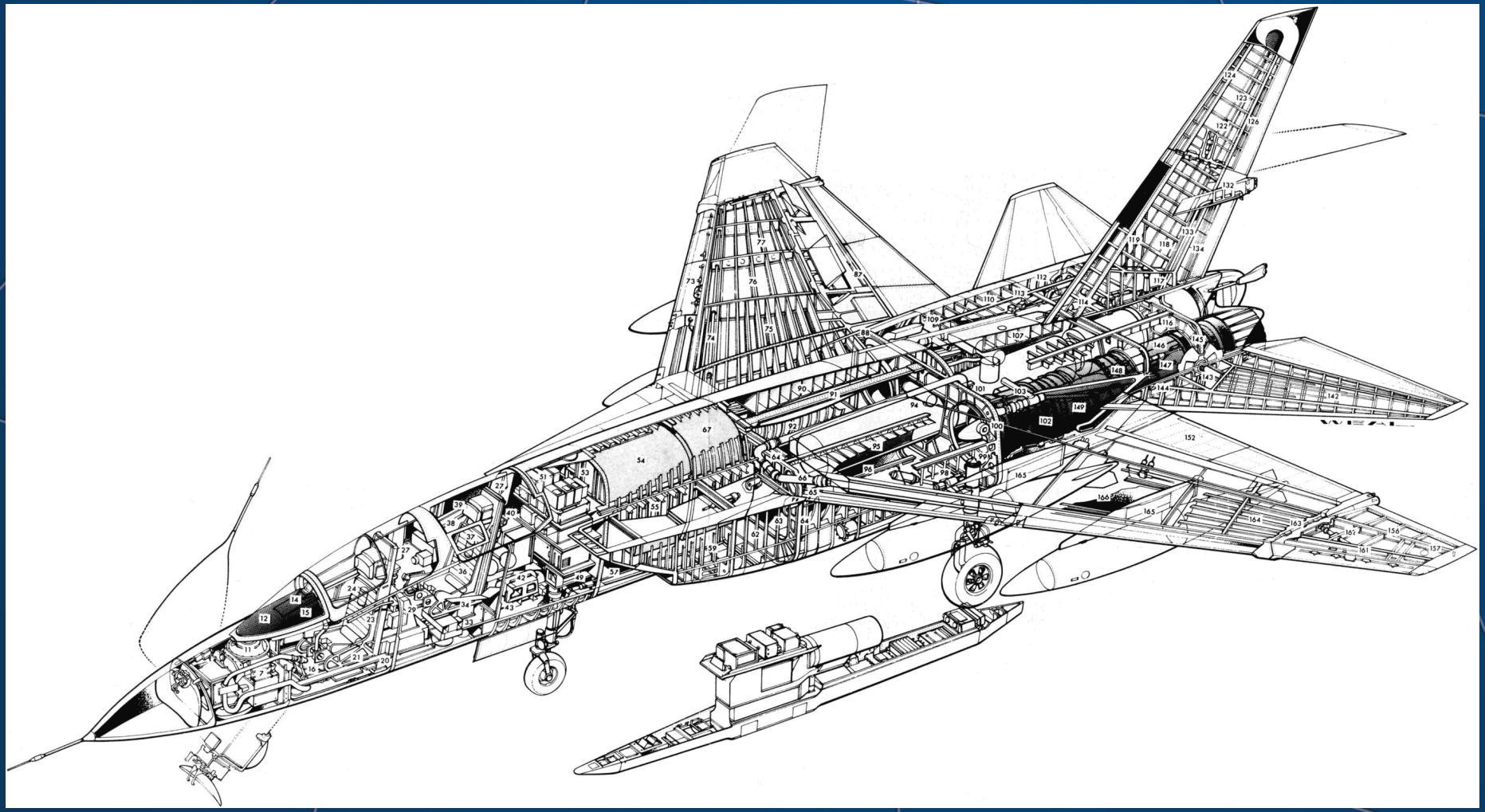


Breguet 904 Nymphale (1956)


Breguet 904 "Nymphale"
B.R.904
F-C C D



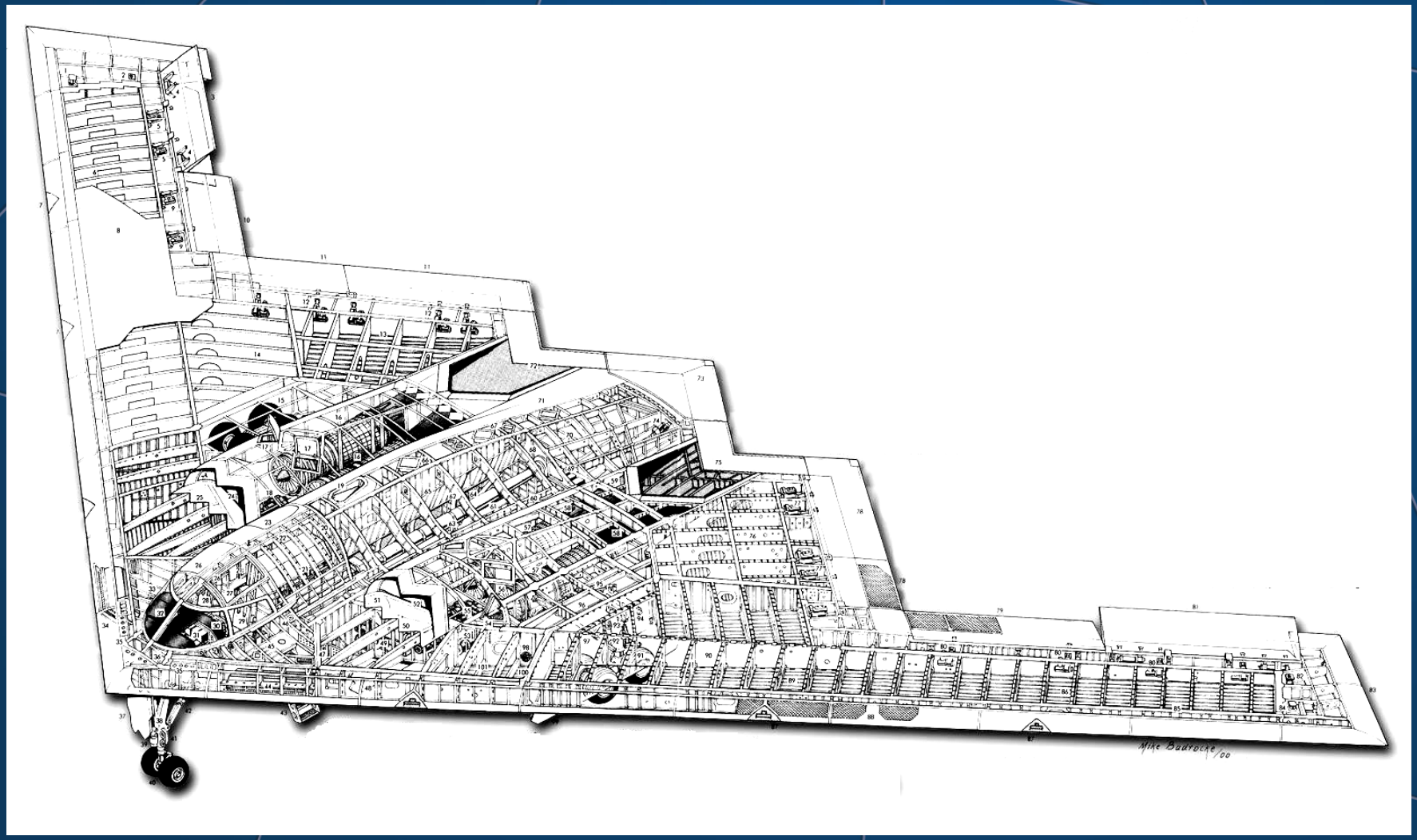
North American RA-5C “Vigilante” (A-5 1958)



North American RA-5C “Vigilante” cutaway



Northrop Grumman B-2 “Spirit” (1989)



Northrop Grumman B-2 “Spirit” cutaway (composite)

Akaflieg Stuttgart FS24 Phönix (1957)

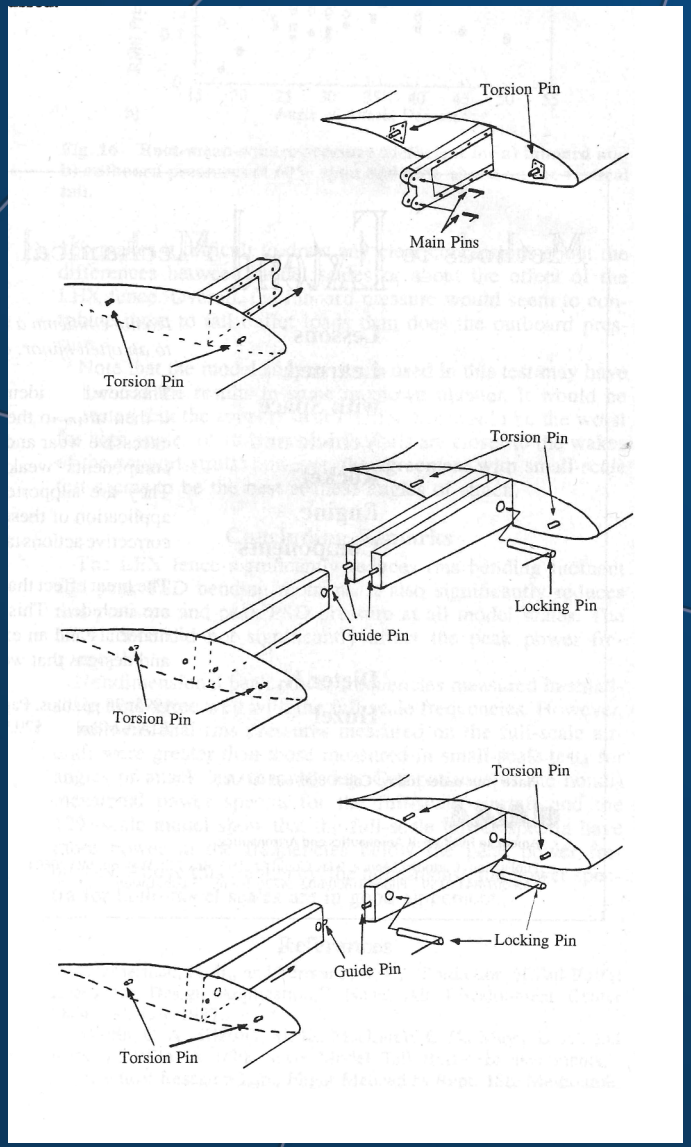




Bölkow Phönix T (1961)



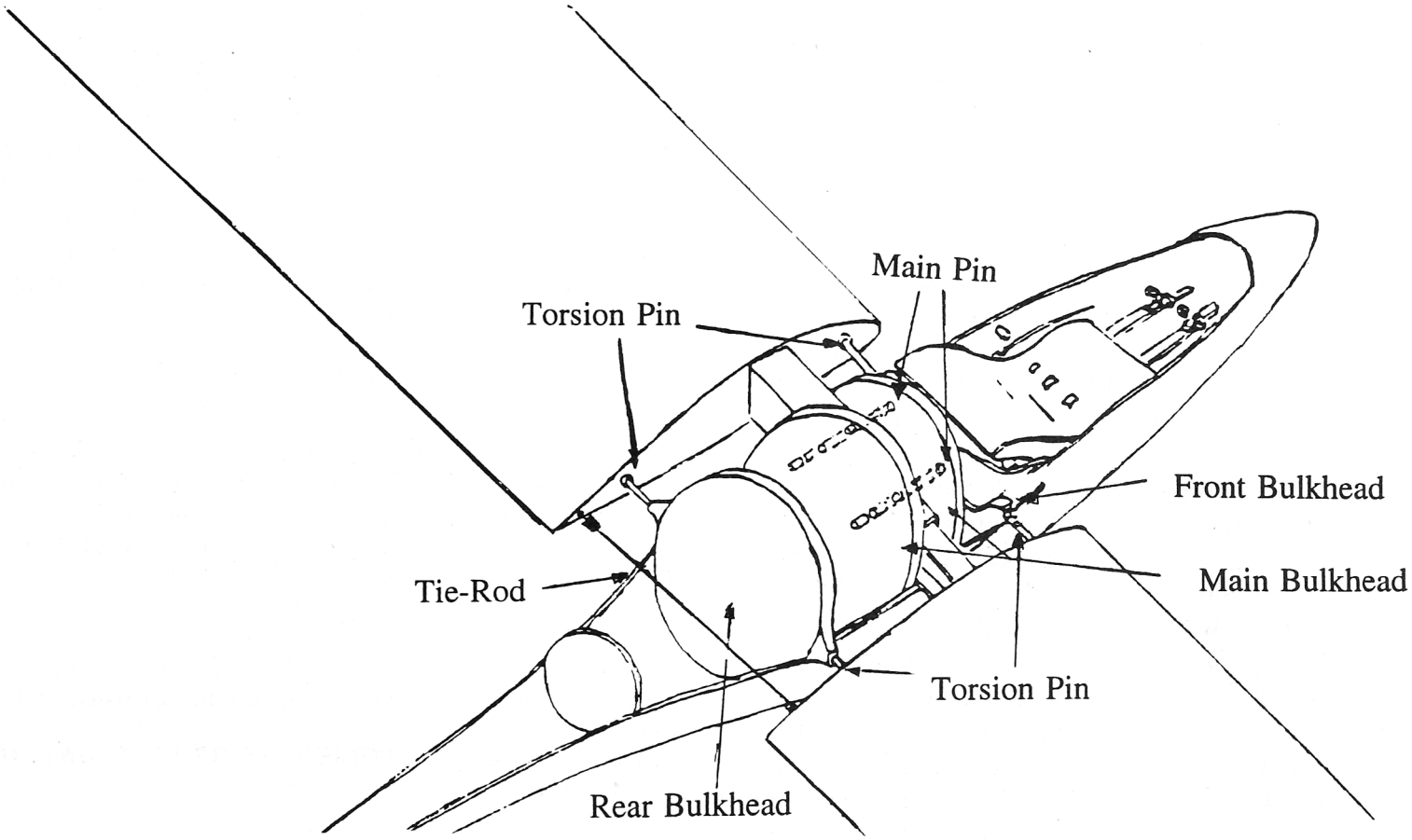
Wing Spar Carry-through



Traditional wooden
(circa 1950)

Fiberglass composite materials
(ca. 1972)

Graphite-reinforced-epoxy composite
(ca. 1988)



Box and beam spar carry-through of Rensselaer Polytechnic Institute RP-3 (ca. 1989)



Root connection



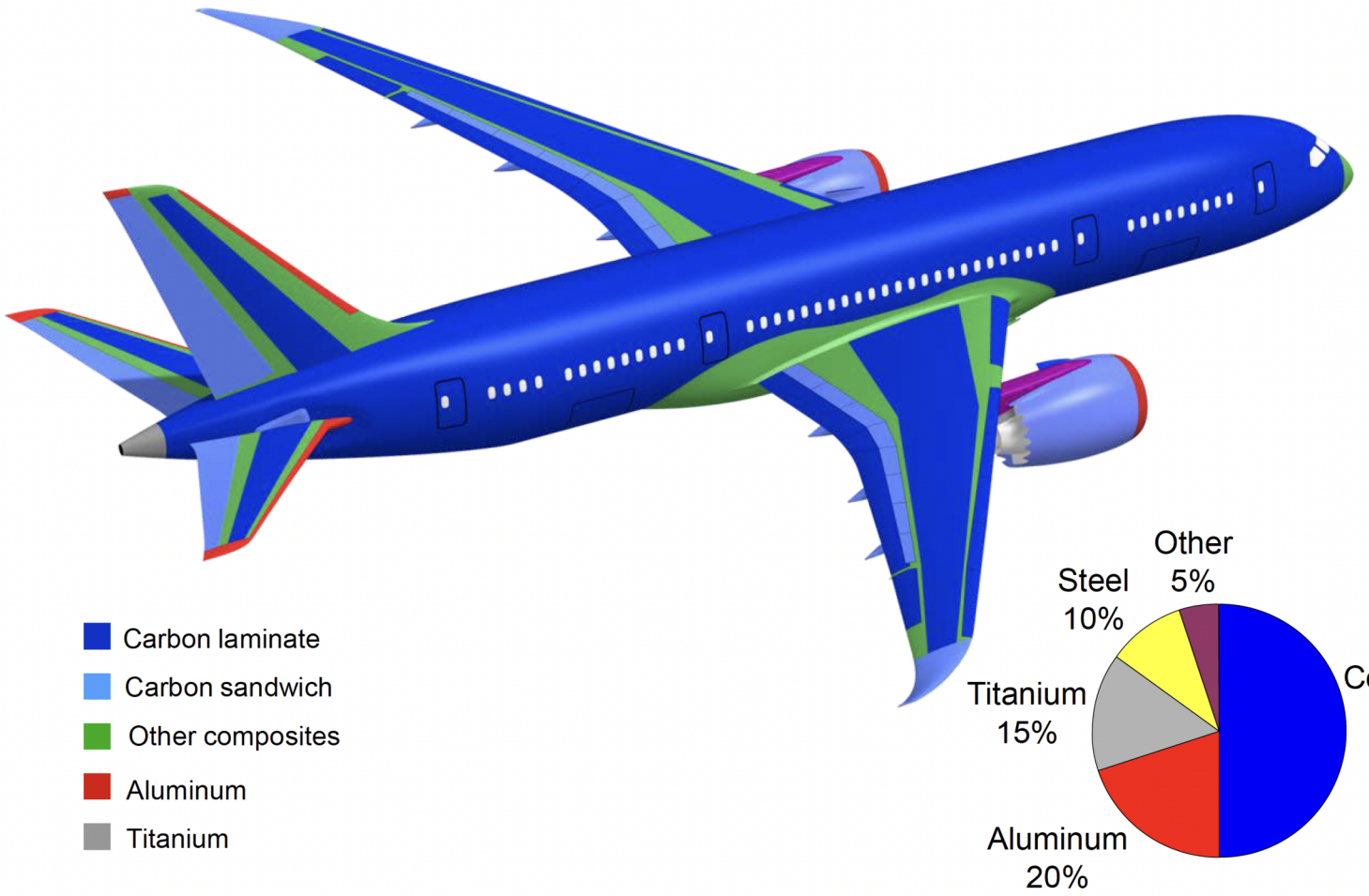
Outer end of inner panel



Outer panel connection to inner panel;

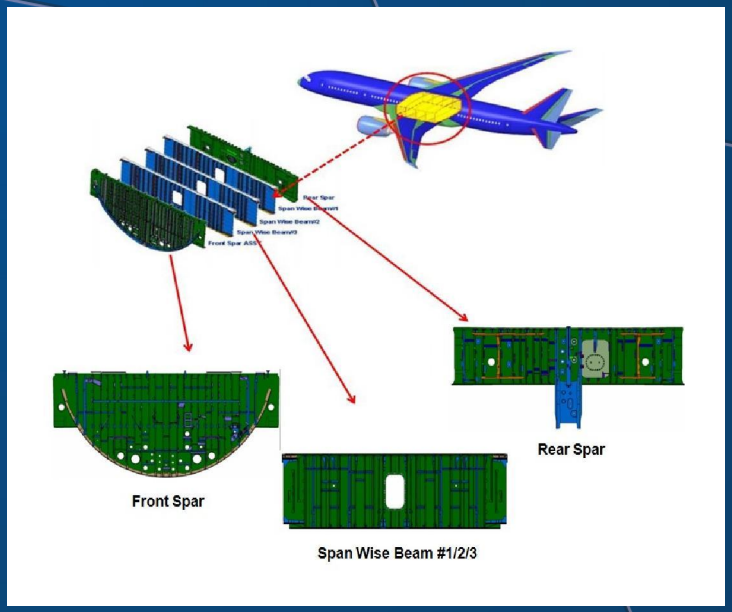


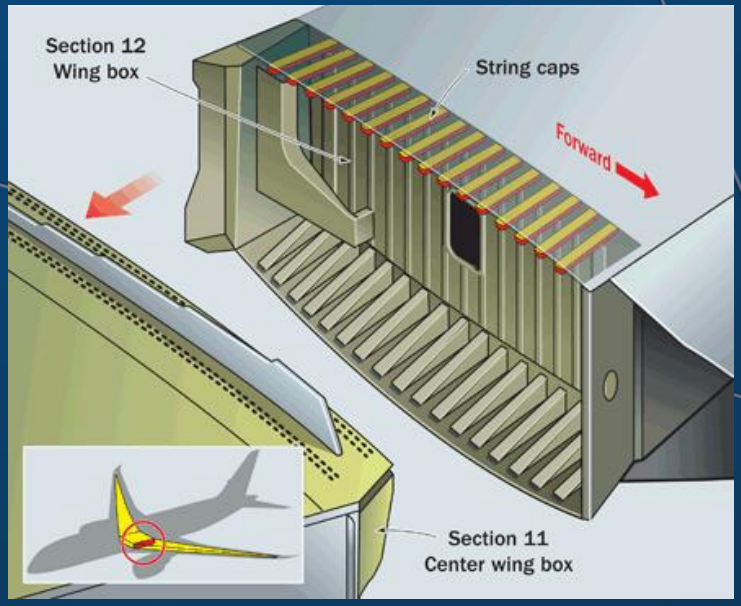
Tool used to insert pin into spar



Composite structure content of the Boeing 787 “Dreamliner”







Composite wing center box and wing box of Boeing 787 “Dreamliner”

Primary Question #4

Why have aircraft structures evolved from wood and fabric to metal monocoques to composites?

Wood

- Spruce
- Birch plywood
- Balsa

- Grain direction
  (Anisotropic, not isotropic)
- Moisture

Spruce : ribs, spars, stringers
Birch plywood: formers, wing skins
Balsa: wood “sandwich” construction

Stresses need to oriented along the grain
Moisture affects size, particularly across the grain
Joints must be constructed such that there are no stress risers

Fabric

- Extremely light
- Excellent in tension
- Almost no compression capability
- Needs a supporting framework

The structural usefulness of a material depends on how it is loaded

Aluminum Alloys

- Lightweight (35% of steel, 60% of titanium)
- Relatively strong (depends on alloy formula)
- Stiff (depends on configuration – sheet vs channel)
- Easily formed (bent, rolled, stamped, machined...)
- Subject to fatigue (even with low stresses)
- Subject to corrosion (particularly Galvanic)
- Can be riveted

Steel & Titanium

- High strength
- High density
- Formable
- Subject to corrosion

- High strength
- Lightweight
- Difficult to form
- Corrosion resistant

Localized high-load applications and fittings

Fiber Composites

- Glass fiber
- Carbon fiber
- Aramid fiber (Kevlar)
- Epoxy bonding

Fiber orientation

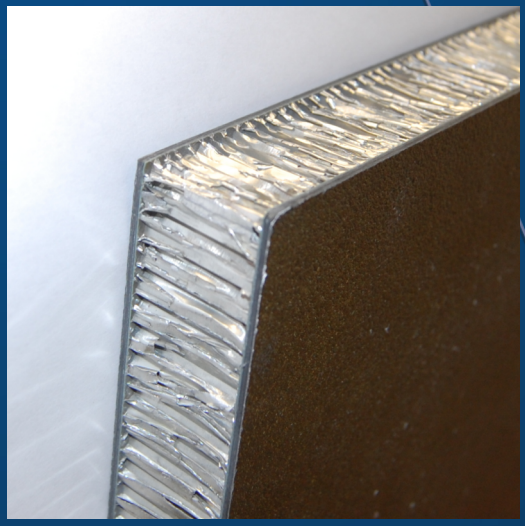
Laminate

“Sandwich” construction

“Sandwich” Construction

Skin + Core + Skin

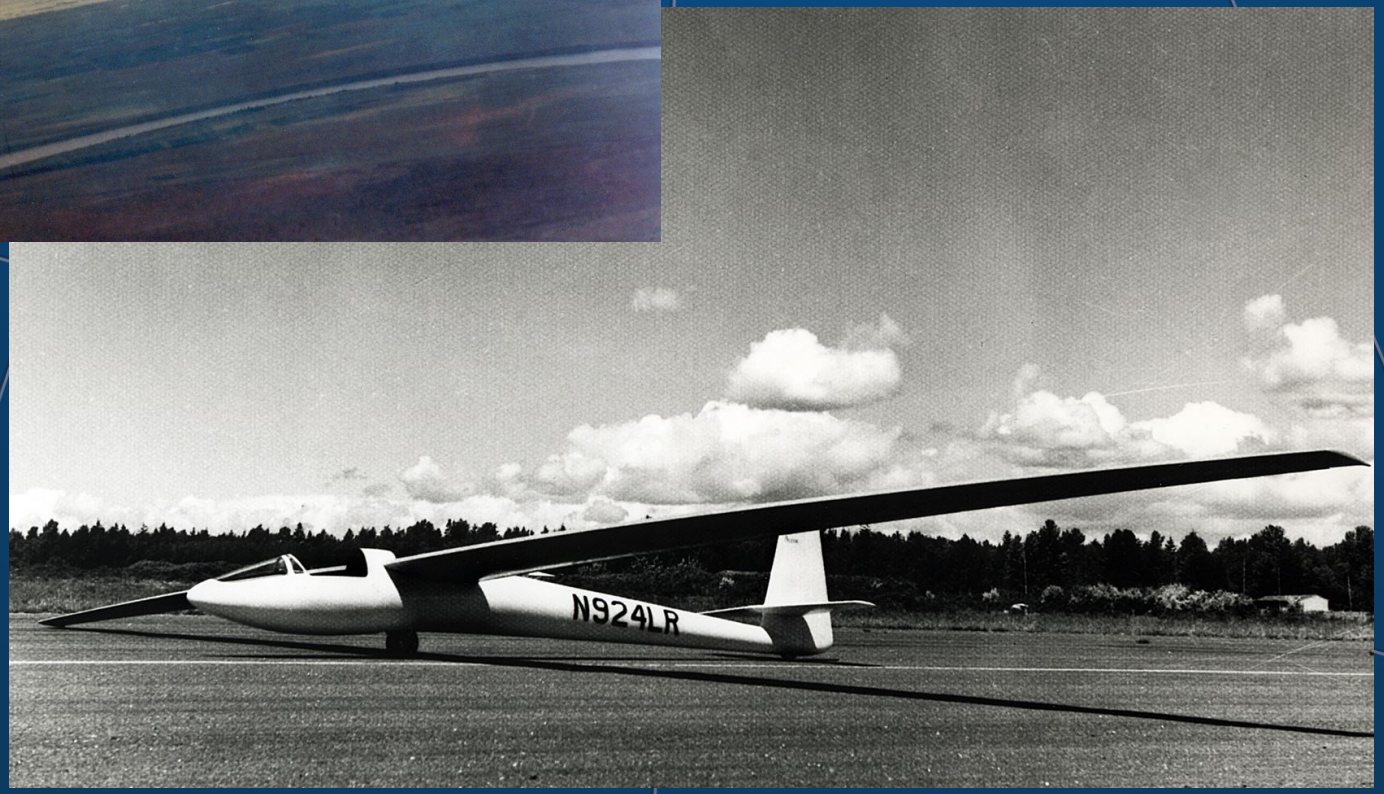
- Skin can be plywood, fiberglass or carbon
- Core can be honeycomb, rigid foam, end-grain balsa



- Similar to a conventional beam (spar) structure
- Horizontal shear loads are spread over a large area
- Susceptible to crushing under concentrated loads

Lamson L-106 Alcor





Looking Forward to Part 2

What happens when we take a full size aircraft and simply use the same materials and scale every dimension to 1/4?

- Does the structure have the same load paths?
- Is the weight 1/4?
- Are the loads 1/4 as great?
- Is the spar 1/4 as strong?
- Is the wing 1/4 as stiff?
- Is the Reynolds number 1/4 as large?

End of Part 1