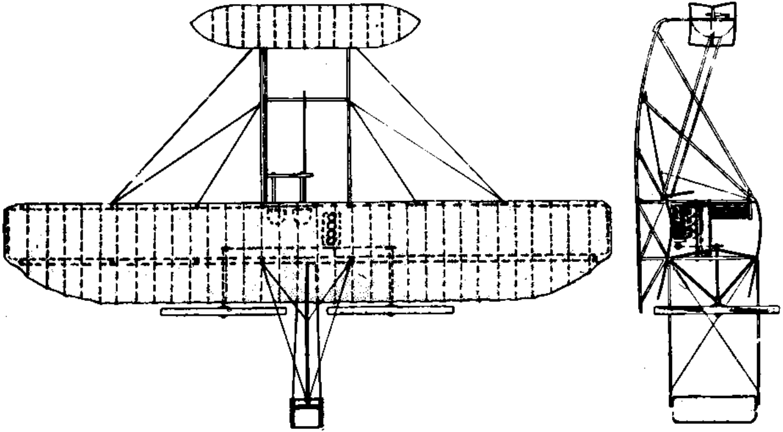
Aircraft Structures

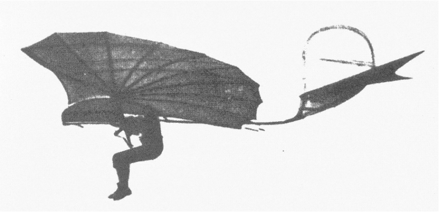
Ing. Simon Bergé

Maitre assistant, ISIB

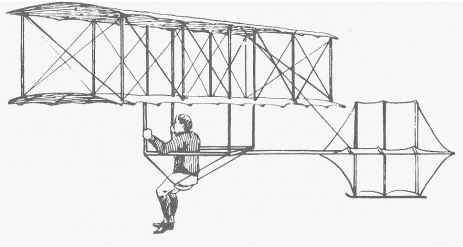
The trussed aeroplane



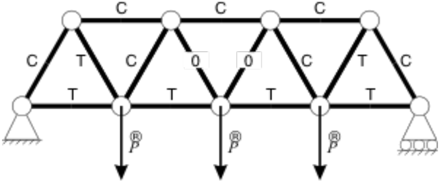
Dawn of the aeroplane



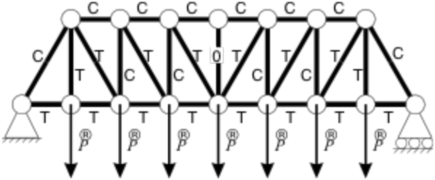
Lilienthal glider, 1894



Chanute glider, 1896

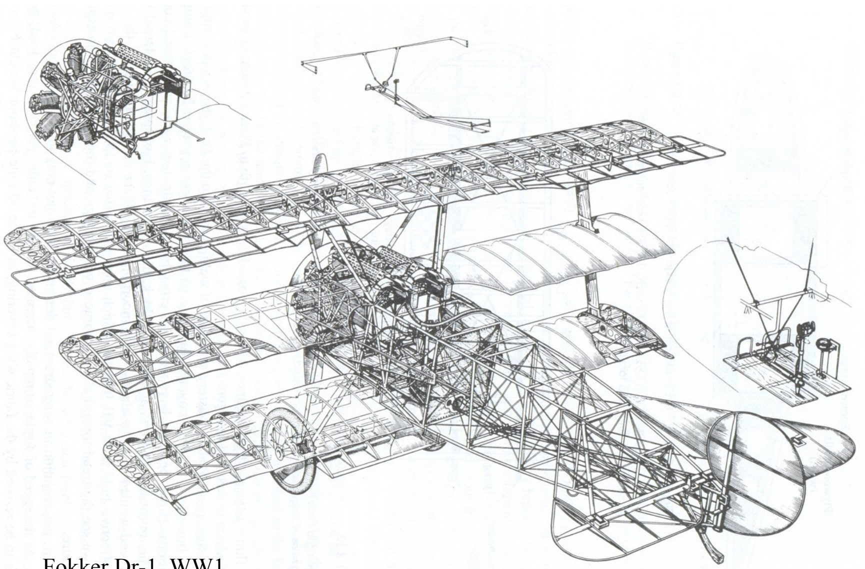


Warren bridge truss



Pratt bridge truss

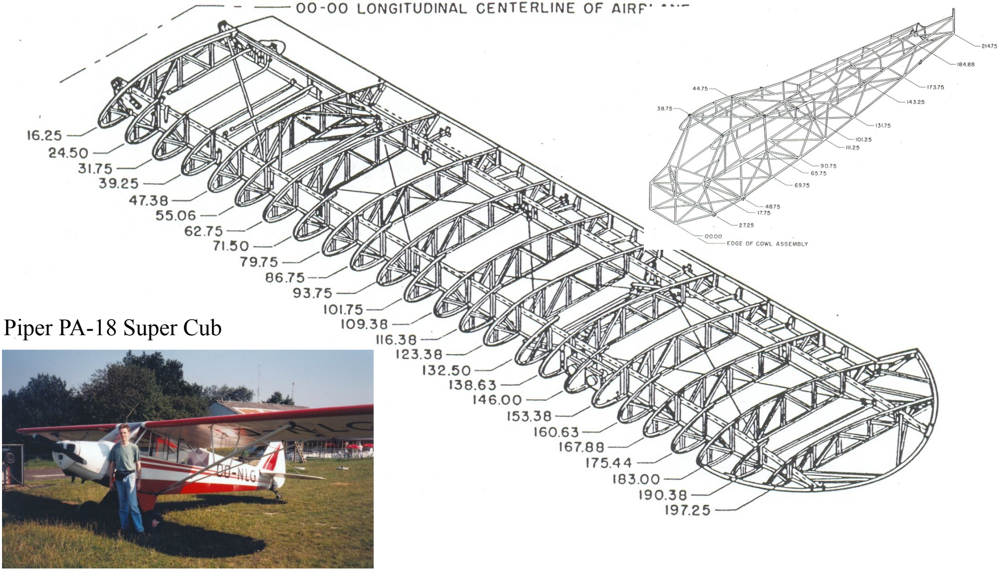
External brace / cantilever



Fokker Dr-1, WW1

Bleriot Model XI, 1909

1950s trussed aeroplanes



Piper PA-18 Super Cub

Exercise

Global sizing of a typical trussed wing

(CS-23 certification)

Piper PA-18 Super Cub

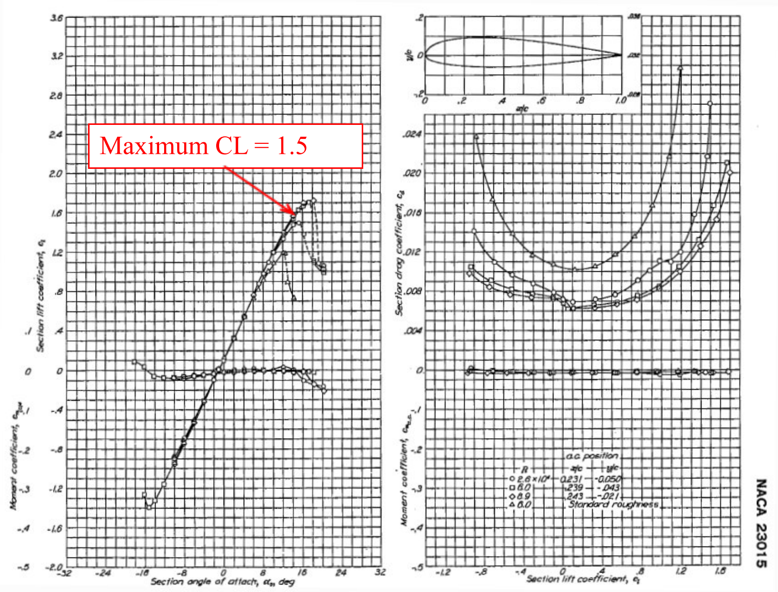
Basic problem

- Project guidelines
  - Your company plans to market an « old-timer » aeroplane, based on the famous Piper « Super Cub » (PA-18), but with updated engine technology.
  - You should perform a preliminary sizing of the wing structure.
  - The aeroplane is to be certified according to CS-23 standards (utility category).
  - Airfoil section is to be NACA 23015.

Reverse engineering

- Estimated performance data
  - Taken from the flight manuel
  - Maximum TO weight 1500 lbs
  - Wing span 35 feet
  - Wing chord 6 feet
  - Nominal stall speed 45 mph
  - Manoeuvring speed 95 mph
  - Maximum structural cruising speed 110 mph
  - Maximum diving speed 138 mph

Aerodynamic data



Expected speeds

- Unit conversions
  - CS documents are still using knots
  - 1 mph = 1.609 344 km/h
  - 1 kt = 1.852 km/h
  - 1 mph = 0.868 976 2 kt

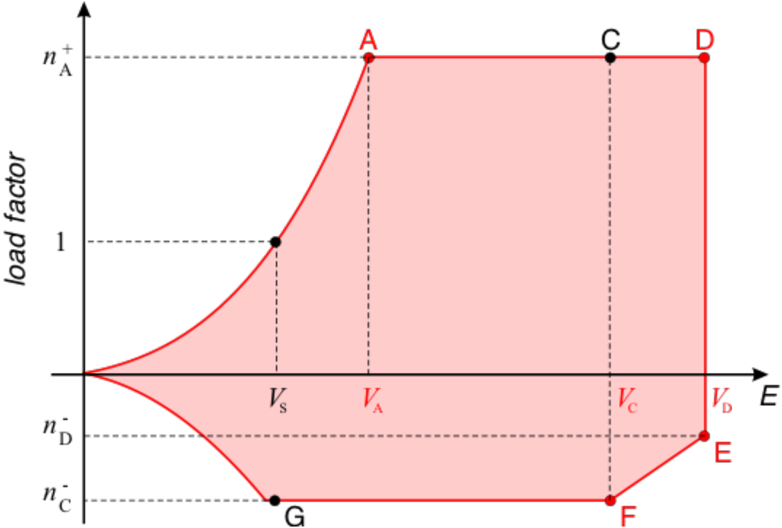
Speeds	Reported	Minimal CS 23	Final
Stall	39 kts		
Maneuvring (VA)	83 kts		
Cruising (VC)	96 kts		
Diving (VD)	120 kts		

Load envelope

- Each CS prescribes a V-n diagram
  - Loads are aero: they depend on speed
  - Loads are inertial: they depend on maneuvers
- Maneuvering envelope
  - Aka “V-n diagram”
  - Prescribes the ***load factors*** to withstand as a function of flight speed
  - n = actual lift / weight

Manoeuvring envelope

➢Typical CS-23 manoeuvring envelope



Manoeuvring envelope

- CS-23 specifications
  - Positive limit load factors
    - Normal and commuter $$n_A^{+} = 2.1 + \frac{24\,000}{W + 10\,000}$$
    - Utility $nA+ = 4.4$
    - Aerobatic $nA+ = 6.0$
  - Negative limit load factors
    - Normal and commuter $nC- = -0.4\, nA+$; $nD- = 0.0$
    - Utility $nC- = -0.4\, nA+$; $nD- = -1.0$
    - Aerobatic $nC- = -0.5\, nA+$; $nD- = -1.0$
- Our design
  - $nA+ = 4.4$; $nA- = -1.76$

Manoeuvring envelope

- CS-23 specifications
  - Design cruising speed VC
    - VC [kts] may not be less than

$$V_C < k\sqrt{W/S} \quad \text{lb/ft2)}$$

$$k = k_0 + \frac{k_{100} - k_{20}}{80}(W/S - 20)$$

- Normal, commuter, utility: $k20 = 33.0$; $k100 = 28.6$
- Aerobatic: $k20 = 36.0$; $k100 = 28.6$

    - VC need not be greater than 0.9 VH (max lvl spd @ max pwr)
- Our design
  - $W/S = 7.14$ lb/ft2
  - Thus, $k = 33.0$ so $VC > 88$ kts
  - We can choose $VC = 95$ kts

Manoeuvring envelope

- CS-23 specifications
  - Design diving speed VD
    - May not be less than 1.25 VC
    - May not be less than *k VC,min*
      - Normal, commuter: k20 = 1.4 ; k100 = 1.35
      - Utility: k20 = 1.5 ; k100 = 1.35
      - Aerobatic: k20 = 1.55 ; k100 = 1.35
- Our design
  - VD > 1.25 Vc = 1.25 x 95 = 119 kts minimum
  - VD > 1.50 Vc,min = 1.5 x 88 = 132 kts minimum

Manoeuvring envelope

- CS-23 specifications
  - Design maneuvring speed VA
    - VA [kts] may not be less than $V_S \sqrt{n_A^+}$
    - VA need not be greater than VC
  - Requires knowledge of the stall speed
- Our design
  - NACA 23015 has maximum *CL* of 1.5
  - VS can be estimated from baseline data
    - W = 1500 lb = 6675 N
    - S = 210 ft2 = 19.51 m2
    - VS = 19.3 m/s = 69.5 km/h = 37.5 kts so 39 kts is conservative
  - VA > 82 kts

Manoeuvring envelope

- CS-23 specifications
  - Design speed for maximal gust intensity VB
    - Commuter category only $V_S \sqrt{n_A^{\,+}}$
    - May not be less than the minimum of:
      - the intersection between the line of maximal normal force coefficient (stall line) and the line of rough air gust intensity
      - the intersection between the stall line and the line of strong gust intensity
    - VB need not be greater than VC
- Our design
  - Irrelevant (utility category)

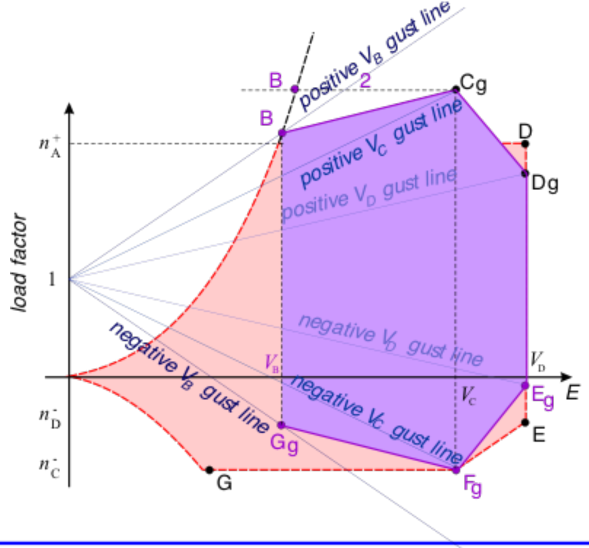
Final speed data

- Results of CS-23 definitions of minimum speeds
  - Note: CS-23 imposes VS < 61 kts.

Speeds	Reported	Minimal CS 23	Final
Stall	39 kts	61 kts	39 kts
Maneuvring (VA)	83 kts	82 kts	82 kts
Cruising (VC)	96 kts	88 kts	95 kts
Diving (VD)	120 kts	132 kts	132 kts

Gust envelope

➢ Typical CS-23 gust envelope



Gust envelope

- CS-23 specifications
  - Gust velocities for low-altitude (up to 20 000 ft)
    - Rough air: 66 fps (20.12 m/s)
    - Strong gust: 50 fps (15.24 m/s)
    - Weak gust: 25 fps (7.62 m/s)
  - Gust velocities for high-altitude (above 50 000 ft)
    - Rough air: 38 fps (11.58 m/s)
    - Strong gust: 25 fps (7.62 m/s)
    - Weak gust: 12.5 fps (3.81 m/s)
  - Gust velocities at intermediate altitudes
    - Linear interpolation between low- and high- bounds

Gust envelope

➢ CS-23 specifications

➢ Gust lines equation (all SI units):

- Based on the alleviated sharp-edged gust analysis concept

$$n_G = 1 \pm \frac{k_g \rho_0 U_g V a}{2\,(W/S)}$$

- Gust alleviation factor *kg*: given as a function of the aeroplane mass ratio μ*g*

$$k_g = \frac{0.88\,\mu_g}{5.3 + \mu_g}$$

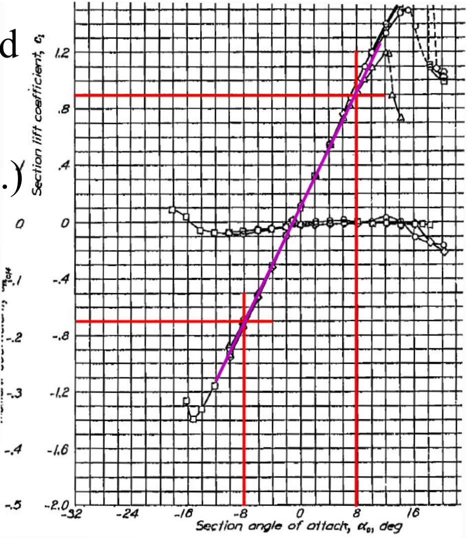
➢ Gust loads specifications:

- Weak gust to be accounted for at *VD* ;
- Strong gust to be accounted for at *VC* ;
- Rough air gust to be accounted for at *VB* *for commuter category only*

$$\mu_g = \frac{2\,(W/S)}{\rho\, c\, a\, g}$$

Wing lift data

- Airfoil lift coefficient
  - $ao = 0.1/° = 5.729$ /rad
  - $Cl = 0.1$ a + 0.1
  - $Cl,max = 1.5$ (approx.)
- Wing lift coefficient
  - Assume lifting line
  - Assume elliptic wing
  - AR = 5.83
  - $a = 4.365$ / rad
  - $CL = 0.0762$ a + 0.1



Gust envelope

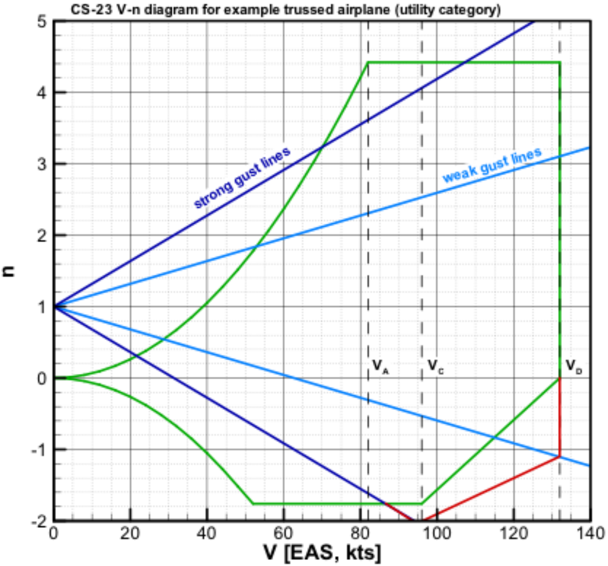
- Our design
  - $\mu g = 7.128$
  - $kg = 0.505$
  - $nweak = 1 + 0.03\ V$
  - $nstrong = 1 + 0.06\ V$

$$n_G = 1 \pm \frac{k_g \rho_0 U_g V a}{2\ (W/S)}$$

$$\mu_g = \frac{2\ (W/S)}{\rho\, c\, a\, g}$$

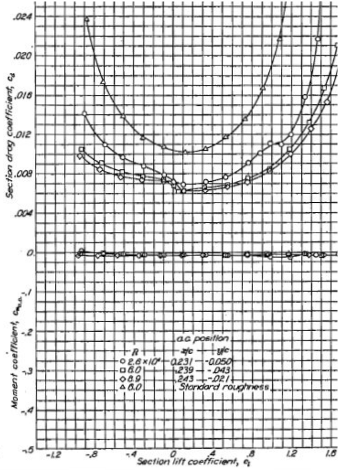
$$k_g = \frac{0.88\, \mu_g}{5.3 + \mu_g}$$

Final envelope



Loads for VA case

- Profile drag data
  - The VA condition is at maximum lift coefficient
    - *Vst* = 39 kts = 20.0 m/s
    - *CL,max* = 1.40
    - *Cd,f* = 0.018
- Moment data
    - *CL,max* = 1.40
    - *Cm,ac* = - 0.007



Loads for VA case

- Lift load
  - Load factor = 4.4
  - Lift = 4.4 x 6675 N = 29370 N
- Moment load
  - VA = 82 kts = 42.2 m/s
  - c = 6 ft = 1.82 m
  - Pitching moment = - 271 Nm

Loads for VA case

- Drag load
  - Shape drag
    - VA = 82 kts = 42.2 m/s
    - $CD\text{o} = Cd,f = 0.018$
  - Induced drag
    - Aspect ratio 5.83, Oswald efficiency 0.845
    - $CL,max = 1.40$
    - $CD,i = 0.1266$
  - Total drag = 3033 N

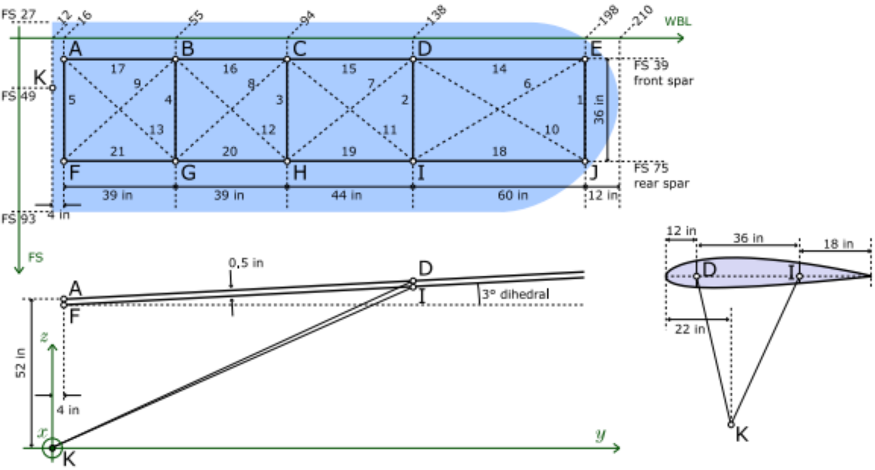
Structural loads

- Simplified approach
  - Neglect wing actual geometry
  - Consider only aircraft angle of attack
    - $CL = 0.0762\ a + 0.1$
    - Angle of attack at maximum CL is 17°
  - Transform loads in structural reference frame
    - $N = L \cos a + D \sin a = 28\,973$ N
    - $T = D \cos a - L \sin a = -\,5686$ N
    - « drag » (force tangent to airfoil) is negative; this is called « antidrag »

Structural loads

- Load summary
  - Lift = 29370 N
  - Drag = 3033 N
  - Pitching moment = - 271 Nm
- Actual wing geometry
  - Wing dihedral angle 3°, no twist
  - Wing angle of incidence t.b.c. (about 0.5°)
  - Detailed geometry follows

Proposed structural layout



Approximate loading

- Hypothesis for preliminary design
  - Load normal to wing surface (positive in lift)
    - Constant from WBL 12 to strut hinge (D and I)
    - Linear decrease from strut hinge to tip (WBL 210)
    - Tip value is half of root value
    - Applied at the aerodynamic centre (25% c)
  - Load tangent to wing surface (positive in drag)
    - Spanwise constant from WBL 12 to WBL 210
    - Applied on the rear beam
  - Pitching moment (positive nose up)
    - Spanwise constant

Distributed loading

- Load summary
  - Perpendicular to wing surface
    - Constant distributed force 20 lb/in to strut end
    - Decreasing distributed force to 10 lb/in outboard
  - In-plane loads
    - Constant distributed force –2.2 lb/in (antidrag!!)
  - Aerodynamic pitching moment
    - Constant distributed moment –6.5 lb in/in
    - Reference point for moment is AC (25% chord)