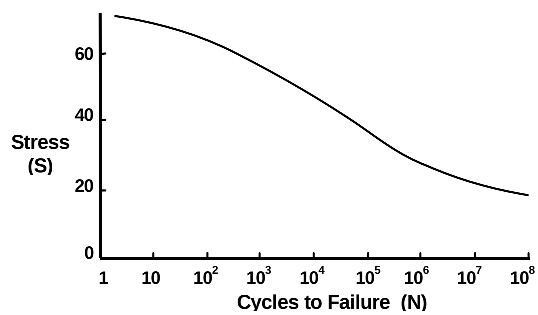
Section 9 Material Strength

Section 9 Abbreviations

A	cross-sectional area (ft^2)
DLL	design load limit
E	modulus of elasticity or Young's Modulus (lb/ft^2)
e	strain (non-dimensional)
EK	gage factor
GW	gross weight
KU	effective gust velocity (ft/sec)
L	lift force
L	length (ft)
N_{zb}	normal load factor, along aircraft z-axis
P	applied load (lb)
R	unstrained resistance
ΔR	change in resistance due to load
S	wing area (ft^2)
V	flight speed
V_s	stall speed
V_e	equivalent airspeed
W	aircraft weight
W/S	wing loading
ν	Poisson's ratio
σ	stress (lb/ft^2)
σ	air density ($slugs/ft^3$)

9.1 Loads Terminology

Annealing	A heat treatment that eliminates the effects of cold working.
Brittleness	Measure of a material's lack of ductility (by one definition breakage at five percent or less strain implies brittleness.
Creep rate	The rate at which a material continues to stretch when stress is applied at high temperature.
Cold Working	Deformation of a metal below its recrystallization temp., thereby strengthening and reshaping it.
Design Load Limit	Maximum loads expected in normal service.
Ductility	Ability of a material to deform without breaking.
Durability	Ability to resist cracking, corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage over time.
Elastic Deformation	Deformation of the material that is recovered when the applied load is removed.
Elasticity	Ability of a material to return to its undeformed shape after all loads have been removed.
Endurance Limit	The stress below which a material will not fail in a fatigue test.
Factor of Safety	Ratio of the predicted failure stress to the maximum stress anticipated in normal operation (*DLL*). For aircraft, the Factor of Safety is typically 1.5 *DLL*.
Fatigue	The failure of a material when subjected to repeated loads less than the ultimate sustainable load. This effect is presented in an *S-N* diagram such as



Fatigue life The number of cycles at a particular stress before a material fails by fatigue.

Hardness Resistance to plastic deformation resulting from impact loads.

Impact Energy The energy required to fracture a specimen when the load is suddenly applied.

Limit Stress The maximum stress where the Modulus of Elasticity remains constant (proportional limit).

Margin of Safety Any load-bearing capability greater that the ultimate load, calculated as

$$\frac{\text{failure load as a factor of } DLL}{1.5\, DLL} - 1$$

Notch Sensitivity Measure the effect of a notch on impact energy

Plastic Deformation Permanent deformation of a material applied load. Plasticity Material deformation charac teristics beyond its elastic limit.

Resilience A measure of the amount of energy a material can absorb elastically in a unit volume of the material.

Rupture time The time required for a specimen to fail by creep at a particular temperature and stress.

Stiffness A qualitative of the elastic deformation produced.

Strain (e) The deformation of a material under an applied load.

Strength Ability to withstand external loads without failure.

Stress (σ) The ability of a material to react a force distributed over some area.

Thermal stress Stress resulting from expansion (strain) of a material subjected to heating.

Tempering A low-temp. heat treatment which reduces hardness.

Tensile strength The stress that corresponds to the maximum load in a tensile test.

Toughness Total energy absorbed before failure occurs (area under the stress-strain curve).

Transition Temperature The temperature below which a material behaves in a brittle manner in an impact test.

True Strain The actual strain produces when a load is applied.

Ultimate Stress The stress point at which additional load cannot be reacted.

Wing Loading Aircraft weight per wing area, W/S, a ready measure of air loads for steady level flight.

Yield Stress The stress applied to a material that just causes permanent plastic deformation.

9.2 Material Stress & Strain

Stress (σ) is the ability of a material to react a force distributed over some area. In the simple axial load case this can be presented as

$$\sigma = P/A$$

where P = the applied axial load
A = cross-sectional area over which the load is applied

Strain (e) is the deformation of a material under an applied load. In the basic form this can be presented as

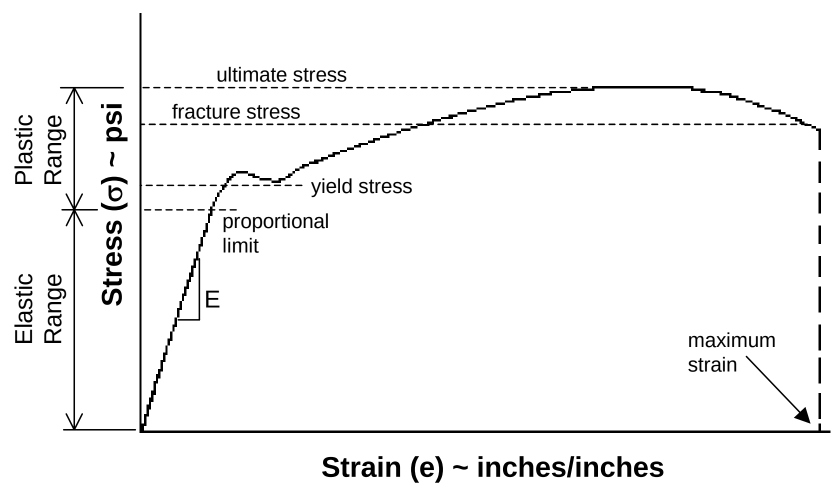
$$e = \Delta L/L$$

where ΔL is the change in dimension due to some load, and L is the original dimension

The *stress-strain relationship* is linear (proportional) for a large percentage of the applied load to the maximum, as expressed by the *Modulus of Elasticity* (*Young's Modulus*)

$$E = \sigma/e$$

A typical stress & strain relationship for a material is illustrated as



9.3 V-n Diagram

Flight Path Normal Load Factor (N_{zw}) can be expressed during level flight, as

$$N_{zw} = 1/cos\phi = L/W$$

where C_L = lift coefficient
F_n = net thrust
L = lift force = wing lift + thrust lift = $C_L qS + F_n sin\alpha_F$
q = dynamic pressure
S = wing area
W = gross weight
α_F = incidence angle between thrust line and relative wind
ϕ = angle of bank

Body Axis Normal Load Factor (N_{zb}) is calculated as

$$N_{zb} = [N_{zw} - N_{xb}\sin\alpha]/\cos\alpha$$

where N_{zb} = load factor along aircraft body x-axis
α = angle of attack

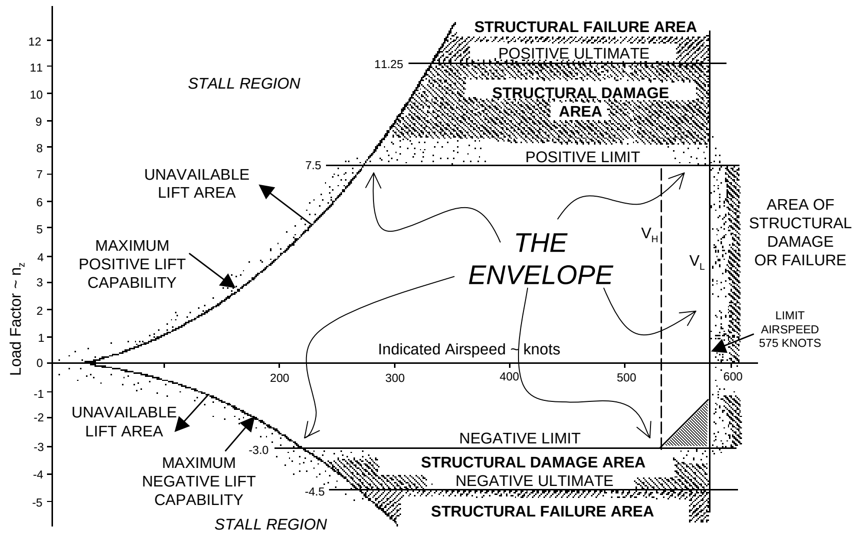
For the simplified case of negligible thrust lift, the maximum achievable N_{zb} at any flight speed can be calculated as

$$N_{zb} = (V/V_s)^2$$

where both speed must be the same units
(i.e., true, equivalent, calibrated)
V = flight airspeed
V_s = stall speed

A general normal load flight envelope (V-n diagram) would appear as

- The envelope typically varies with: asymmetric loading; aircraft configuration; for air loads other than along the normal axis; and other structural, system, and safety considerations.



- It is frequently desirable to correct measured (test) N_{zb} data to a standard weight or design gross weight (*GW*) using the relationship

$$N_{zb} = (\text{test } N_{zb})(W_t/W_s)$$

where W_t = test weight
W_s = standard weight

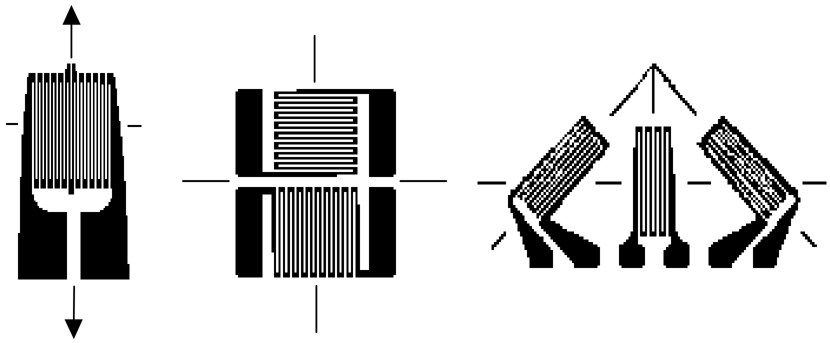
- The increase in load factor due to a vertical gust (Δn) is calculated as

$$\Delta n = 0.115 m V_e (KU)/(W/S)$$

where m = slope of $C_{L\alpha}$ curve
V_e = equivalent airspeed (knots)
KU = effective gust velocity (fps)
W/S = wing loading (psf)

9.4 Strain Gages

The three strain gage configurations most commonly used are



Strain (e) is measured using the electrical resistance measured via the strain gage in a material subject to load. For the uniaxial gauge

$$K = (\Delta R/R)/e$$

where K = gage factor (provided by manufacturer)
R = unstrained resistance
ΔR = change in resistance due to load
(+ΔR for tension)

- For the bi-axial gage oriented coincident with the principal axes (maximum strain), each leg of the gage is analyzed as a uniaxial gage using the above equation for the principle strains. The associated stresses are

$$\sigma_{max} = E(e_{max} + \upsilon e_{min})/(1 - \upsilon^2)$$
$$\sigma_{min} = E(e_{min} + \upsilon e_{max})/(1 - \upsilon^2)$$

where e_{max} and e_{min} are the measured principal strains in the appropriate legs of the bi-axial gage,
E is the Young's Modulus of the material, is Poisson's ratio for the material.
(ratio of compression and tension strains)

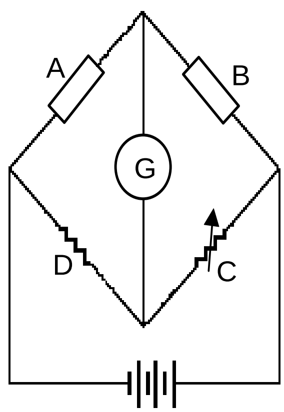
- For the Rosette gage, the principal strains and stresses are derived as

$$e_{max,\ min} = 0.5(e_a + e_c) \pm 0.5\sqrt{(e_a - e_c)^2 + (2e_b - e_a - e_c)^2}$$

$$\sigma_{max,\ min} = E/2\left[(e_a + e_c)/(1 - u)\right] \pm \sqrt{(e_a - e_c)^2 + (2e_b - e_a - e_c)^2}/(1 - u)$$

where *e*'s denote the strains in each of the three legs of the Rosette (+ is used for the maximum and - for the minimum).

To accurately measure the very small resistance changes in a strain gage, a *Wheatstone Bridge* is typically used



A = active or strain-measuring gage
B = temperature compensating (dummy) gage
C = D = internal resistance in instrument
G = galvanometer

9.5 References

9.1 Dole, Charles E., *Fundamentals of Aircraft Material Factors*, University of Southern California, Los Angeles, California, 1987.

9.2 Norton, William J., *Structures Flight Test Handbook*, AFFTC-TIH-90-001, Air Force Flight Test Center, Edwards AFB, California, November 1990.

Additional Reading

Military Specification Airplane Strength and Rigidity - *General Specification*, MIL-A-8860.

Military Specification Airplane Strength and Rigidity, Sonic Fatigue, MIL-A-008893.

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