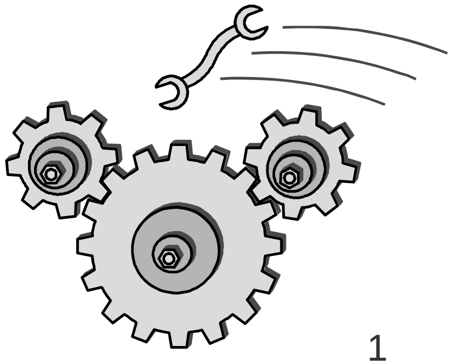
Chapter 8
Design for Reliability

8.1 Reliability Specification

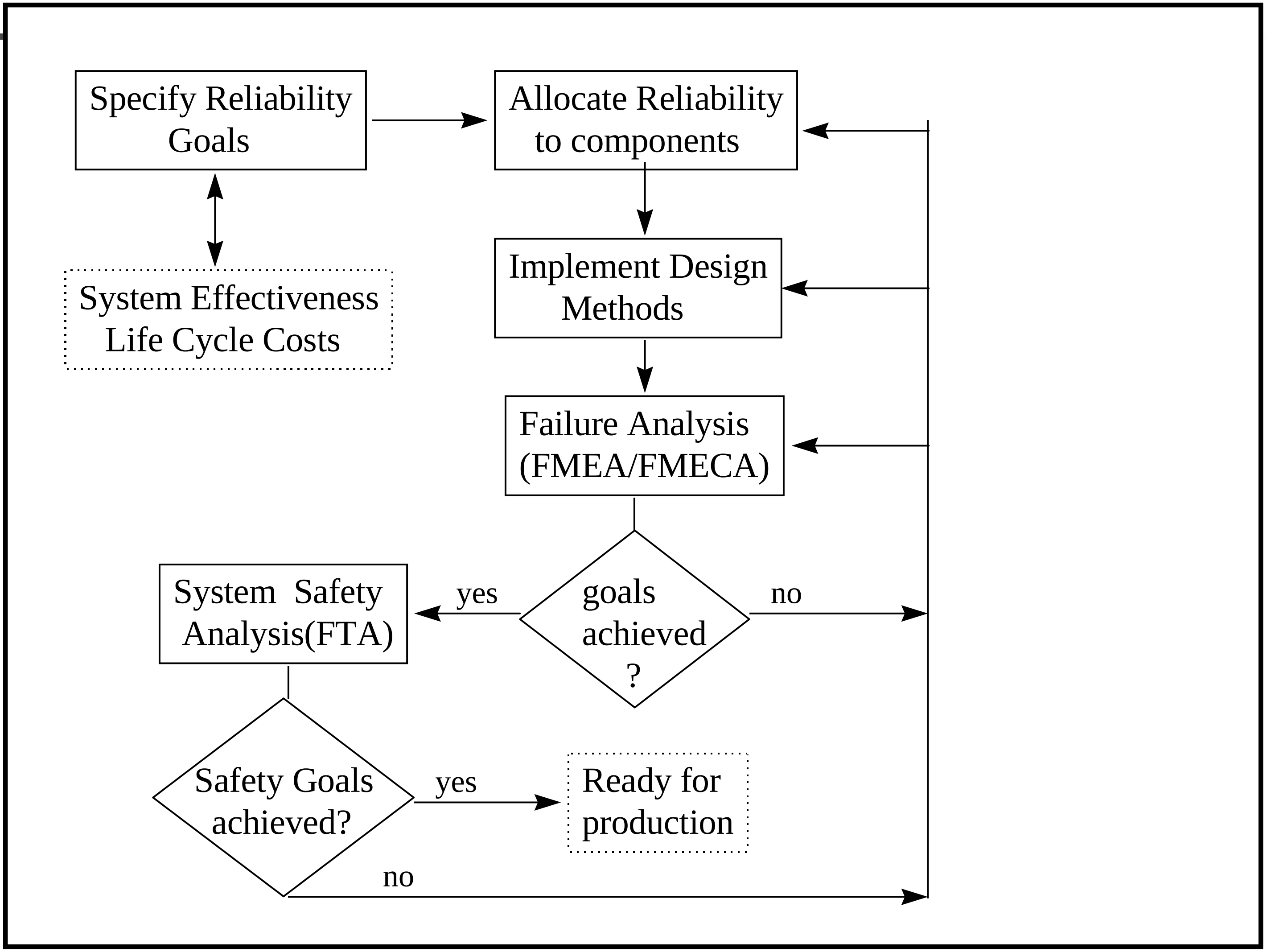
8.2 Reliability Allocation

8.3 Design Methods



8.1 Reliability Specification

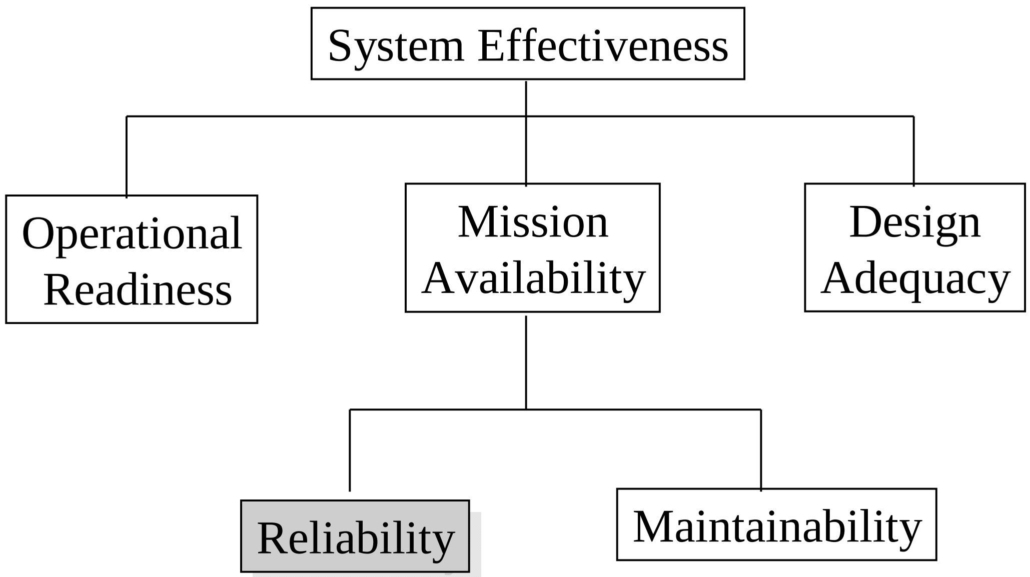
The Reliability Design Process



Reliability Activities & Product Life Cycle

Development Phase	Conceptual & Preliminary Design	Detailed Design, Development & Prototyping	Production & Manufacture	Product Use & Support
	Specification Allocation Design Methods	Design Methods Failure Analysis Growth Testing Safety Analysis	Acceptance test Quality Control Burn-in & Screen Testing	Preventive & Predictive Maintenance Modifications Parts Replacement

System Effectiveness



Life Cycle Cost Categories

Acquisition Costs	Operations and Support Costs	Phase-out
Research and Development	**Operations**	Salvage value
Management	Facilities	Disposal Costs
Engineering	Operators	
Design and Prototyping	Consumables (energy & fuel)	
Engineering Design	Unavailable time or downtime	
Fabrication	**Support**	
Testing & evaluation	Repair resources	
Production	Supply resources	
Manufacturing	repairables	
Plant facilities & overhead	expendables	
Marketing & Distribution	tools, test & spt equip	
	Failure Costs	
	Training	
	Technical Data	

Life Cycle Cost

LCC = Acquisition Costs + Operations Costs + Failure Cost + Support Costs - Net Salvage Value

where Net Salvage Value = Salvage Value - Disposal Cost

Discount Monetary Values

8.2 Reliability Allocation

In general: $h(R_1(t), R_2(t), \ldots, R_n(t)) \geq R^*(t)$

where $R_i(t)$ is the reliability at time t of the ith component,

and $R^*(t)$ is the system reliability goal at time t.

or $g(MTTF_1, MTTF_2, \ldots, MTTF_n) \geq MTTF^*$

For series related components: $$\prod_{i=1}^{n} R_i(t) \geq R^*(t)$$

Exponential Case

$$\prod_{i=1}^{n} e^{-\lambda_i t} \geq R^*(t)$$

$$\sum_{i=1}^{n} \lambda_i \leq \lambda_s$$

ARINC Method

Assume components are in series, are independent, and have constant failure rates.

$$\text{new } \lambda_i = w_i \lambda^*$$

$$w_i = \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i} \quad i = 1, 2, \ldots, n \text{ ; since}$$

$$\sum_{i=1}^{n} \text{new } \lambda_i = \sum_{i=1}^{n} w_i \lambda^* = \sum_{i=1}^{n} \frac{\lambda_i \lambda^*}{\sum_{i=1}^{n} \lambda_i} = \frac{\lambda^*}{\sum_{i=1}^{n} \lambda_i} \sum_{i=1}^{n} \lambda_i = \lambda^*$$

AGREE Method

t = system operating time

$R^*(t)$ = system reliability goal at time t

n = number of components

n_i = the number of modules within component i

N = total number of modules in system = Σn_i

t_i = the operating time of the ith component, $t_i <= t$

λ_i = the failure rate of the ith component

w_i = the probability the system will fail given component i has failed

Allocating an equal share of the reliability to each module results in component i’ s contribution to the system reliability being

$$[R^*(t)]^{\frac{n_i}{N}}$$

AGREE Method

$$w_i(1-e^{-\lambda_i t_i}) = 1 - [R^*(t)]^{\frac{n_i}{N}}$$

$$\lambda_i = -\frac{1}{t_i}\ln\left(1-\frac{1-R^*(t)^{n_i/N}}{w_i}\right)$$

note that $\prod_{i=1}^{n} e^{-\lambda_i t_i} \le R^*(t)$

AGREE Method - Example

Component	Import Index (w_i)	Oper hrs (t_i)	Nbr of modules -n_i
Receiver	.8	1000	25
Antenna	1	1000	15
Transmitter	.7	500	23
Power Supply	1	1000	70

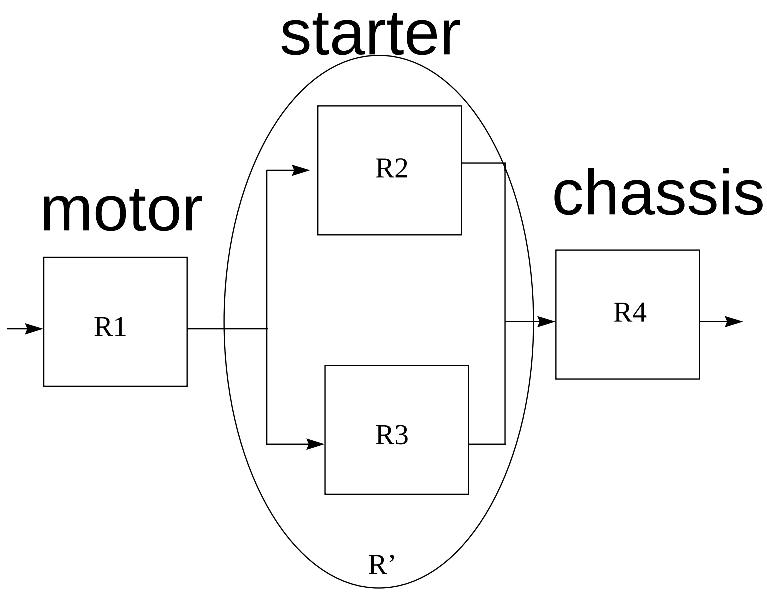
The total module count is 133. If the system reliability goal is .99, then the reliability to be allocated to the ith component is $.99^{ni/133}$.

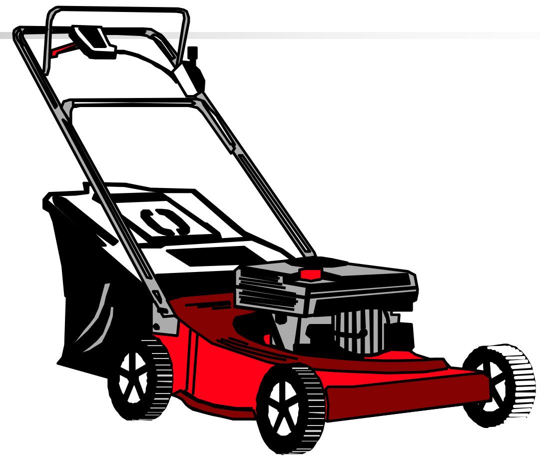
AGREE Method - Example

Component	Failure Rate	MTTF	Reliability	System Rel
Receiver	2.362 x 10-6	423,369	.99764	.99811
Antenna	1.1335 x 10-6	882,227	.99887	.99887
Transmitter	4.9676 x 10-6	201,303	.99752	.99826
Power Supply	5.2896 x 10-6	189,048	.99472	.99472
System	1.3753 x 10-5	72,713	.98879	.99

From the above table, the probability of a component failure is 1-.98879 while the probability of a system failure is 1-.99.

Redundancy





$$R^* = R1 \times R' \times R4$$

$$R' = 1 - (1 - R2)(1 - R3) = R2 + R3 - R2\,R3$$

$$R_2 = \frac{R' - R_3}{1 - R_3}$$

or $R' = 2R - R^2$

with solution $R = 1 - (1 - R')^{.5}$

8.3 Design Methods

Parts and Material Selection

Derating

Stress-Strength Analysis

Complexity

Choice of Technology

Redundancy

Material Selection

Structure
atomic bonding
crystal structure
defect structure
microstructure

MATERIALS SCIENCE →

Material Properties
yield strength
hardness
fatigue life
creep

MATERIALS ENGINEERING

Manufacturing Process
casting
machining (cutting)
joining
heat treatment
assembly

MANUFACTURING ENGINEERING

← **Service Performance**
Stresses
corrosion
temperature
radiation
vibration

R(t)

Design Methods
Parts and Material Selection

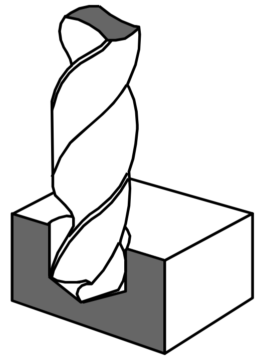
Tensile Strength

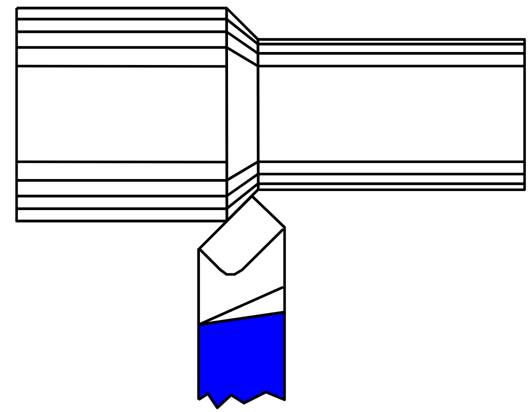
Hardness

Impact Value

Fatigue Life

Creep





Property of Materials

Metals

Composites

Polymers

Ceramics

Material Selection

Metals	Ceramics	Polymers
strong	strong	weak
stiff	stiff	compliant
tough	brittle	durable
electrically conducting high thermal conductivity	electrically insulating low thermal conductivity	electrically insulating temperature sensitive

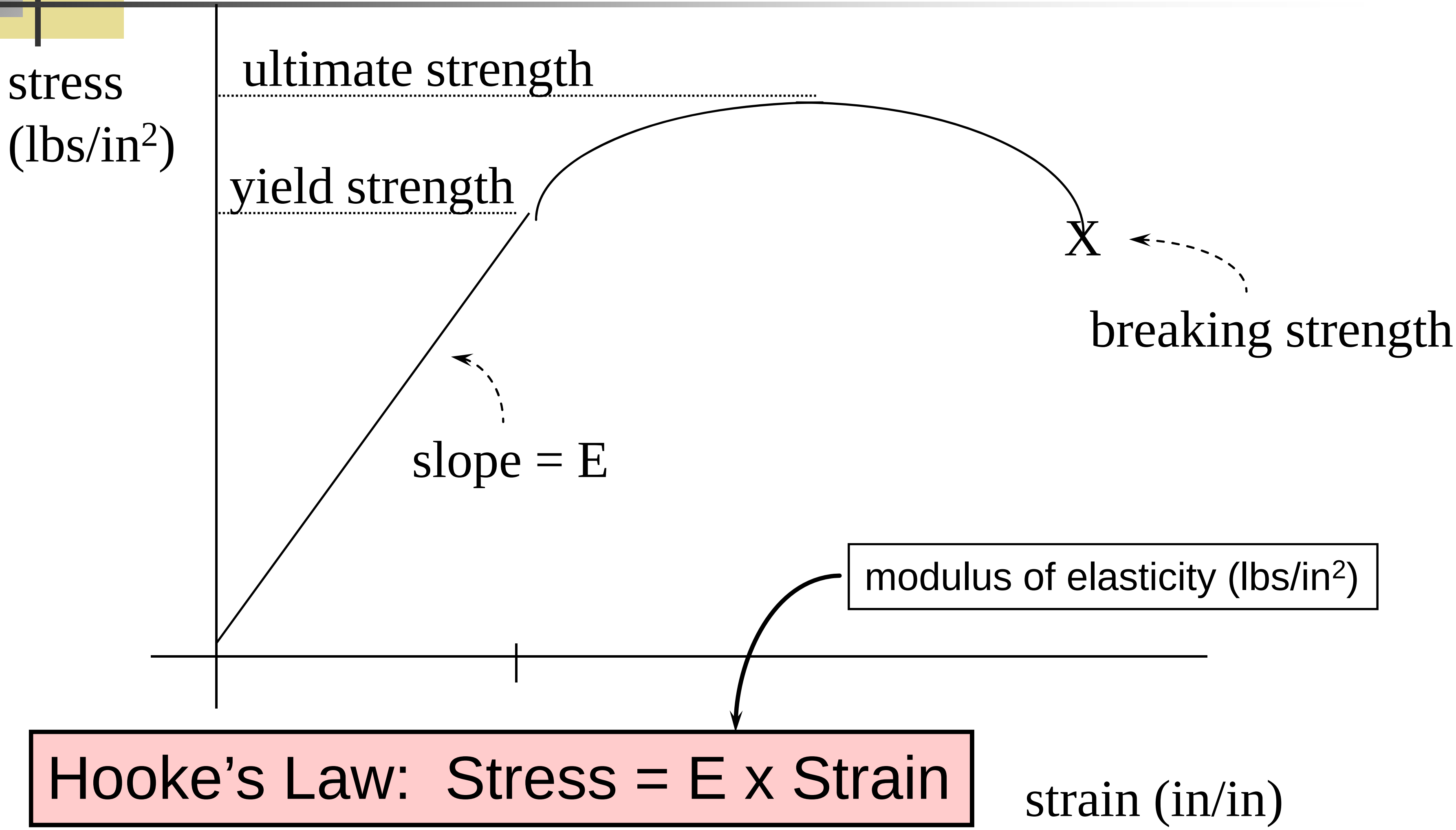
Tensile strength

Tensile strength measures the force required to pull something such as rope, wire, or a structural beam to the point where it breaks.

- Specifically, the maximum amount of stress that it can be subjected to before failure
- Yield strength - The stress a material can withstand without permanent deformation.
- Ultimate strength - The maximum stress a material can withstand.
- Breaking strength - The stress coordinate on the stress-strain curve at the point of rupture.

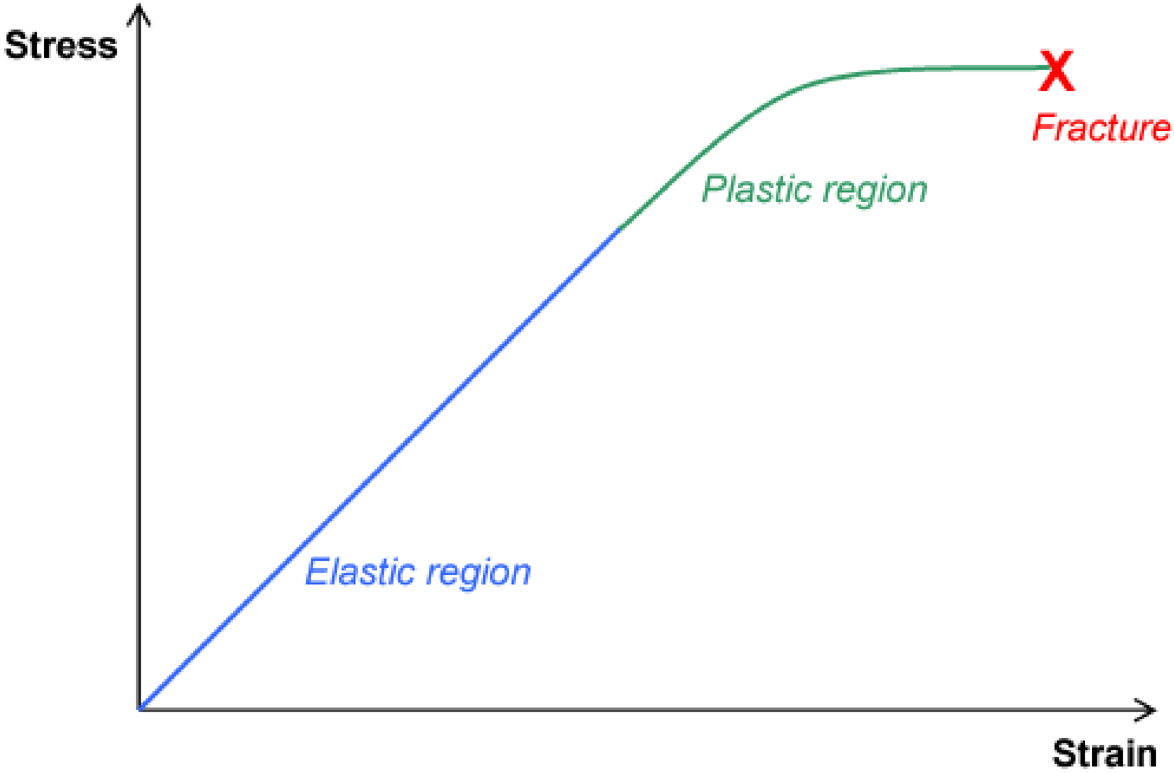
Compressive strength is the capacity of a material to withstand axially directed **pushing** forces. When the limit of compressive strength is reached, materials are crushed. Concrete can be made to have high compressive strength.

Parts and Material Selection
Tensile Strength



Hooke's Law: Stress = E x Strain

Another Stress-Strain Curve



Hardness

MINERAL	HARDNESS	COMMON TESTS
Talc	1	Scratched by fingernail
Gypsum	2	
Calcite	3	Scratched by copper coin
Fluorite	4	Scratched by a knife blade or window glass
Apatite	5	
Feldspar	6	Scratches a knife blade or window glass
Quartz	7	
Topaz	8	
Corundum	9	
Diamond	10	Scratches all common materials

resistance of material to the penetration of an indenter - used in analyzing service wear.

Brinell - B_{hn} (kg/mm_2)

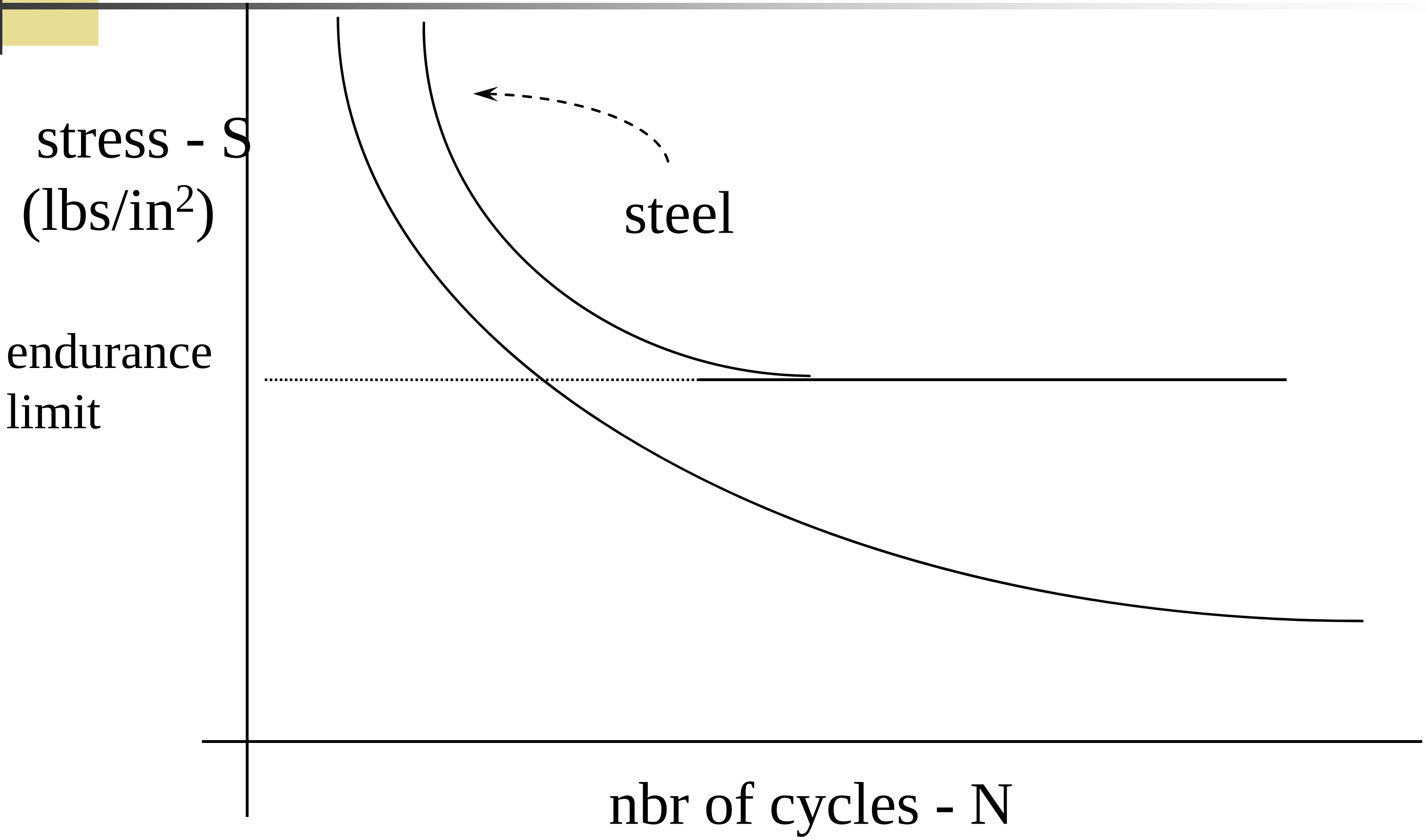
Rockwell - R

Vickers - V_{hn}

Fatigue

- The progressive, localized, and permanent structural damage that occurs when a material is subjected to cyclic or fluctuating strains at nominal stresses that have maximum values less than the static yield strength of the material.
  - The resulting stress may be below the ultimate tensile stress, or even the yield stress of the material, yet still cause catastrophic failure.
- In high-cycle fatigue situations, materials performance is commonly characterized by an *S-N curve*. This is a graph of the magnitude of a cyclical stress (*S*) against the cycles to failure (*N*).

Parts and Material Selection
Fatigue Life



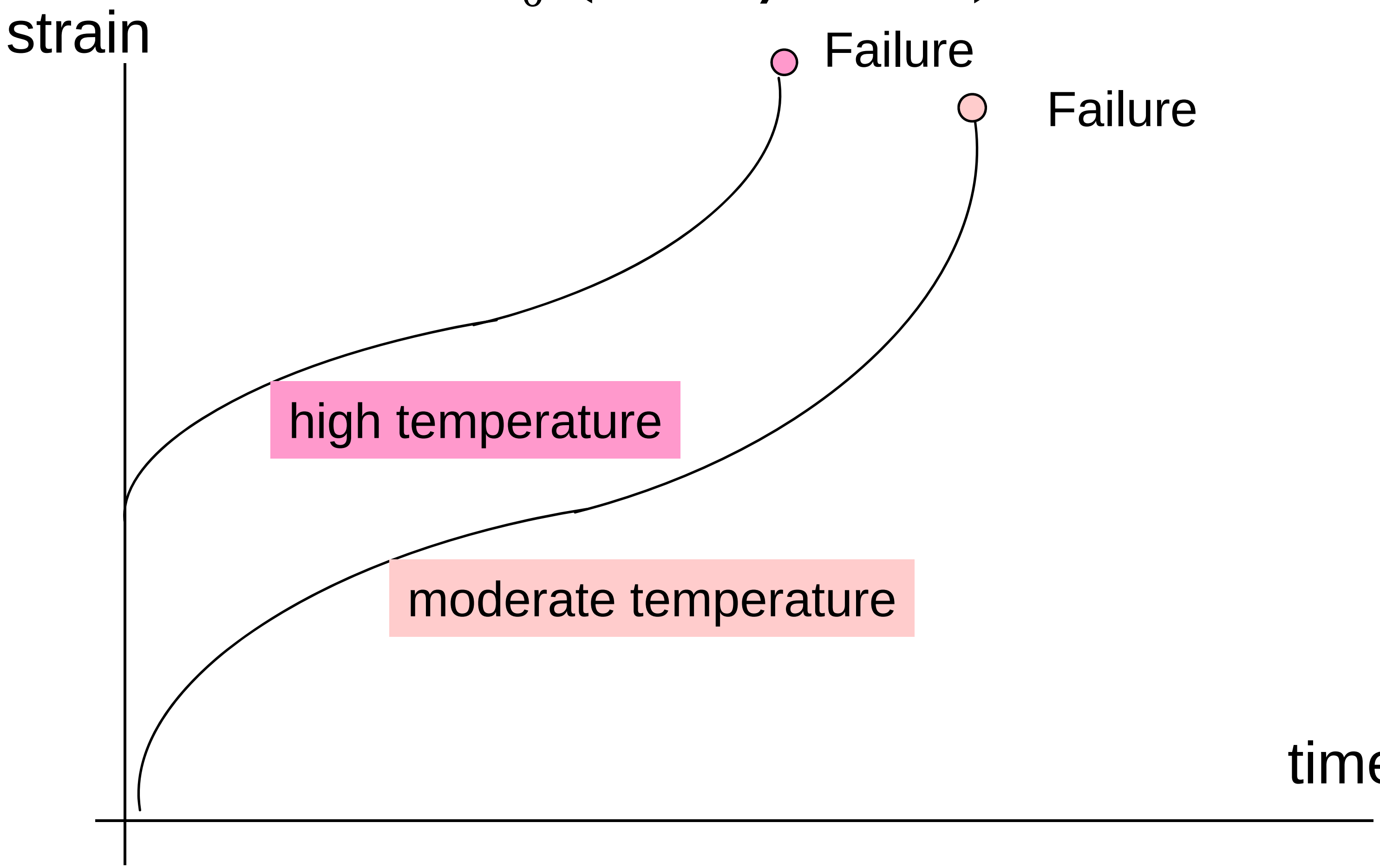
S-N Curve: $N = c\,S^{-m}$ where $c, m > 0$

Creep

- The tendency of a material to move or to deform permanently to relieve stresses.
- Material deformation occurs as a result of long term exposure to levels of stress that are below the yield or ultimate strength of the material.
- Creep is more severe in materials that are subjected to heat for long periods and near melting point.
- The rate of damage is a function of the material properties and the exposure time, exposure temperature and the applied load (stress).

Parts and Material Selection - Creep

$$\varepsilon = \varepsilon_0 (1 + \beta t^{1/3}) e^{kt}$$



Failure modes

Failure Mode		Material Property
gross yielding	→	yield strength
buckling	→	compressive strength
creep	→	creep rate
brittle fracture	→	impact energy
Low cycle fatigue	→	ductility
high cycle fatigue	→	fatigue properties
corrosion	→	electrochemical potential
wear	→	hardness
thermal fatigue	→	coefficient of expansion

Material Failure Mechanisms

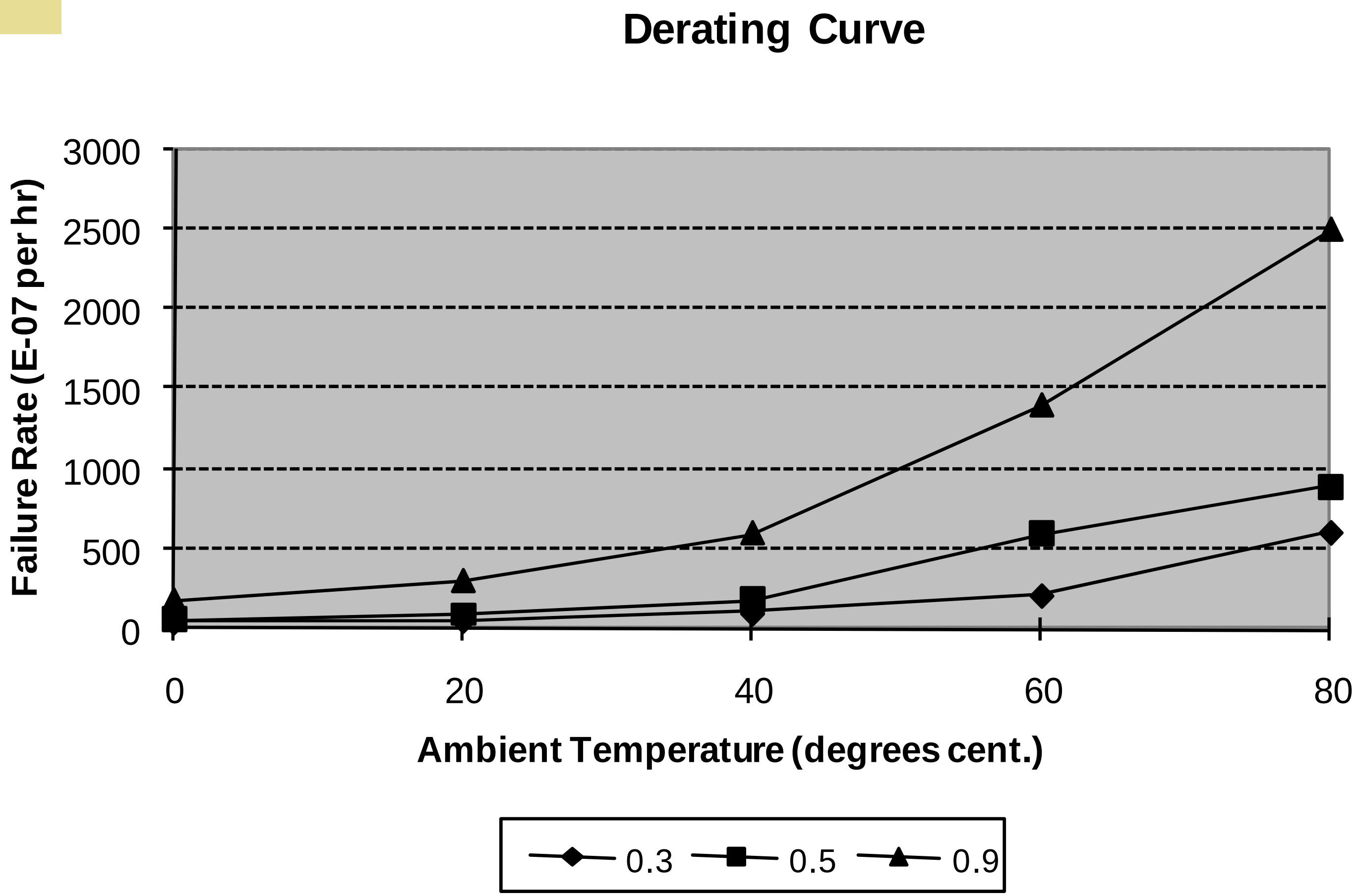
Overstress Failures

- brittle fracture
- ductile fracture
- yield
- buckling
- large elastic deformation
- thermal breakdown

Wear-out Failures

- corrosion
- dendritic growth (electrolytic process)
- interdiffusion
- fatigue crack propagation
- diffusion (molecular migration)
- radiation
- creep
- adhesive wear

Derating

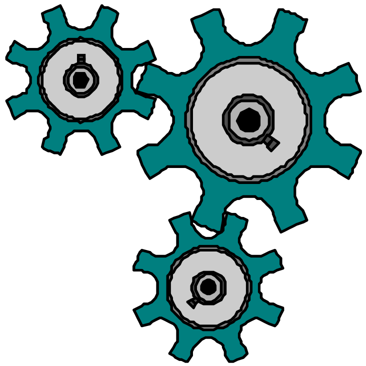


(applied voltage) / (rated voltage)

More Derating

Failure Rate of a gear: $$\lambda = \lambda_b \left(\frac{s}{s_d}\right)^{.7} \left(\frac{L}{L_d}\right)^{4.69} \left(\frac{v_s}{v}\right)^{.54} \left(\frac{c}{c_s}\right)^{.67} \left(\frac{T}{T_s}\right)^{3}$$

λ_b = base failure rate specified by the manufacturer
s = operating speed
s_d = design speed
L = operating load
L_d = design load
v = viscosity of lubricant used
v_s = viscosity of specification lubricant
c = concentration of contaminants
c_s =standard contamination level
T = operating temperature
T_s = specification temperature

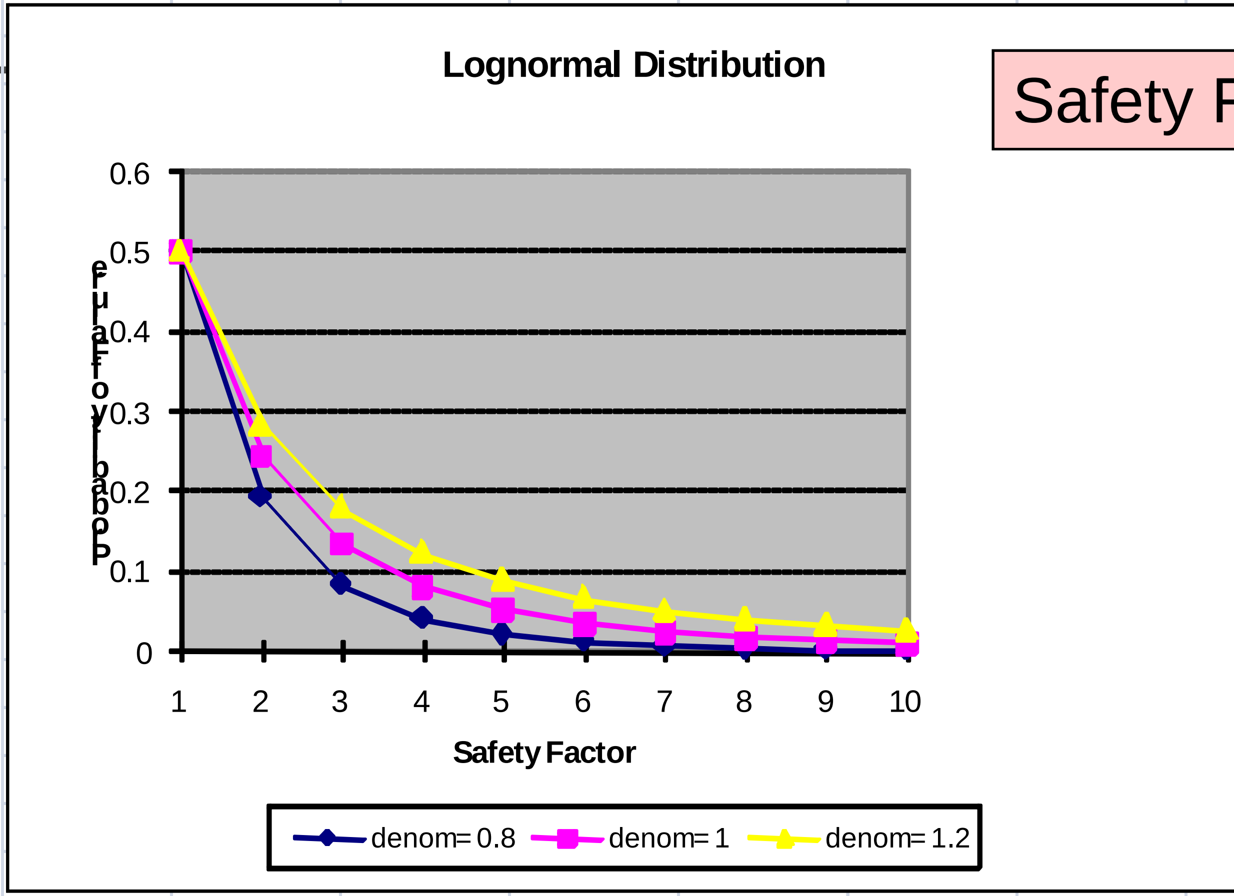


Stress-Strength Analysis

- Concerned when abnormal loads are possible
- Probabilistic compare the magnitude of the stress with the design strength.
- Use physical models
- Major categories of stress
  - electrical
  - thermal
  - mechanical
  - chemical
- Two design approaches
  - select parts with sufficient strength against max load
  - protect part against excessive stresses

Looking for strength to cope with the stress!

Stress - Strength Analysis



Safety Factor = Y/X

$$R = \Phi\left(\frac{\ln SF}{\sqrt{s_y^{\,2} + s_x^{\,2}}}\right) \quad where \ SF = \frac{m_y}{m_x}$$

Stress Protection

Electronic Circuit Boards

Stress	Failure Mode	Design activity
high temperature	insulation deteriorates	dissipate heat, use fans, increase conductor size
thermal shock	mechanical damage	shielding
mechanical shock	component and connector damage	mechanical design - use of mountings
vibration	early wearout, connector failure	mechanical design
humidity	corrosion	sealing, use of silica gel
dust	increased contact resistance	sealing
biological effects	decayed insulation material	chemical protection

Redundancy

- Redundancy
  - Active
    - Parallel
    - Load Sharing
    - K out of N
  - Standby
    - Failures in Standby
    - Multiple Units in Standby
    - Switching Failures
  - Combined Active/Standby

Redundancy

Advantages

- Quickest way to improve reliability
- May be cheapest vs. cost of redesign
- May be the only solution if specified reliability is beyond the state of the art

Disadvantages

- Sensors and switching may increase cost and reduce reliability
- May exceed size, weight or power constraints
- Increases maintainability requirements

Conclusion

As an engineer, I can assure you that these design methods work.