Chapter1. Introduction

Mechanical Strengths and Behavior of Solids

Contents

Objectives

- **To gain an overview of the types of material failure that affect mechanical and structural design**

$$\text{Failure: } G(\text{load}) > G_c(\text{strength})$$

- **To understand in general how the limitation on strength and ductility of materials are dealt with in engineering design**

- **To develop an appreciation of how the development of new technology requires new materials and new methods of evaluating the mechanical behavior of materials**

- **To learn of the surprisingly large costs of fracture to the economy**

1.1 Introduction

- **Mechanical behavior of materials**
  - Study of deformation and fracture in material
  - Excessive deformation, crack, and fracture should be avoided in design

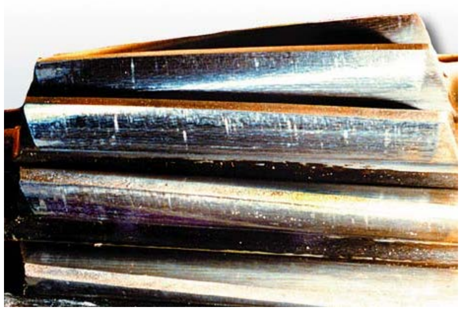
- **Topics**
  - Physical testing of samples of materials (Ch4)
  - Designing a structure to satisfy the stress fall behind the strength (Ch5-7)
  - Effect of material's flaw on strength (Ch 8,10)
  - Stress that applied for long periods of time (Ch 9,11)
  - Plastic deformation behavior (Ch12-14)
  - Creep and Damping (Ch 15)

1.2 Types of material failures

- **Deformation failure**
  - Change of physical dimension which is sufficient for its function to be lost
- **Fracture**
  - Crack to the extent that a component is separated more than two pieces
- **Corrosion**
  - Loss of material due to chemical action
- **Wear(or Erosion)**
  - Surface removal due to sticking between solid-solid (or solid-fluid) surface

Fracture of tensile test specimen

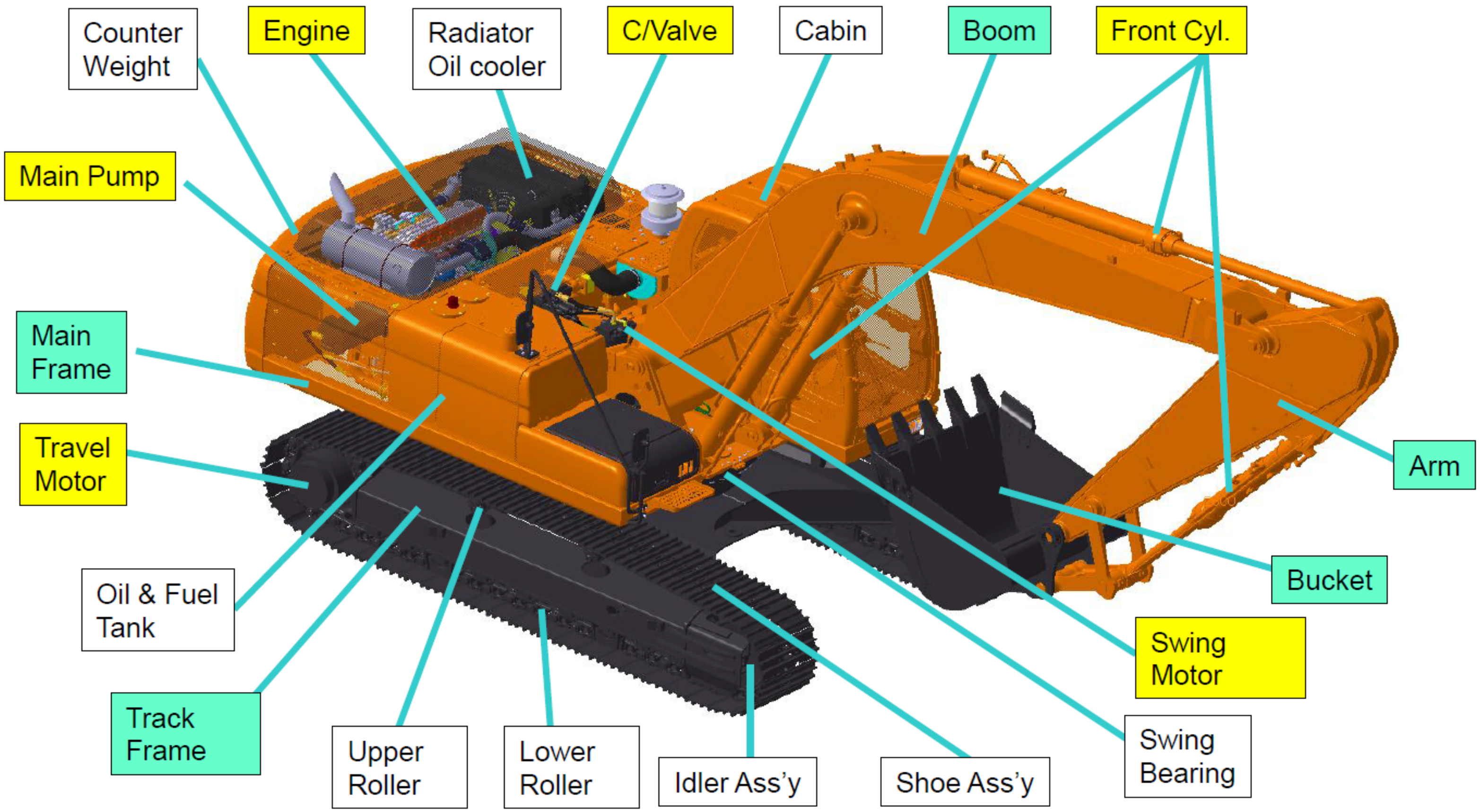
Corrosion on exposed metal bolt



Wear out of gear tooth

Excavator and Its Main Components

주요 구성 부품(Crawler)



[구조체] 와 [구동체] 고장

구조체

Front 연결부 Pin 절손

목표 반복 작업하중에 **의한 Front 연결부 Pin 절손** 위험 감소

방안 SG Data와 Parameter **관계식**으로 **하중 스펙트럼 추정 Pin 부위 과도 하중**을 **모니터링**

Front 용접부 균열

목표 작업하중에 의한 **Front 용접부**의 **피로 균열** 및 이로 인한 **Front Panel 파손** 예방 및 유지보수 전략 수립

방안 SG Data와 Parameter **관계식**으로 **하중 스펙트럼 추정** 후 피로파괴 Model 기반 **피로균열해석** 수행

구동체

하부 주행체 Track 장력

목표 **과도한 장력**으로 인한 하부 주행체 **무한궤도** 및 **연관부품의 파손** 위험 감소

방안 장력과 관련된 변수와 Parameter **관계식**으로 **주행체 장력 추정** 및 **과도한 장력 모니터링**

감속기어 고장진단

목표 유성감속기어의 **초기 결함**을 **감지**하여 **주행불능**의 **심각한 고장 상태** 예방 및 유지보수 전략 수립

방안 **진동기반의 고장진단** 기법을 활용 **정상**상태와 **현재**상태의 진동신호의 구분을 통한 고장진단

1.2 Types of material failures

- **Deformation failure**
  - Change of physical dimension which is sufficient for its function to be lost
- **Fracture**
  - Crack to the extent that a component is separated more than two pieces

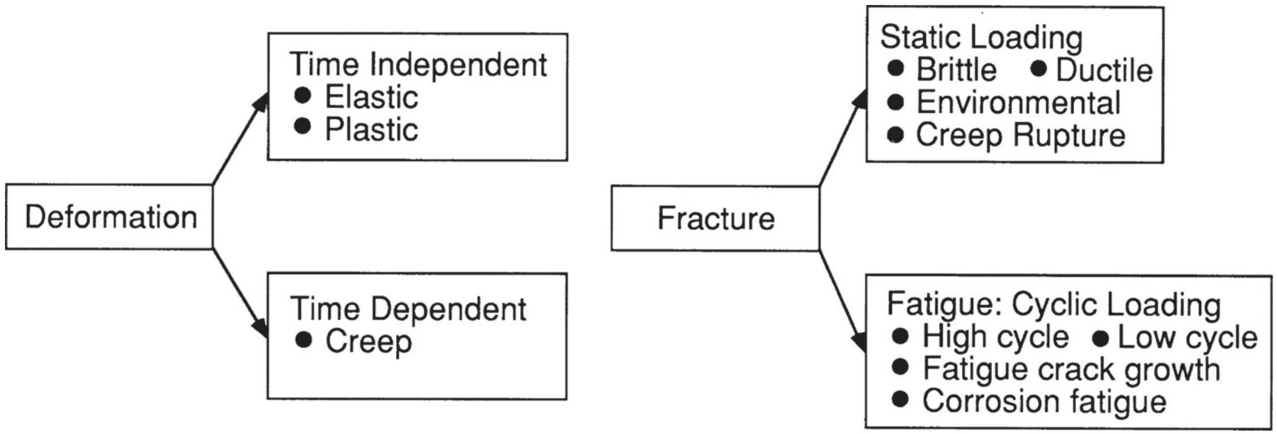


Figure 1.1 Basic types of deformation and fracture.

1.2.1 Elastic and Plastic Deformation

- **Deformation(e.g. bend, twist, stretch) is cumulative effect of strain**
  - Excessive elongation of spring, sway of tall building, unbalanced shaft
- **Elastic deformation: recovered upon unloading**
  - Elastic modulus
- **Plastic deformation: NOT recovered upon unloading**
  - Yielding, yield strength

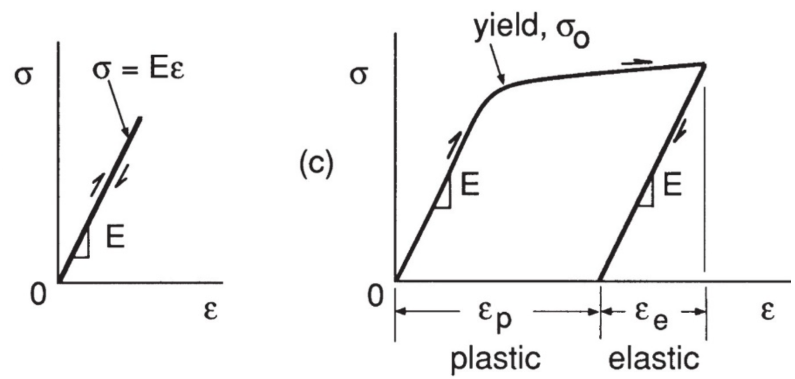
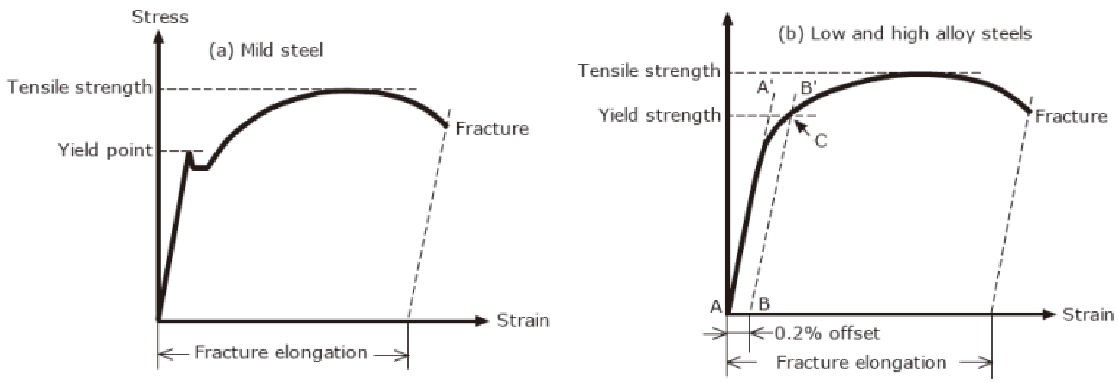


Figure 1.2 Stress-Strain curve with elastic deformation, and elastic + plastic deformation

1.2.1 Elastic and Plastic Deformation

- **Ductile behavior: sustaining large amount of plastic deformation**
  - Low-strength steel, copper, lead, plastics, and polyethylene
- **Brittle behavior: fracture without much plastic deformation**
  - Glass, stone, acrylic plastic, high-strength steel
- **Low carbon steel**
  - 0.05~0.3% carbon, Ultimate=750MPa, Young's modulus=200GPa
  - Cheap, good machinability(welding), structural steel, plate, pipe, bolt, nut
- **High carbon steel**
  - 0.9~2% carbon, Ultimate=1000MPa, Young's modulus=200GPa
  - High tensile strength, tool steel, crank shaft, wheel, rail, spring

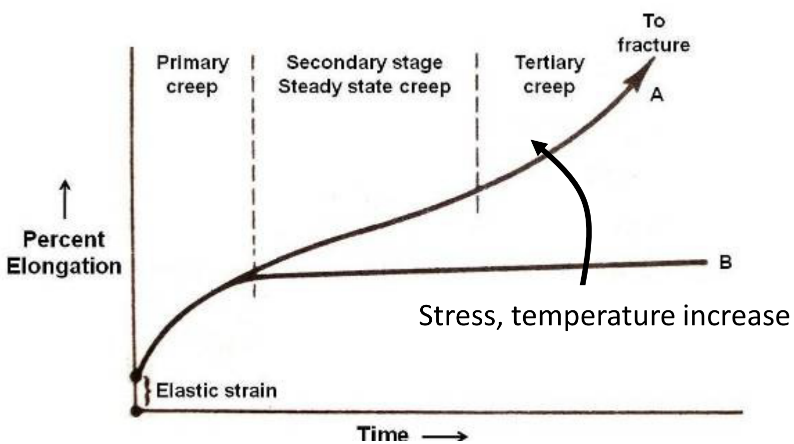


(a)Low carbon steel, 2 yielding point, (b)High carbon steel, Stress-Strain curve

http://hsc.csu.edu.au/engineering_studies/application/civil/3032/Crack_theory.html

1.2.2 Creep Deformation

- **Creep: accumulated deformation with time**
  - Result of long term exposure to stress
  - Severe where high temperature is encountered, near melting point
  - e.g. gas-turbine engines blade, concrete, solder(low-melting temp metal), tungsten light bulb filament
- **Creep strength: stress level that make strain rate zero**



Typical creep curve, strain as a function of time with constant stress

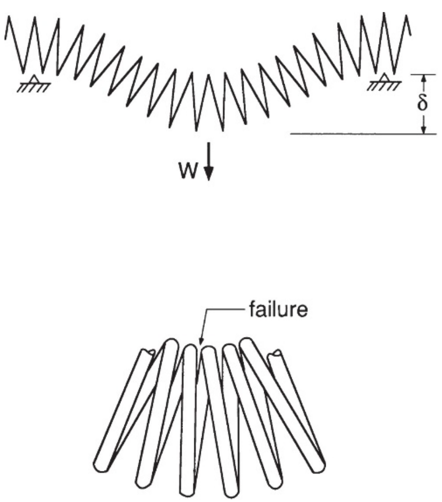


Figure 1.4 A tungsten lightbulb filament sagging under its own weight. The deflection increases with time due to creep

1.2.3 Fracture under Static Loading

- **Ductile fracture/Brittle fracture**
- **Ultimate tensile strength(σ_u), Strain at fracture(ε_f)**
- **Toughness: energy absorption before fracture**

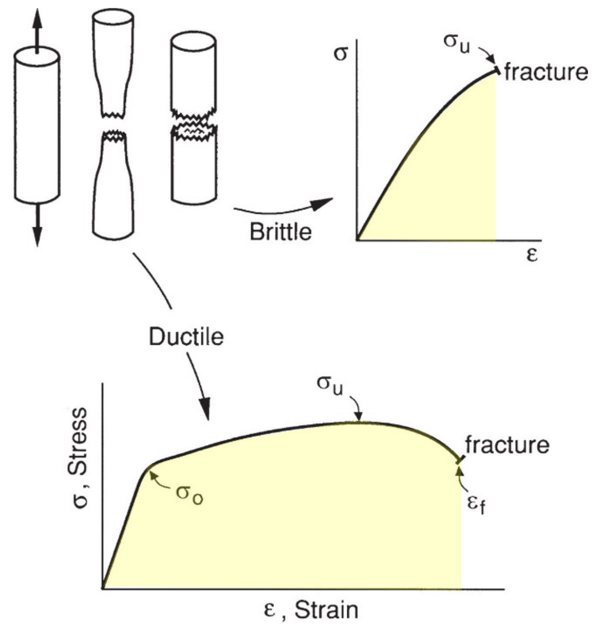
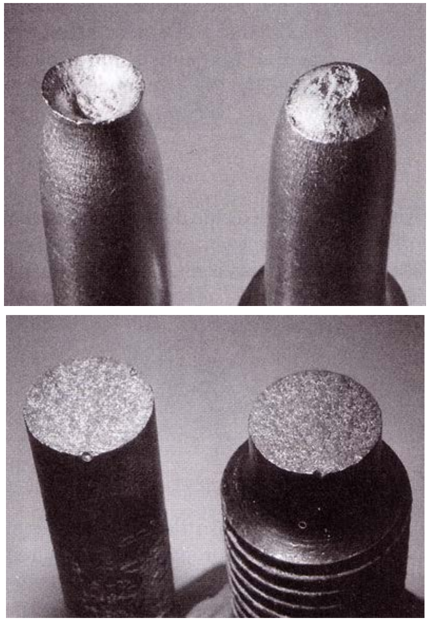


Figure 1.3 Tension test showing brittle and ductile behavior. There is little plastic deformation for brittle behavior, but a considerable amount for ductile behavior.



Fracture surface of (a) ductile(aluminum) with cup-cone and necking (b) brittle(Mild steel) material

1.2.3 Fracture under Static Loading

- **Fracture mechanics: study of cracks in solid, stress concentration**
  - Griffith(1921): Explain difference between <u>theoretical atomic force</u> and <u>experimental fracture strength</u> in **brittle material**
  - Fracture toughness(K): **ability of resisting brittle fracture** in the presence of crack or flaw
  - Irwin(1957): Explain fracture mechanics in ductile material with plastic deformation
  - Higher yield(ultimate) strength, lower fracture toughness

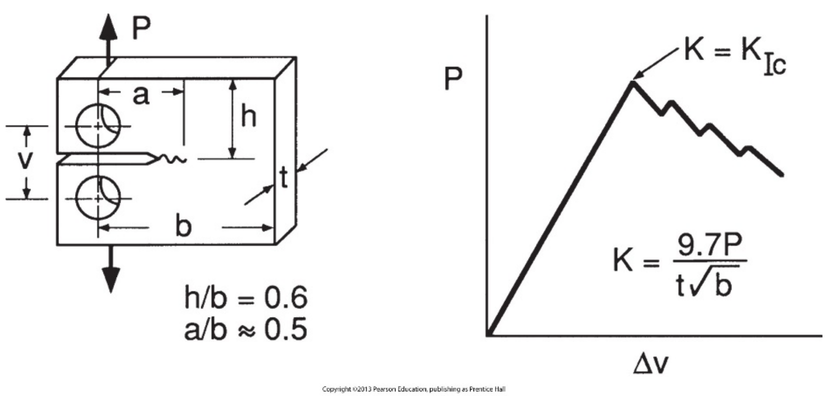


Figure 1.5 Fracture toughness test. K is a measure of the severity of the combination of crack size, geometry, and load. K_{Ic} is the particular value, called the fracture toughness, where the material fails.

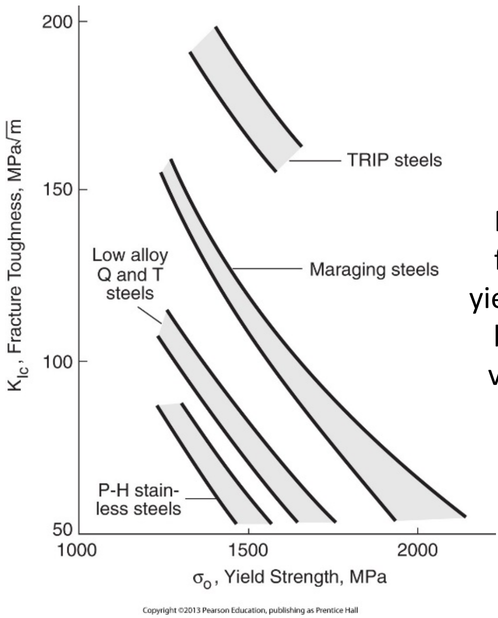


Figure 1.6 Decreased fracture toughness, as yield strength is increased by heat treatment, for various classes of high-strength steel

1.2.4 Fracture under Cyclic Loading

- **Fatigue: failure due to repeated loading (wiki: fatigue)**
  - Tiny cracks start in the material, and grow until complete failure occurs
  - Vehicle weight over bridge, bicycle pedals, heat/cooling, rotary machines
  - High-cycle fatigue: >10^6 cycles, small elastic deformation
  - Low-cycle fatigue: <10^3 cycle, significant plastic deformation
  - Fatigue Crack Growth(FCG): estimate crack size, used to schedule inspection and repair of aircraft, and etc.

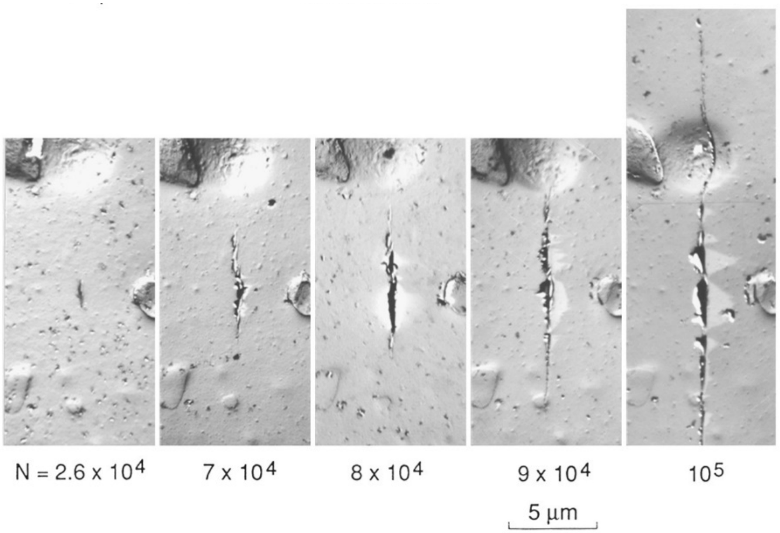
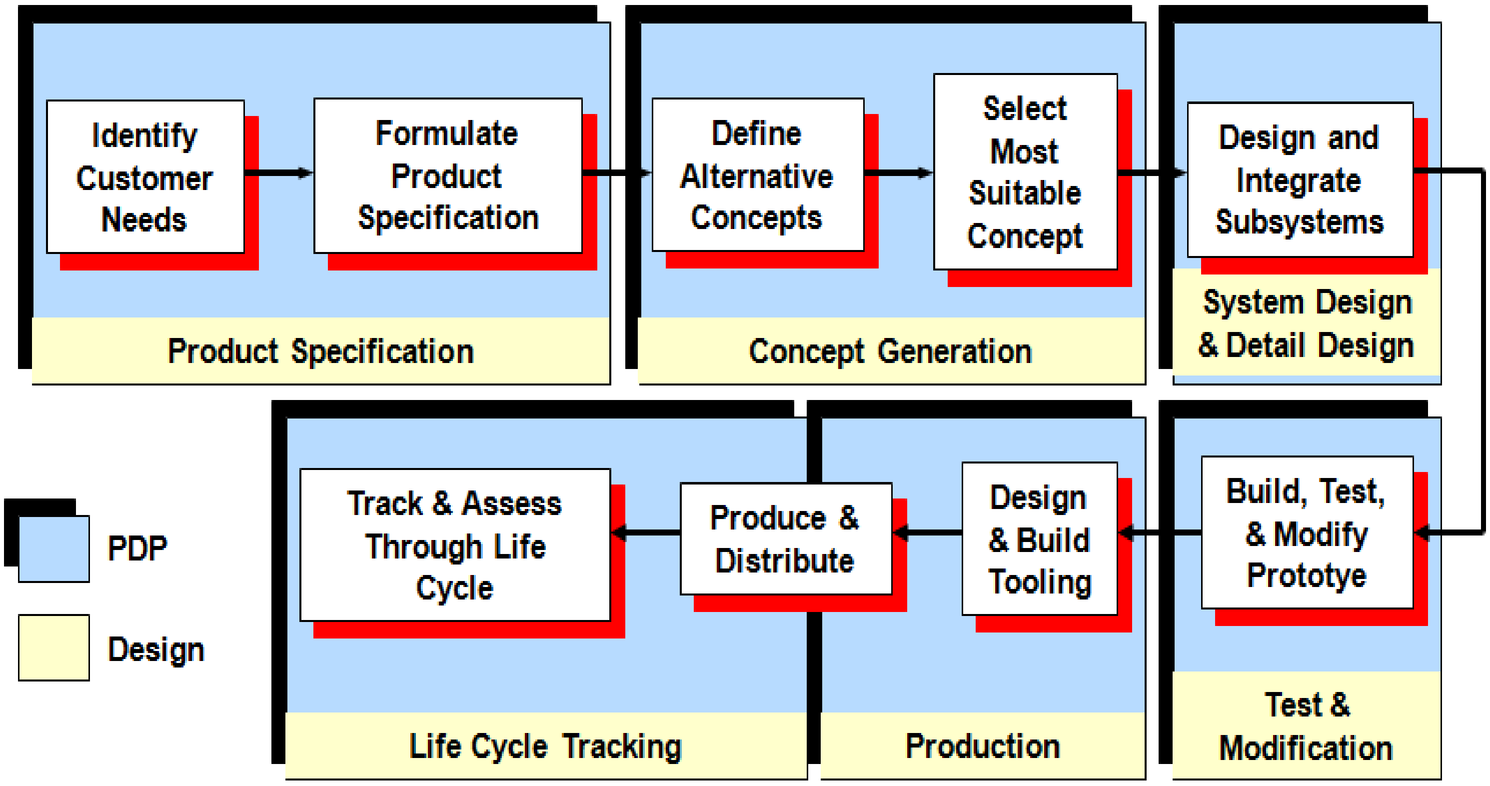


Figure 1.8 Development of a fatigue crack during rotating bending of a precipitation-hardened aluminum alloy. Photographs at various numbers of cycles are shown for a test requiring 400,000 cycles for failure

Figure 1.11 Fuselage failure in a passenger jet that occurred in 1988.

1.3 Design and Material Selection:
Product Development Process (PDP)



1.3 Design and Material Selection

- **Design is process of choosing the geometric shape, materials, manufacturing method**
  - Assure that an item meets functional, economical, manufactural aspects
  - When involving safety and durability, the concept of safety factor is often used.

$$\text{S.F.} = \frac{\text{stress causing failure}}{\text{stress in service}}$$

  - Compromise between conflicting requirements
  - Estimation of applied load
  - Yield stress, fatigue, brittle fracture, creep
  - Prototype to verify assumptions
  - Service experience

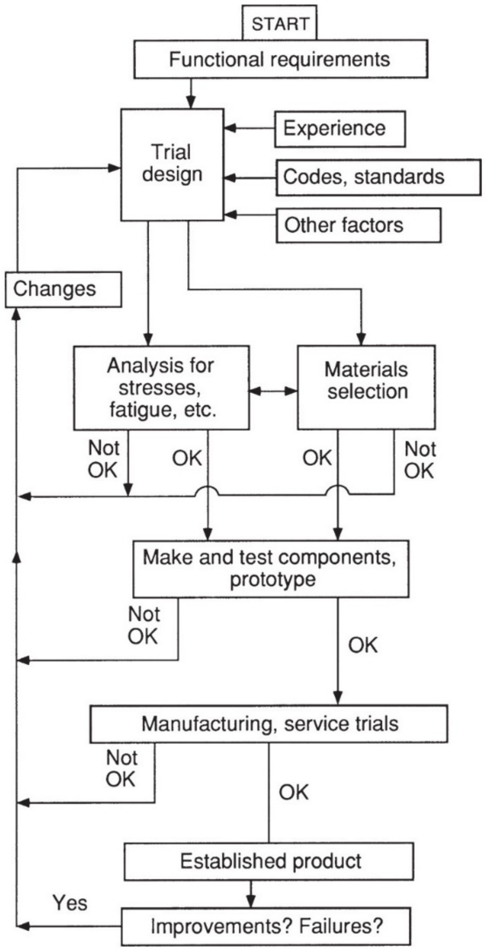


Figure 1.12 Steps in the design process related to avoiding structural failure

1.3 Design and Material Selection

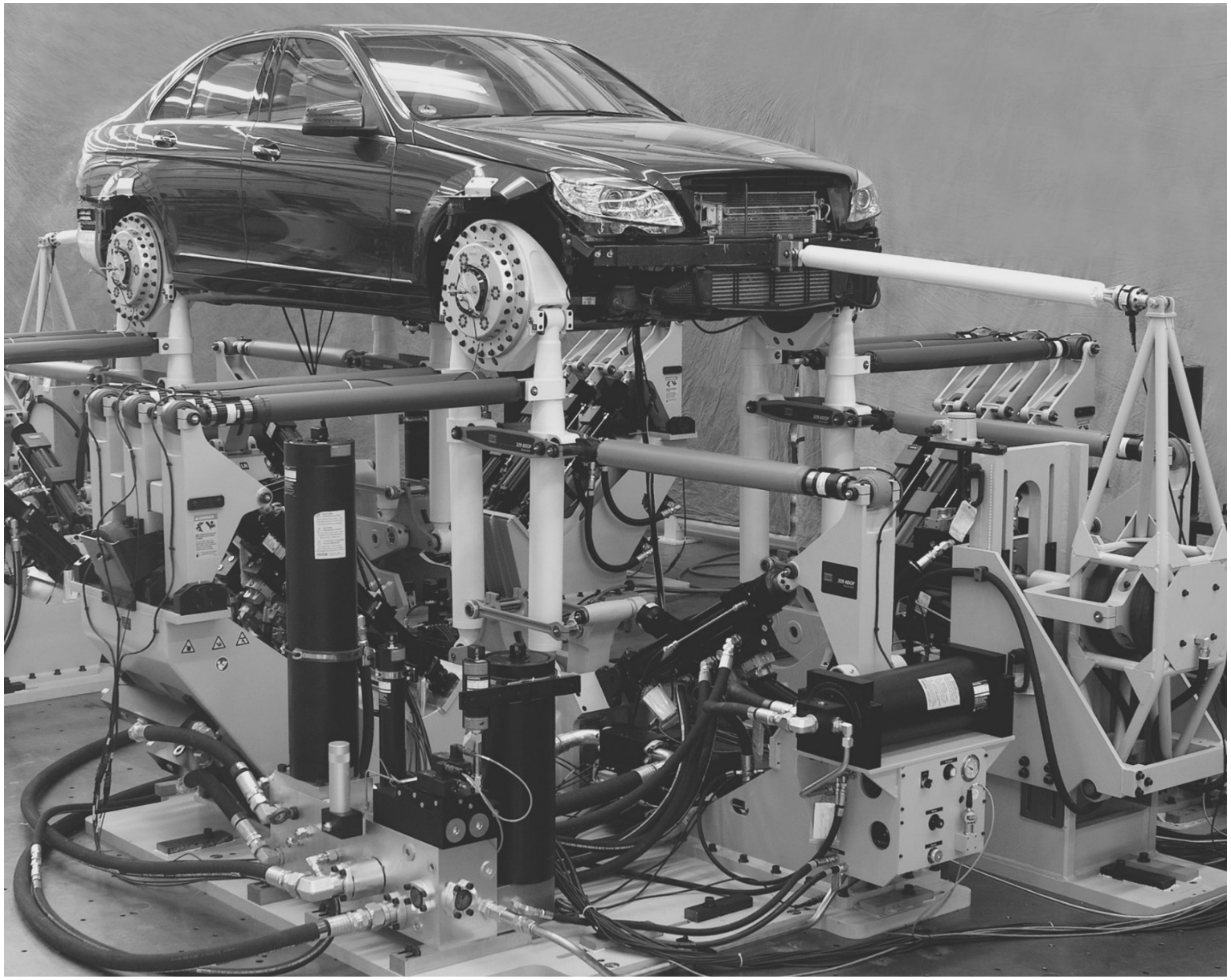


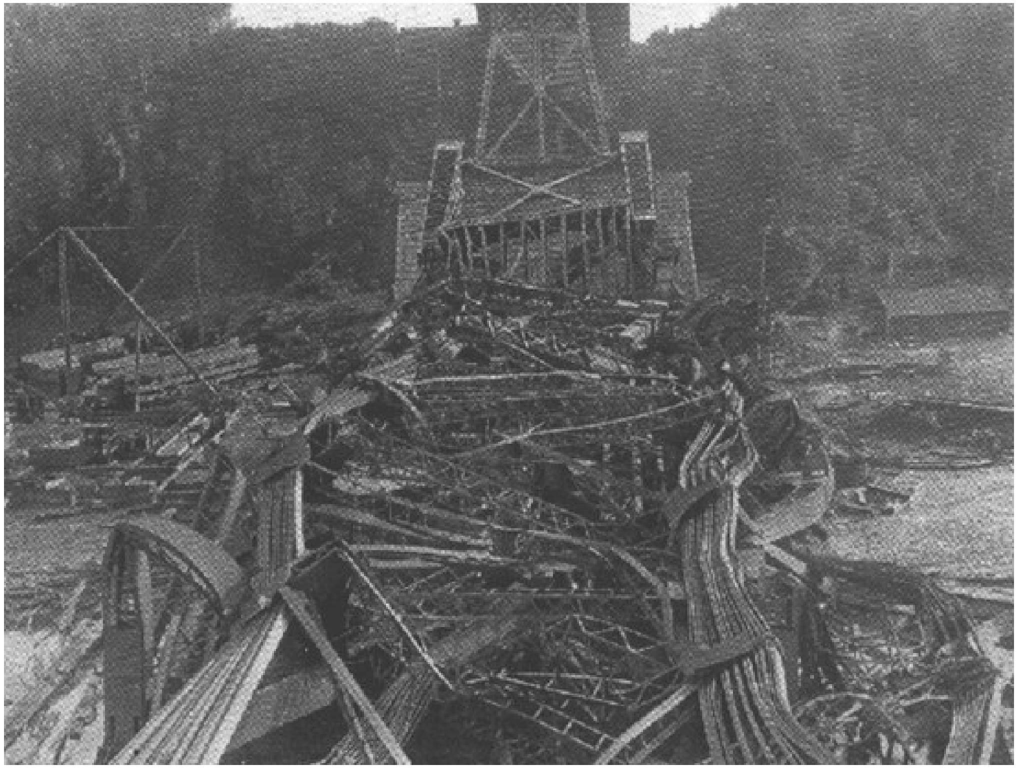
Figure 1.13 Road simulation test of an automobile, with loads applied at all four wheels and the bumper mounts

1.4 Technological Challenge

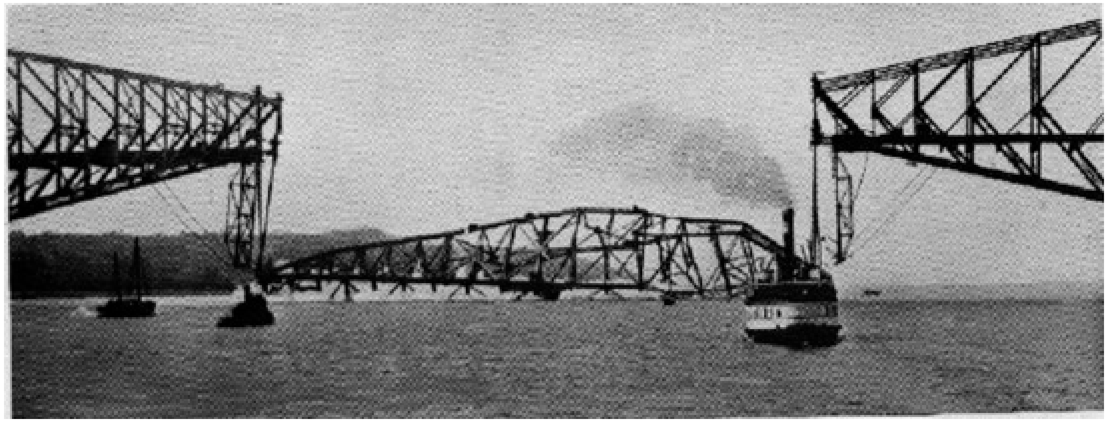
Table 1.1 Some Major Technological Advances from 1500 A.D., the Parallel Developments in Materials and Materials Testing, and Failures Related to Behavior of Materials

Years	Technological Advance	New Materials Introduced	Materials Testing Advances	Failures
1500's 1600's	Dikes Canals Pumps Telescope	(Stone, brick, wood, copper, bronze, and cast and wrought iron in use)	Tension (L. da Vinci) Tension, bending (Galileo) Pressure burst (Mariotte) Elasticity (Hooke)	
1700's	Steam engine Cast iron bridge	Malleable cast iron	Shear, torsion (Coulomb)	
1800's	Railroad industry Suspension bridge Internal combustion engine	Portland cement Vulcanized rubber Bessemer steel	Fatigue (Wöhler) Plasticity (Tresca) Universal testing machines	Steam boilers Railroad axles Iron bridges
1900's 1910's	Electric power Powered flight Vacuum tube	Alloy steels Aluminum alloys Synthetic plastics	Hardness (Brinell) Impact (Izod, Charpy) Creep (Andrade)	Quebec bridge Boston molasses tank

Quebec bridge



1907.8.29 1st collapse



1916.9.11 2nd collapse

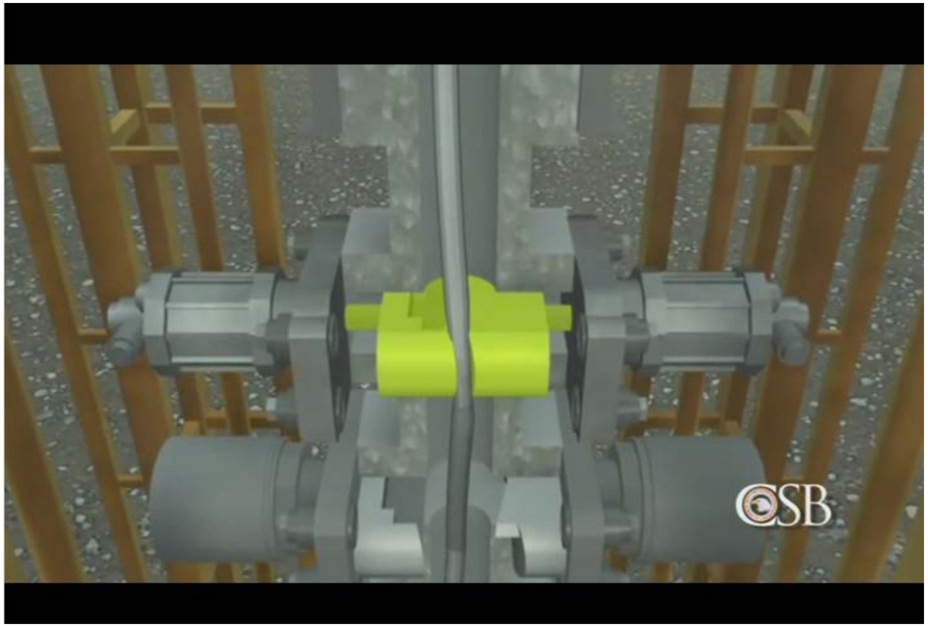
1.4 Technological Challenge

Table 1.1 Some Major Technological Advances from 1500 A.D., the Parallel Developments in Materials and Materials Testing, and Failures Related to Behavior of Materials

Years	Technological Advance	New Materials Introduced	Materials Testing Advances	Failures
1920's 1930's	Gas-turbine engine Strain gage	Stainless steel Tungsten carbide	Fracture (Griffith)	Railroad wheels, rails Automotive parts
1940's 1950's	Controlled fission Jet aircraft Transistor; computer Sputnik	Ni-base alloys Ti-base alloys Fiberglass	Electronic testing machine Low-cycle fatigue (Coffin, Manson) Fracture mechanics (Irwin)	Liberty ships Comet airliner Turbine generators
1960's 1970's	Laser Microprocessor Moon landing	HSLA steels High-performance composites	Closed-loop testing machine Fatigue crack growth (Paris) Computer control	F-111 aircraft DC-10 aircraft Highway bridges
1980's 1990's	Space station Magnetic levitation	Tough ceramics Al-Li alloys	Multiaxial testing Direct digital control	Alex. Kielland rig Surgical implants
2000's 2010's	Sustainable energy Extreme fossil fuel extraction	Nanomaterials Bio-inspired materials	User-friendly test software	Space Shuttle tiles Deepwater Horizon offshore oil rig

Gulf of Mexico Deepwater horizon oil spill
-2010.4.20

Failure of blowout preventer



[Homework: http://www.youtube.com/watch?v=FCVCOWejlag#t=160](http://www.youtube.com/watch?v=FCVCOWejlag#t=160)

1.5 Economic Importance of Fracture

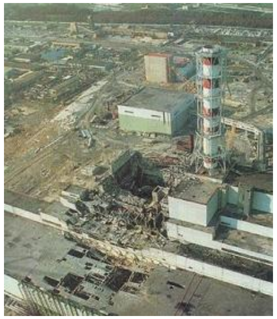
- **Fracture of material cause $119 billion (4% of GNP) loss in the U.S.(1982)**
- **Total cost for material durability would increase up to 10% of GNP**

  - Extra cost for design/manufacture/analysis and testing

  - Repair, maintenance, and replacement

  - Recall, litigation, insurance
- **2/3 of cost can be eliminate through better technology**

1.5 Economic Importance of Fracture



Chernobyl disaster, April 26 1986
due to **Operational Uncertainty**
Consequence: **4K deaths & 600K contaminated**, hundreds of billion dollar

I-35 Bridge Failure, August 2007
Adverse events due to **Design Error and Maintenance Fault**
Consequence: 13 deaths, 145 injured, **$2 Billion** annual loss

CNG Bus Explosion, Aug. 9 2010
Adverse events due to **Maintenance Fault (a defect in the gas tank)**
Consequence: 18 injured (riders and pedestrians)

1.5 Economic Importance of Fracture

Power transformer failure, July 6, 2002
Adverse events due to **faulty bushing**
Consequence: **$5 million** property & business loss

UPS Flight 1307 fire, Feb. 7, 2006,
Adverse events possibly due to **faulty Lithium-ion battery**
Consequence: 3 injured, loss of **whole airplane**

Wind turbine failure, Feb. 22 2008
Adverse events due to **Maintenance error (brake failure)**
Consequence: Collapse of **whole wind turbine**

1.5 Economic Importance of Fracture

8100TEU containership sinking, June 17, 2013
Due to **Buckling** of shell plating & **Fatigue** in welded structure
Consequence: about **$500 million** property & business loss

LNG plant explosion, Jan. 19, 2004
Due to **LNG Leak in Pipe**
Consequence: 27 killed, 72 injured, $100 million loss

***Consequence*:**

U.S. solely spends $250 billion/year on reliability and maintenance in 2012