Design

Fracture of Welded Structures

Lecture Scope

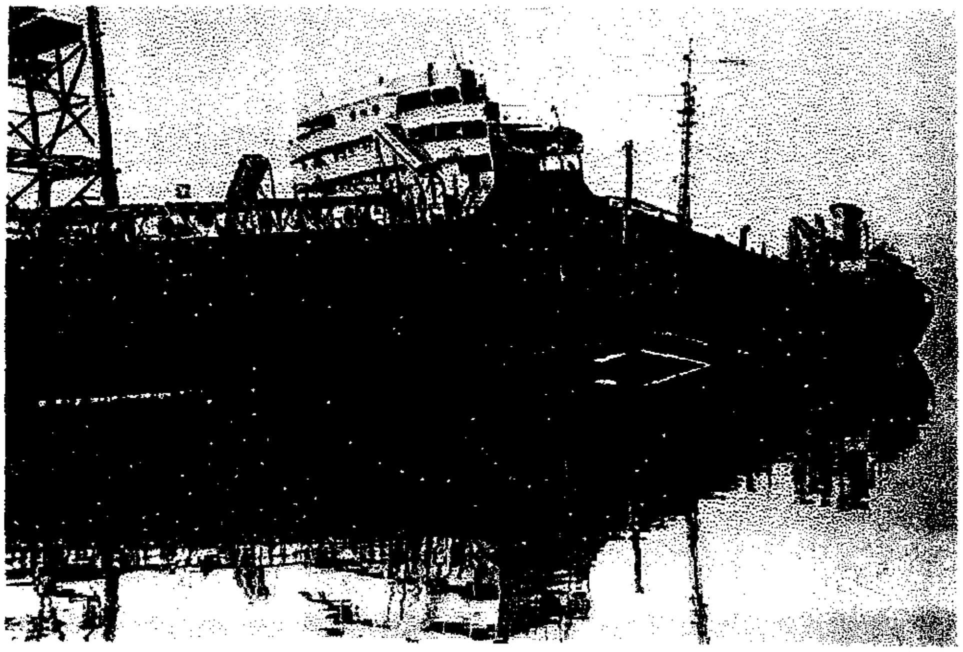
- Fracture fundamentals
- Key fracture variables
- Effects of welding on fracture
- Fracture control in welded structures

Fracture: Introduction

- Fracture of welded structures has been a spectacular though rare part of the engineering scene in the latter half of the century.
- Unfortunately the most susceptible structures, such as bridges, ships, storage tanks and pressure vessels, are those whose failure results in serious loss of life and property
- This fact justifies the effort expended in understanding and preventing fracture of such structures

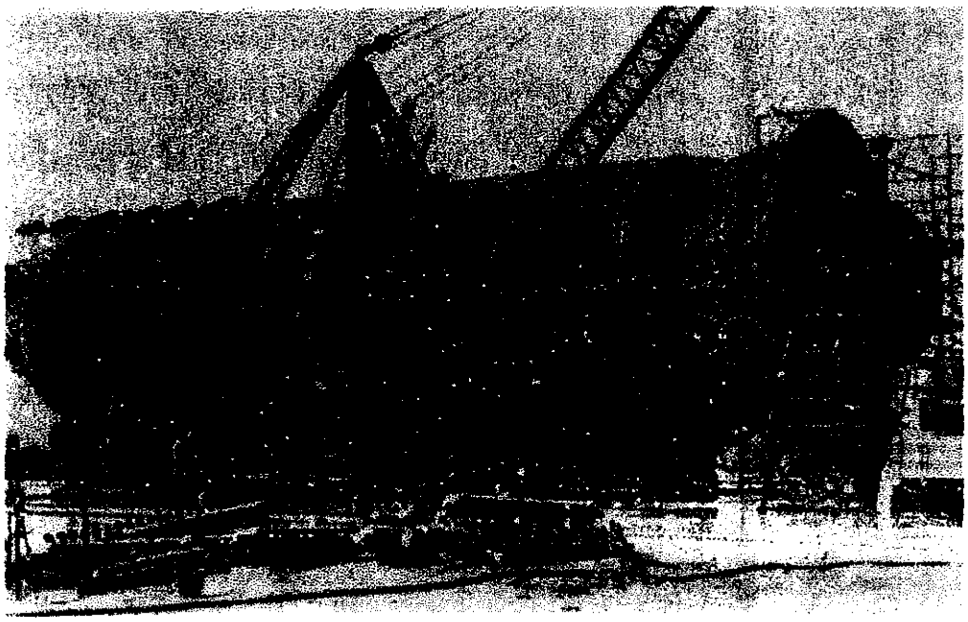
Fracture Examples

The USS Schenectady



Fracture Examples

Fracture of Boiler Shell During Hydrostatic Testing



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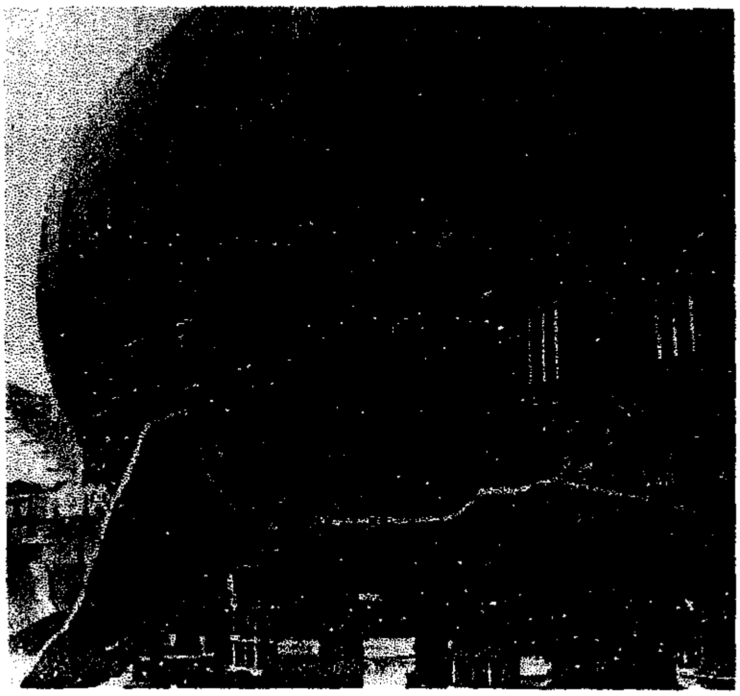
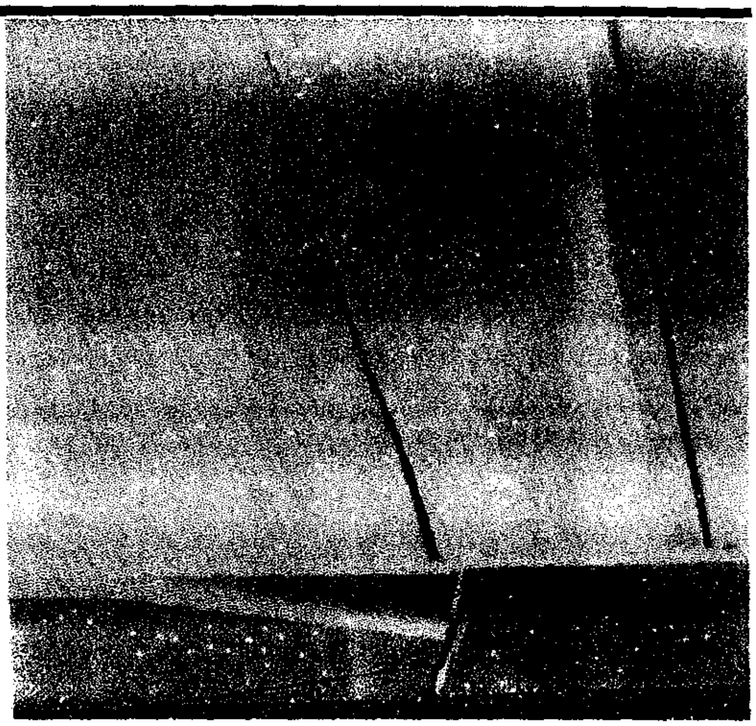


Fracture Examples

Ammonia Heat Exchanger

Fracture Examples

Bridge Girder
Tension Flange
and Web



Fracture-Examples

- The preceding examples contained several common factors:
  - fracture at stresses below the general yield stress
  - stress concentrations or flaws
  - low toughness material condition

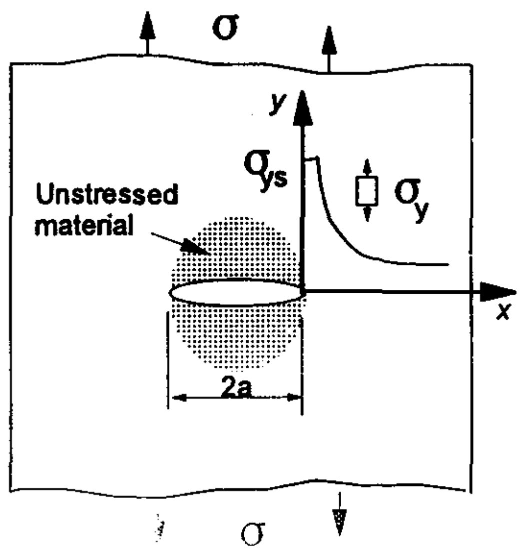
Fracture Definition

- The essence of fast fracture is that it is a failure mechanism that involves the unstable propagation of a crack in a structure.
- This is sometimes described as brittle fracture, although the micro mechanisms by which cracks propagate may be anything from low-strain cleavage to fully ductile shear separation.
- In practical terms the engineering definition of "brittle" refers to the onset of unstable crack propagation when the applied stress is less than the general yield stress

(Knott J.F. *Fundamentals of Fracture Mechanics*, Butterworths 1979)

Stresses at Cracks

- Consider a cracked body under uniform tension
- The elastic stresses at the crack tips are much greater than the applied stress
- The material above and below the crack carries no stress
- At points remote from the crack, the stress is equal to the applied stress



Stresses at Cracks

- Equations for the elastic stresses around a crack were worked out by Inglis in 1913.
- The stresses around the crack are functions of the location with respect to the crack tip and a parameter called the "stress intensity factor," K.
- The stress component normal to the crack, (tending to pull the material apart) at any point x ahead of the crack tip is given by:

$$\sigma_y = \frac{K}{\sqrt{2\pi x}}$$

where:

$$K = \sigma\sqrt{\pi a}$$

Crack Propagation

- Griffith in 1921 realized that a crack propagates when the elastic energy it releases by unloading the material exceeds the energy absorbed in creating new surfaces.
- He used Inglis' equations to calculate the energy release rate as the crack advances, i.e.:

$$G = \frac{K^2}{E}$$

- The critical value of energy release rate is expressed as follows, where S is the energy absorption rate:

$$G_{crit} = \frac{K_c^2}{E} = S$$

- Hence fracture occurs at an applied stress defined by:

$$\sigma_f = \frac{K_c}{\sqrt{\pi a}}$$

Key Fracture Parameters

- Griffith's equation indicates that a crack propagates unstably at an applied stress governed by the crack length and a critical value of the stress intensity factor K_c
- The critical stress intensity K_c can be thought of as a measure of the fracture toughness of the material.

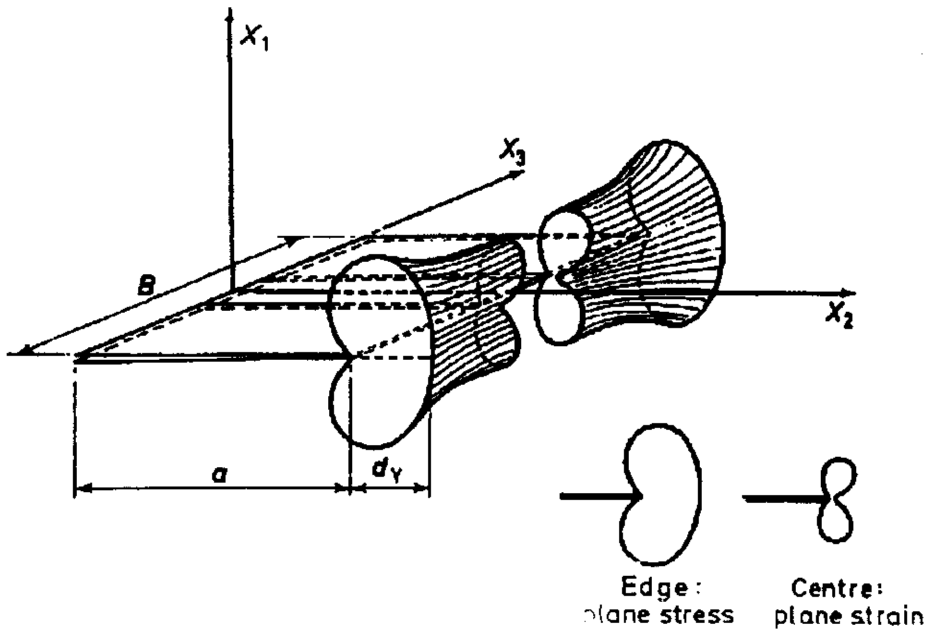
Fracture Toughness of Metals

- In ductile metals, fracture toughness is related to the absorption of energy by plastic deformation of the material at the crack tip.
- K_c is a material property
  - varies from material to material
  - varies with material condition (e.g. heat treatment)
  - decreases with decreasing temperature
  - inversely related to strain rate
- K_c also depends on geometry
  - plastic constraint around cracks
  - thickness effects

Thickness Effects

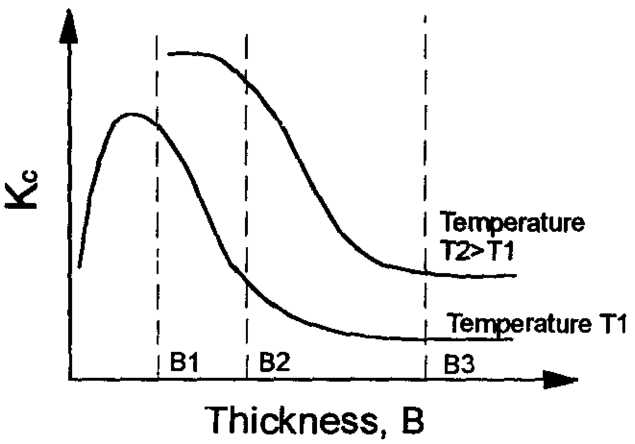
- In "thin" material, the material is free to deform in the through-thickness direction
  - "plane stress"
- In "thick" material, local deformation in the through-thickness direction is restrained
  - "plane strain"
  - Triaxiality limits plastic deformation and causes high stresses ahead of crack

Crack Tip Plastic Zone Size



Thickness Effects

- Limited plastic deformation under plane strain conditions reduces the fracture toughness
- Higher temperature increases fracture toughness
- Thicker materials have higher toughness transition temperatures



Defect tolerance

- The "critical flaw size" may be estimated from LEFM as follows:

$$2a_c = \frac{1}{\pi}\left(\frac{K_c}{\sigma_d}\right)^2$$

- This shows that the tolerance of a material to defects is determined by the ratio of fracture toughness to design stress.
- As tensile strength increases, so must the fracture toughness to give the same critical defect size

Critical Flaw Sizes

	K_{Ic} (MPa√m)	YS (MPa)	$2a_c$ (mm)	Cv (J)
C-Mn steel	75	275	105	7
Low-alloy steel	75	500	32	24
18% Ni Maraging steel	75	1800	3	

- The table shows critical flaw sizes for various steels based on typical properties (σ_d = 0.67 YS)
- High-strength materials are sensitive to small flaws
- Structural steels are normally tolerant of large flaws

LEFM vs GYFM

- The preceding ideas are the essential results of Linear Elastic Fracture Mechanics
  - so called because it assumes that behaviour is governed by linear elasticity with limited plastic deformation.
- LEFM is inaccurate when significant yielding occurs
  - For more accurate results need Elastic Plastic methods (J, COD)
  - But basic concepts still apply and LEFM is conservative.

Effects of Welding on Fracture

- Design Factors
  - continuous highly-stressed structures
  - stress concentrations
- Metallurgical Effects
  - weld metal & HAZ toughness
  - weld defects
  - residual stresses

Design Factors

- Fractures in older, mechanically-fastened structures such as riveted ships were confined to a single member
- However, welded structures are continuous
- The efficiency of welded joints encourages the use of increased design stresses
- Hence large welded structures are inherently more susceptible to unstable fracture than those that older technology was capable of.

Weld Metal Fracture Toughness

- Weld metal toughness is governed by
  - weld metal composition (depends on filler composition and flux type)
  - welding procedure (mainly heat input)
- Most welding consumables give weld metal toughness that matches or exceeds that of the parent material

HAZ Fracture Toughness

- The HAZ toughness depends on
  - steel composition and processing
  - weld thermal cycle (mainly peak temperature and cooling rate)
- For a given steel and welding procedure, the toughness varies at different locations across the HAZ due to the varying thermal cycle

Heat Treatment

- Stress relief:
  - reduces residual stress and tempers heat affected zones
  - usually improves fracture resistance
- Normalizing
  - grain refining treatment after welding improves toughness but rarely applied except in special cases, e.g. electroslag welding of pressure vessels.

Weld Defects

- Welds may contain defects
- Inspection and NDE cannot be relied on to find all defects
- What effect do weld defects have on fracture?

Weld Defects

- Most weld defects, e.g. inclusions, cracking, are on a smaller scale than the critical crack length and are therefore unlikely to initiate fracture
- However, another possibility is crack growth in service by fatigue or stress corrosion cracking leading to unstable fracture

Residual Stress Effects

- Most steels exhibit considerable displacements and plastic deformation during fracture--overrides local residual stress effects
- Brittle materials may be affected by residual stress
- Long-range constraint stresses most significant

Fracture Control

- Material toughness controls
- Fracture assessment
- NDE
- PWHT

Material Toughness Controls

- Materials for fracture critical structures are required to meet toughness requirements
- Charpy V notched bar impact tests are often specified
- Cv tests of weld and HAZ are required to meet a minimum toughness value at a temperature related to the service temperature.
- The required toughness and test temperatures are based on experience and fracture mechanics

Codes & Standards

- ASME Section III para NB2300 gives fracture toughness requirements for materials in nuclear pressure vessels
  - Uses "drop-weight" tests and Charpy tests to establish a minimum service temperature for which adequate toughness is retained
- AASHTO Guide for fracture critical members of bridges
  - required Cv toughness values depend on expected minimum service temperature, thickness and tensile strength
- ABS rules for ships
  - four steel grades meeting Cv values at successively lower temperatures

Design Fracture Assessments

- ASME Section III Appendix G contains rules for design fracture assessment based on LEFM
- Appendix G:
  - gives a lower bound curve of Kc vs temperature for reactor pressure vessel steels
  - specifies postulated flaw sizes (e.g. 0.25t deep and 1.5t long for 4 < t < 12 inches)
  - describes rules for calculating stress intensity factors due to loadings such as pressure and thermal gradients
  - requires that the sum of the K values produced by each of the specified loadings dies not exceed the reference Kc
- Assures prevention of nonductile fracture even if the defects were about twice as large as the postulated defect

NDE

- Structural steels are tolerant of flaws whose largest dimension is smaller than the thickness
- NDE acceptance standards in most codes are based on workmanship standards
- For fracture critical applications, the NDE sensitivity and the frequency of inspection should be based on
  - the likely flaw distribution
  - growth rate
  - and the critical crack length