Design

Fatigue Failure of Welded Joints

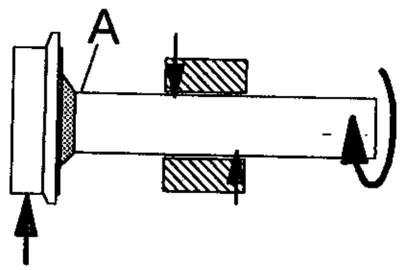
Lecture Scope

- Fundamentals of fatigue failure of metals
- Effects of welding on fatigue
- Fatigue design approaches

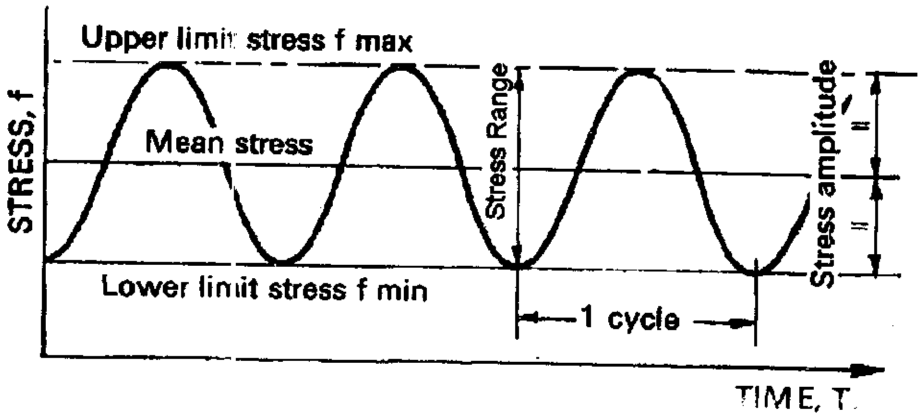
Fundamentals of Fatigue

- Many types of structure experience fluctuating or repetitive loading
  - Bridges
  - Axles or shafts in machinery and vehicles
  - Pressure vessels and piping in cyclic operation

Example: Rotating axle



Stress history at point A

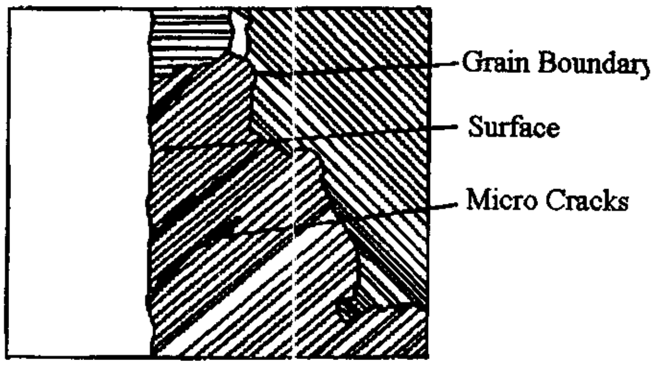


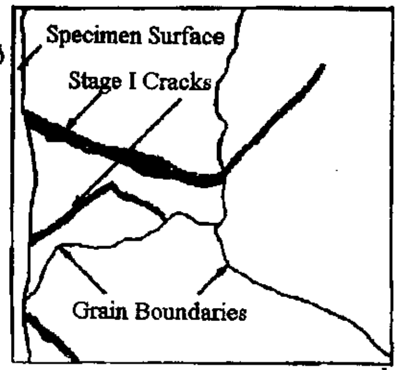
Fatigue Failure

- Fatigue failure is the formation and growth of a crack caused by repeated or fluctuating loading
- Continued crack growth may end in sudden collapse or fracture when the remaining area is insufficient to support the load

Fatigue Crack Initiation

- If the stress range is sufficiently high, plastic slip occurs in surface grains
- After a number of cycles microscopic cracks initiate at the slip regions and at microscopic defects
- "Stage 1" cracks are slow to initiate and grow



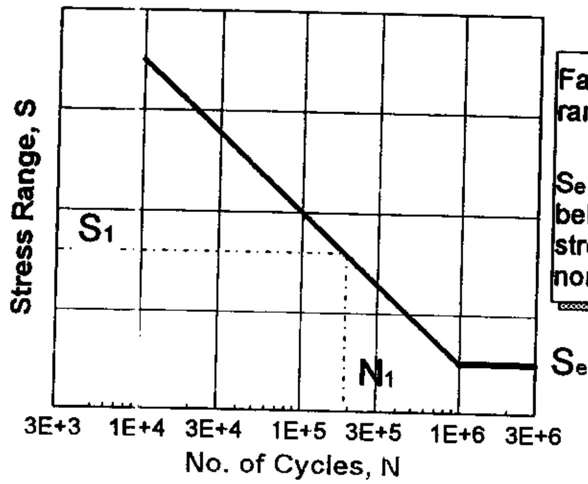


Fatigue Crack Growth

- Stage 2 cracks are less influenced by microstructure. They tend to be oriented normal to the maximum tensile stress
- Each load cycle produces a crack growth increment
- The magnitude of the growth increment depends on the stress intensity, material properties and environment

Fatigue Strength: S-N plot

- Fatigue strength is commonly represented by a plot of stress range against cycles to failure or "S-N plot"
- However, before S-N data can be used the designer has to have a way of accounting for the relevant stresses



Fatigue life at stress range S_1 is N_1 cycles

S_e is "endurance limit" below which alternating stresses are considered non-damaging

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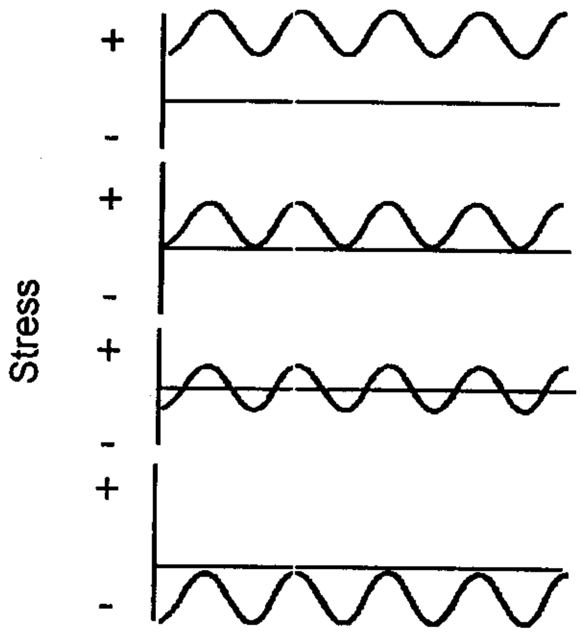
Nature of The Stress Variation

- The loading can be described in terms of
  - the ratio of maximum to minimum stress
  - or the mean stress
  - and the stress range

Nature of The Stress Variation



Type	Stress Ratio Min/Max
Fluctuating tension	R = 0.5
Pulsating tension	R = 0
Alternating stress	R = -1
Pulsating compression	R = 0

Nature of The Stress Variation

- Increasing stress range reduces cyclic life, as shown by S-N plot
- Increasing mean stress reduces cyclic life for a given stress range
- Cyclic life is practically independent of frequency of loading or the shape of the loading cycle

Cumulative Fatigue Damage

- Variable amplitude loading is commonly accounted for by Miner's Rule:

$$\Sigma \frac{n}{N} = \frac{n_1}{N_1} + \frac{n_2}{N_2} \ldots + \frac{n_i}{N_i} = 1$$

- Miners rules states that
  - the fatigue damage at any particular stress is proportional to the number of cycles (n_i) accumulated and the cyclic life (N_i) at that stress
  - The damage accumulates linearly until failure occurs
- Only approximately accurate
- Various methods used for counting load cycles in random loadings, e.g. "rainflow method"

Stress Concentration

- Changes in geometry and stiffness produce local regions of higher stress termed "stress concentration"
- The magnitude of the stress concentration varies with the size of the detail and its "sharpness"
- Fatigue initiation is sensitive to local peak stresses at stress concentrations.

Corrosion Fatigue

- Much fatigue data is based on tests in air
- Metals may display significantly reduced fatigue strength in other environments
  - E.g. ASME Boiler & Pressure Vessel Code fatigue design curves found to be non-conservative for steels in high temperature water
  - Sea water reduces fatigue strength of welded tubular connections in offshore oil rigs
- Termed "corrosion fatigue"
- Fatigue data for the specific environment should be used.

High Tensile Steels

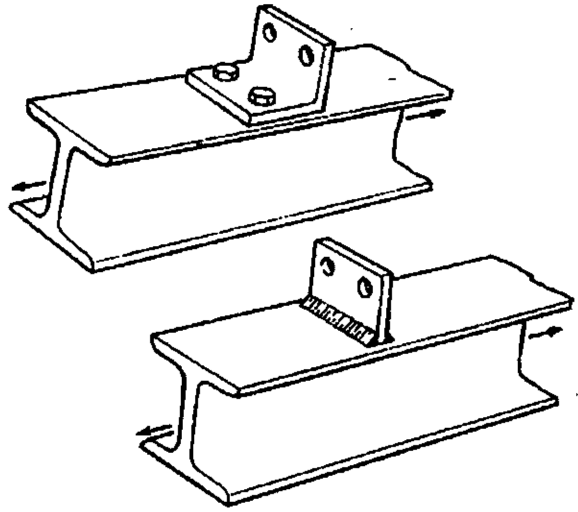
- Under ideal conditions fatigue strength increases with yield strength, but this is not true of welded joints
- Welded specimens of high-tensile steels and lower strength mild steel display similar S-N curves.
- The advantage of high-strength steels is reduced when fatigue is a consideration if design stresses are limited by cyclic life

Fatigue Susceptibility

- Susceptibility to fatigue depends therefore on three basic factors:
  - repeated or fluctuating loads
  - the number of loading cycles
  - stress concentration
- Of these three factors, the one most influenced by designers is the third, through the choice of design details
- More bluntly, this is the one designers most often get wrong!

Effects of Welding on Fatigue

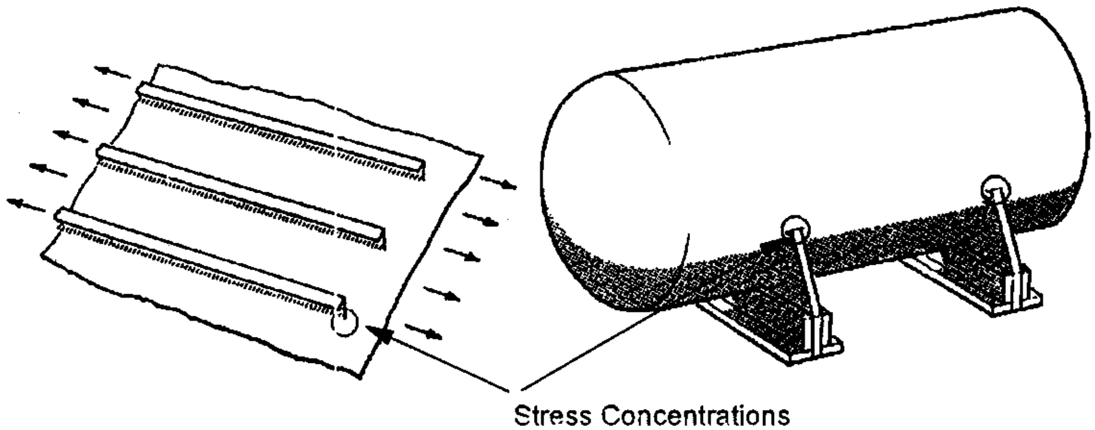
- Unlike bolted or riveted attachments, welds form an integral part of a structure
- Fillet welded brackets, stiffeners, etc. produce severe local stress concentrations due to the sudden change in shape



Source: Richards, K.G.: Fatigue of Welded Structures, The Welding Institute, 1969

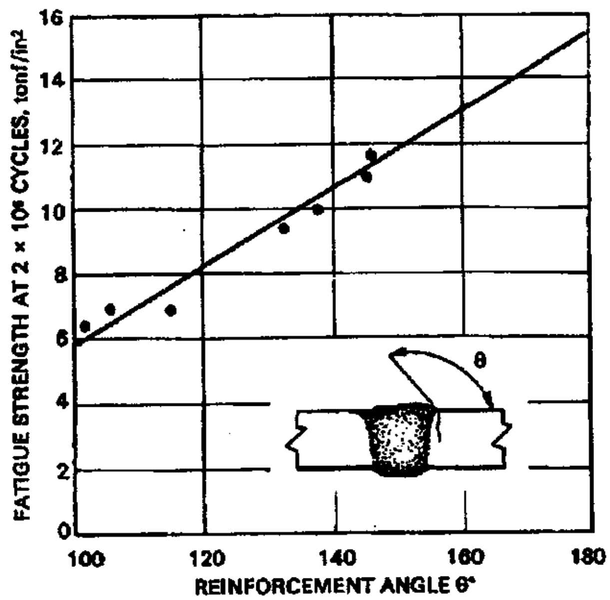
Effects of Welding on Fatigue

- It is easy to create welded details that produce stress concentrations simply because of the arrangement of material
- The "hot spots" arrowed on the stiffened panel and saddle-supported vessel are potential sites for fatigue initiation



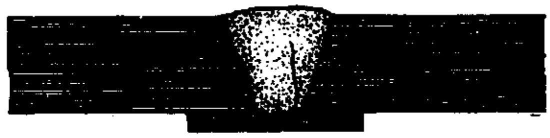
Groove welds

- The fatigue strength of groove welds transverse to the fluctuating stress can be related to the stress concentration at the edges of the weld bead
- Additional details that reduce fatigue strength include misalignment, notches or excessive reinforcement



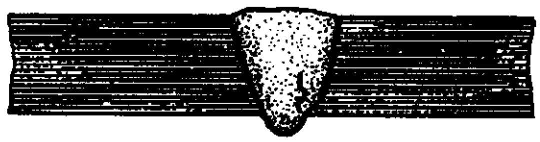
Groove Welds

Backing strip left in place



Misalignment

Excessive root reinforcement



Lack of fusion

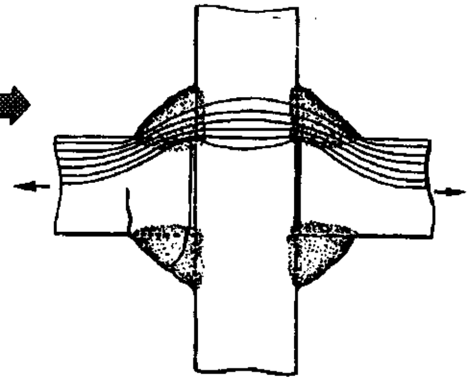
Fillet Welds

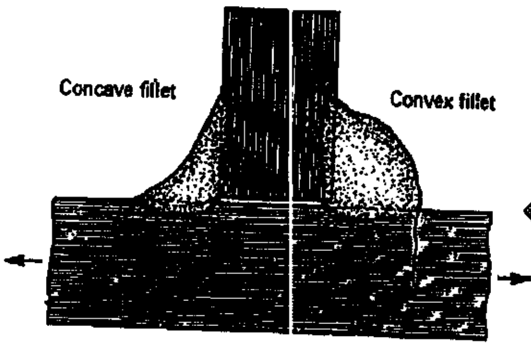
- Fillet welds cause more fatigue problems than groove welds for two reasons:
  - Their inherent shape produces more severe stress concentrations
  - The flexibility they allow in detail design encourages the use of gussets, brackets and other miscellaneous attachments on load-carrying members

Fillet Welds

Even fillet welds that carry no load reduce fatigue strength due to their effect on the profile and stress concentration of the load carrying part

Load carrying fillet welds



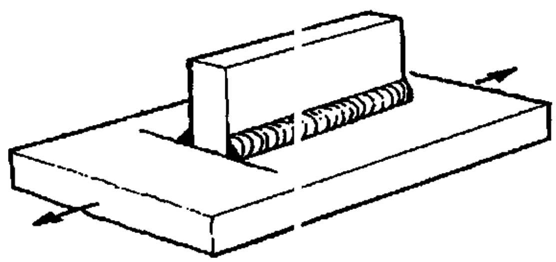


Non-load carrying welds

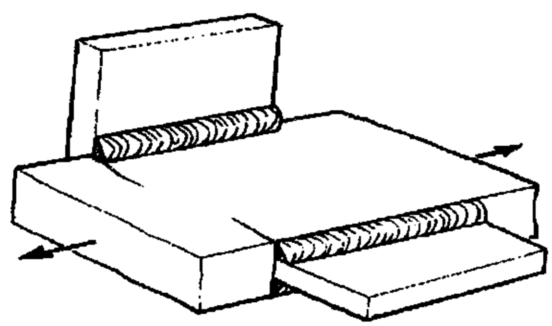
Fillet Welds

- The location of cracking in load-carrying fillet welds depends on the ratio of stress in the weld to the stress in the base metal.
- If the weld is highly stressed, cracks initiate at the root of the weld
- Making the welds bigger increases fatigue strength, until cracking initiates at the weld toes.
- Beyond this, increases in weld size do not increase fatigue strength

Fillet Welds



- There is little advantage to be gained by making fillet welded attachments parallel to the direction of stress



- Attachments made to the edge of a stressed member have even lower fatigue strength than attachments to the plate surface

Effect of Weld Residual Stress

- Welds may contain tensile residual stresses up to yield strength in magnitude
- Residual stresses act as a mean stress and reduce the fatigue strength of the joint
- Residual stresses can result in fatigue failures of welded joints even when the loading is entirely compressive.

Weld Defects

- The fatigue strength of groove and fillet welds is governed primarily by their external profile
- Internal weld defects such as slag inclusions or porosity within normal standards of workmanship have little effect on fatigue strength
- However, in butt welds where the reinforcement has been removed, the fatigue strength can approach that of the parent plate. Internal weld defects may then come into play and reduce fatigue life

Weld Fatigue Improvement

- Design to avoid stress concentration and poor fatigue details on highly-loaded members
- Improve weld profile by grinding to blend with surface
- Reduce residual stress by heat treatment or other means

Fatigue Design of Weldments

- Three basic methods for design
  1. Nominal stress
  2. Geometric 'hot spot" stress
  3. Notch stress
- Each method estimates the fatigue strength from different levels of detailed information about the joint
- Each method must be used with appropriate data for fatigue resistance

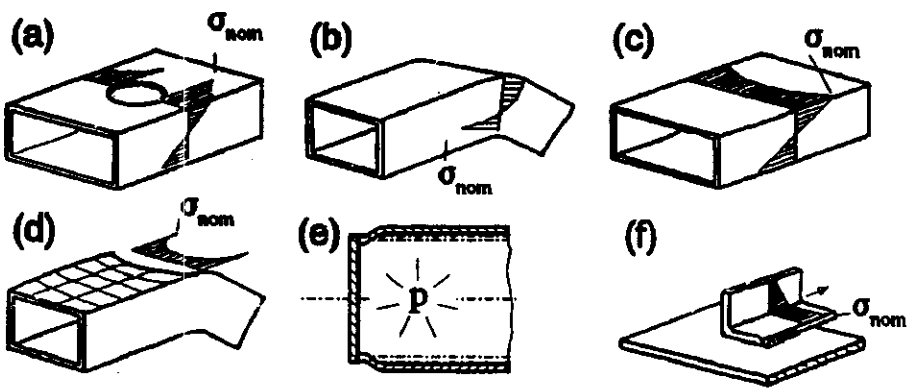
Reference "Fatigue design of welded joints and components" IIW document XIII-1539-96, Abington Publishing, 1996

Nominal Stress Method

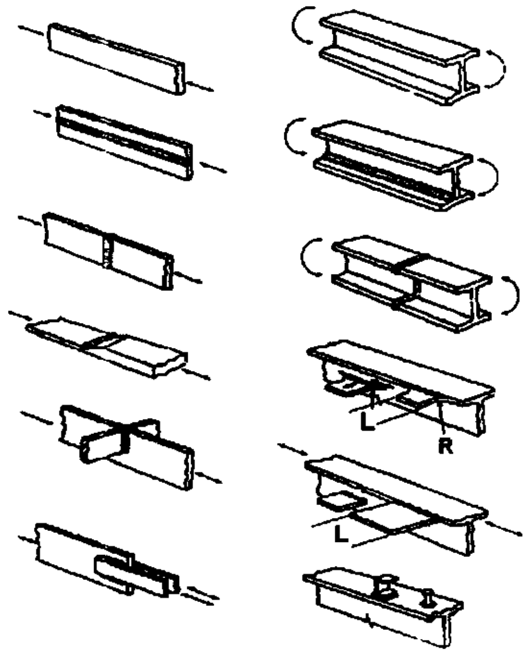
- The nominal stress in the member is compared against fatigue resistance tabulated for different structural details in terms of S-N curves
- The nominal stress method is used by several standards, e.g. AWS D1.1 and CSA W59, for dynamically loaded steel structures such as bridges

Nominal Stress

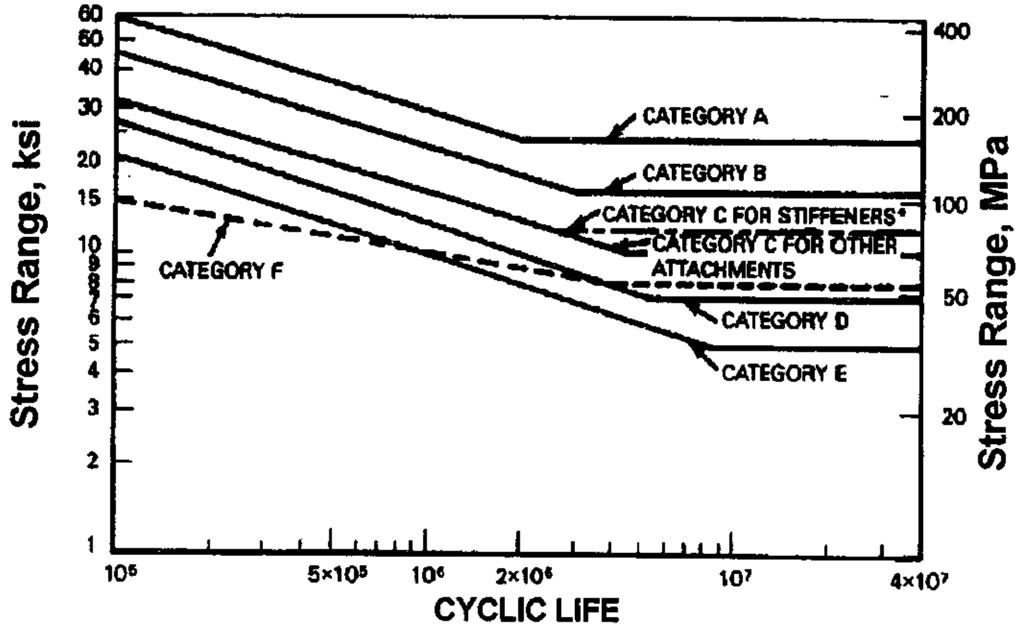
- Nominal stress is the maximum stress calculated in the cross section disregarding local stress concentration effects but including the effects of the macrogeometric shape of the component, e.g. large cut-outs



Fatigue Categories: Examples

Joint Detail	Stress Category
	A B B (ground flush and NDE) C (NDE) B,C,D,E (depending on L, R, see tables) C, D, E F

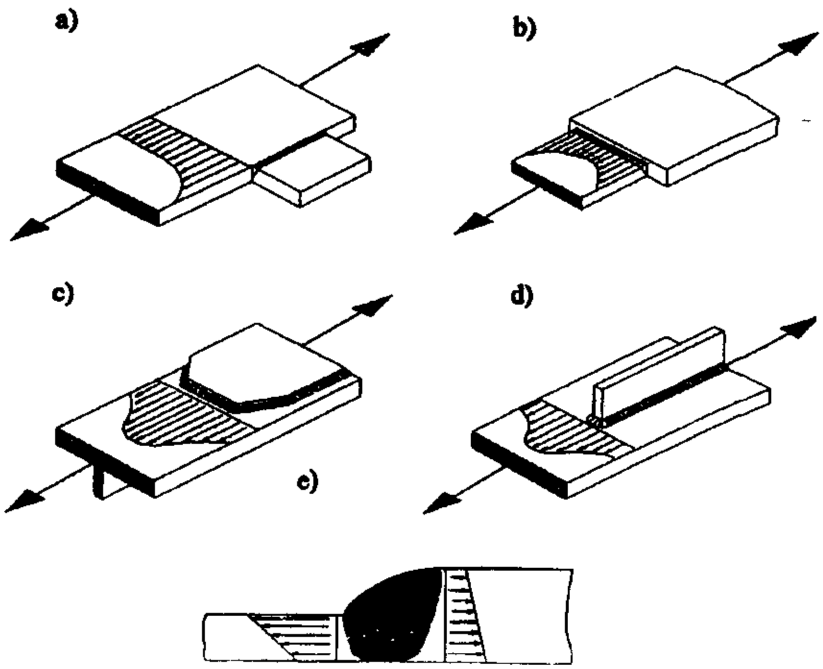
Design Stress Range Curves



Geometric Stress Method

- The structural geometric stress includes all stress-raising effects of the joint geometry, but excludes stress concentrations due to the weld itself
- The stress is compared against S-N curves for the fatigue resistance of the joint detail

Geometric Stress Examples

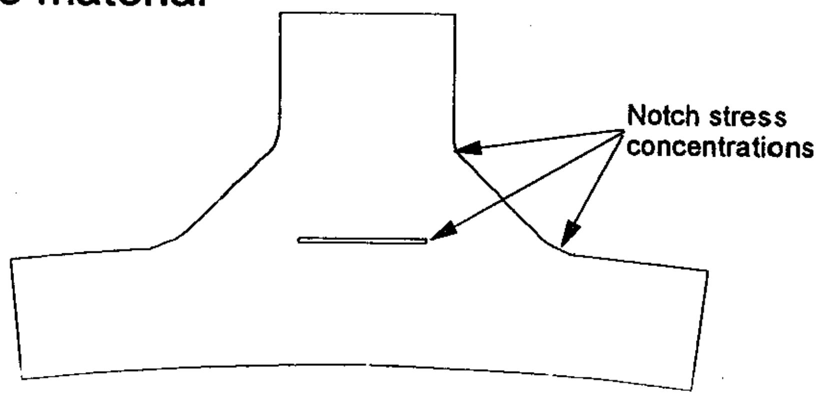


Geometric Stress Method

- This method is recommended when no clearly defined nominal stress exists due to complicated geometry and where the structural discontinuity is not comparable to a tabulated detail.
- For example, AWS D1.1 uses the geometric stress method for fatigue design of joints in steel tubular structures

Notch Stress Method

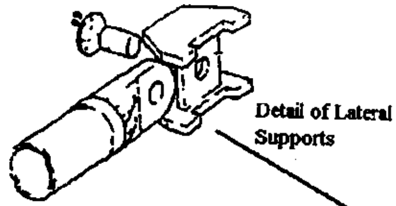
- Effective notch stress is the stress at the root of the notch, assuming linear elastic behaviour
- The notch stress is compared with fatigue resistance in terms of a universal S-N curve for the material

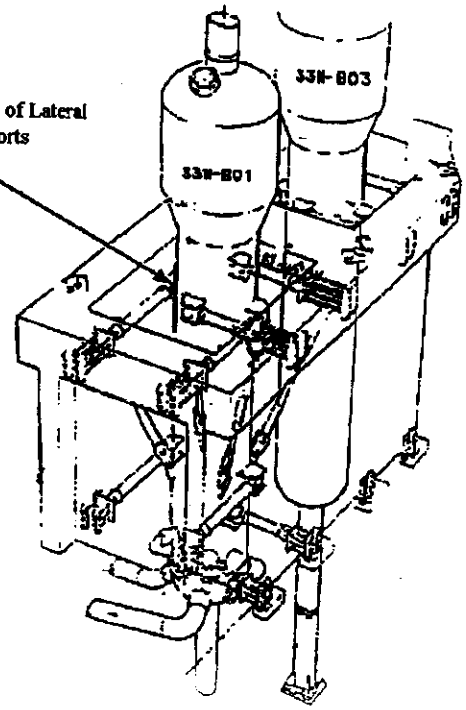


Notch Stress Method

- The ASME B&PV Section III in effect uses the notch stress method for fatigue assessment of welds in nuclear pressure vessels
  - Applies a stress concentration factor for the weld detail to the calculated geometric stress in the vessel shell
  - Compares peak stress against a universal S-N curve

Example - Fatigue Assessment

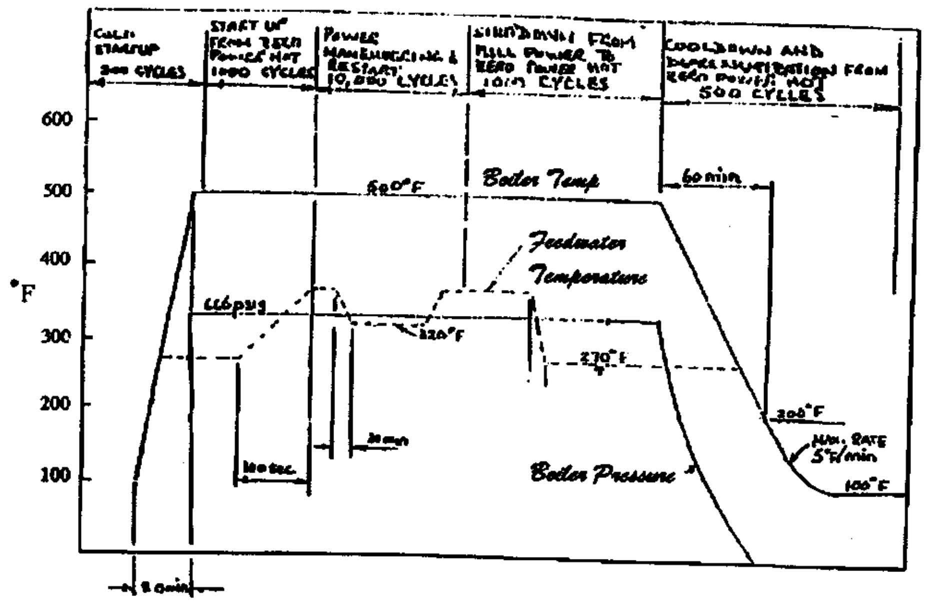




Steam Generator Lateral Restraint Lugs

- Attachments to SG shell
- Subject to thermal gradient stresses during reactor start-up and shutdown

Steam Generator Load Cycle



SG Lug Fatigue Analysis