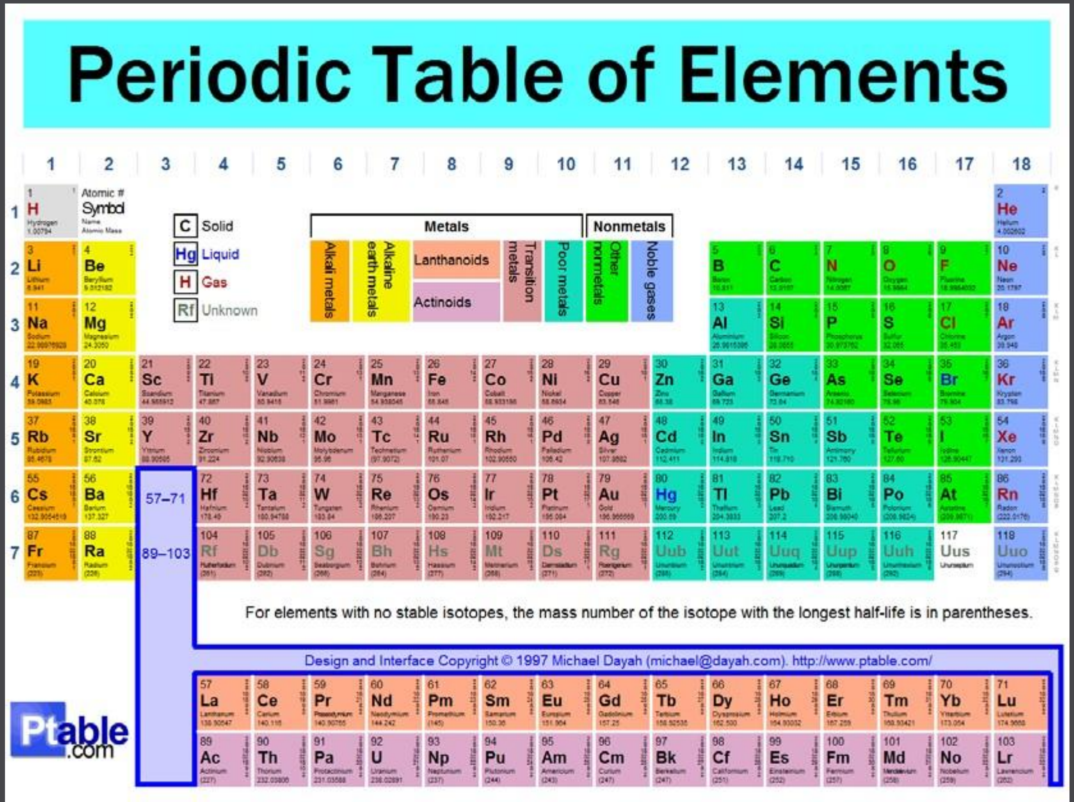
Steel is Real

Outline of Lecture

- How iron and steel are made
- Basic material properties of iron and steel
- Fatigue behavior of steel
- Fatigue behavior of welded steel structures
- Heat straightening of steel structures theory
- Heat straightening of steel structures practice

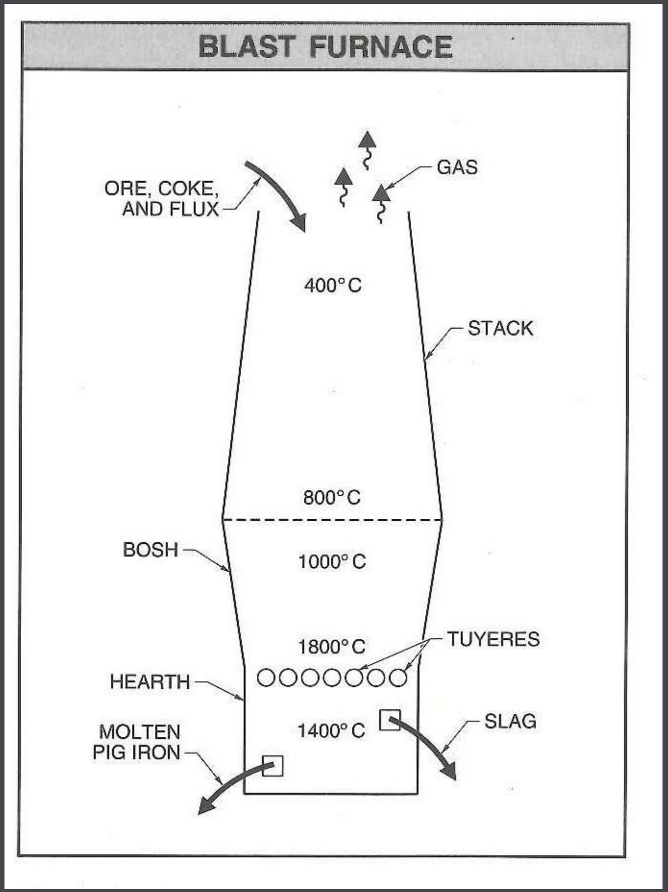


What is iron (Fe)?

- Pure iron is an element on the periodic table that is a metal Fe
- Pure iron is not easily found as iron typically existing as iron oxide Fe_2O_3
- Iron ore contains iron oxide, carbon (C), phosphorus (P), sulfur (S), manganese (Mn), and silicon (Si)
- The additional elements and compounds must be greatly reduced to yield a useable metal

Iron Making

- In the blast furnace iron ore, coke and limestone are added at the top.
- Coke is a rich source of carbon made from heating coal in the absence of oxygen. It provides a reducing agent and heat for the reaction with iron oxide
- Limestone is a fluxing agent used to collect impurities
- Air/oxygen is injected below thru the tuyeres



Iron Making: Stage 1 - Pig Iron

- After several hours of reaction the iron is removed from the bottom of the furnace
- At this point the iron ore has been reduced to pig iron
- Pig iron is still very impure and only good for making other irons and steel

Element	Periodic Symbol	Composition %
Iron	Fe	89 to 96
Carbon	C	3.5 to 4.5
Phosphorus	P	0.05 to 2.00
Sulfur	S	0.01 to 0.1
Manganese	Mn	0.5 to 2.0
Silicon	Si	0.3 to 2.0

Pig iron is further reduced by heat to produce these common forms of iron

- Wrought iron- nearly pure iron (less than 0.1% carbon and 2% silicon) used in architectural applications (fences and gates)
- Ingot iron- very pure iron (less than 0.003% carbon) used in magnets and gaskets. Very soft, low strength
- Enamelling iron – very pure iron (99.07% iron) used for good formability and enameling properties
- Cast iron – Alloys of Fe, C, Si and P with Fe making up 70 to 97% of the composition. Excellent casting properties including pourability and low shrinkage

Cast Irons

- ***Gray iron*** – 3% C 2% Si   95% Fe Most widely used form of cast iron. High carbon content forms graphite flakes within microstructure which is good for vibration damping. Modest strength and poor ductility. Used in engine blocks.
- ***White iron*** – Similar chemistry but is quenched so the excess carbon does not precipitate out into graphite, but forms iron carbides. Very hard and brittle. Excellent wear resistance.
- ***Chilled iron*** – A combination of gray and white iron which produces a relatively tough core with hardened exterior surfaces. Rail road wheels and stamping shoes are made from chilled iron

Cast Irons

- ***Malleable iron*** – White iron that has been tempered or annealed to improve ductility
- ***Ductile iron*** – Also called nodular iron. Same strength as grey iron with improved ductility due to the shape of the graphite (round vs. string)
- ***Compacted graphite iron*** – Graphite shape is between round and string producing better ductility and thermal shock resistance than gray iron. Used for disk brake rotors and diesel engine cylinder heads
- ***Alloy iron*** – Specialized high alloy contents (up to 30%) make for special abrasion, corrosion and thermal shock resistance

Summary of Cast Iron

- Excellent casting properties for making complicated shapes
- Moderate strength 25 to 90 ksi yield strength range
- Low ductility (brittle failure)   typically less then 2% elongation
- Thermal shock, wear and corrosion resistance can be tailored for special uses
- Very difficult to weld, typically brazed if stresses allow
- Typically composed of Fe 90 to 95%, C + Si 5 to 10 %

Solutions and Slurries

- A solution is a miscible mixture of 2 or more substances
- Solutions are homogeneous (same composition in all parts of the mixture)
- Solutions are composed of a solvent (main portion) and the solute (added portion)
- Solutions have physical properties in between those of the solvent and the solute

Example Solution

- Using 1 quart of water (H_2O) at room temperature add 2 table spoons of salt (NaCl) and mix thoroughly
- The solid form salt dissolves completely in the water and you have a 3% salt water solution.
- The salt affects the physical properties of the water including solidification (freezing) and boiling points

Example Saturated Solution

- Continue to add table spoons of salt to the mixture and mixing thoroughly
- After adding approximately 22 to 23 table spoons of salt to the solution it will no longer dissolve anymore salt and the remaining salt is not in solution but solid form
- This is a 35% salt water solution and it is saturated with salt. Anymore added salt will not go into solution.
- You have liquid salt water solution with undissolved solid phase salt

Example Slurry

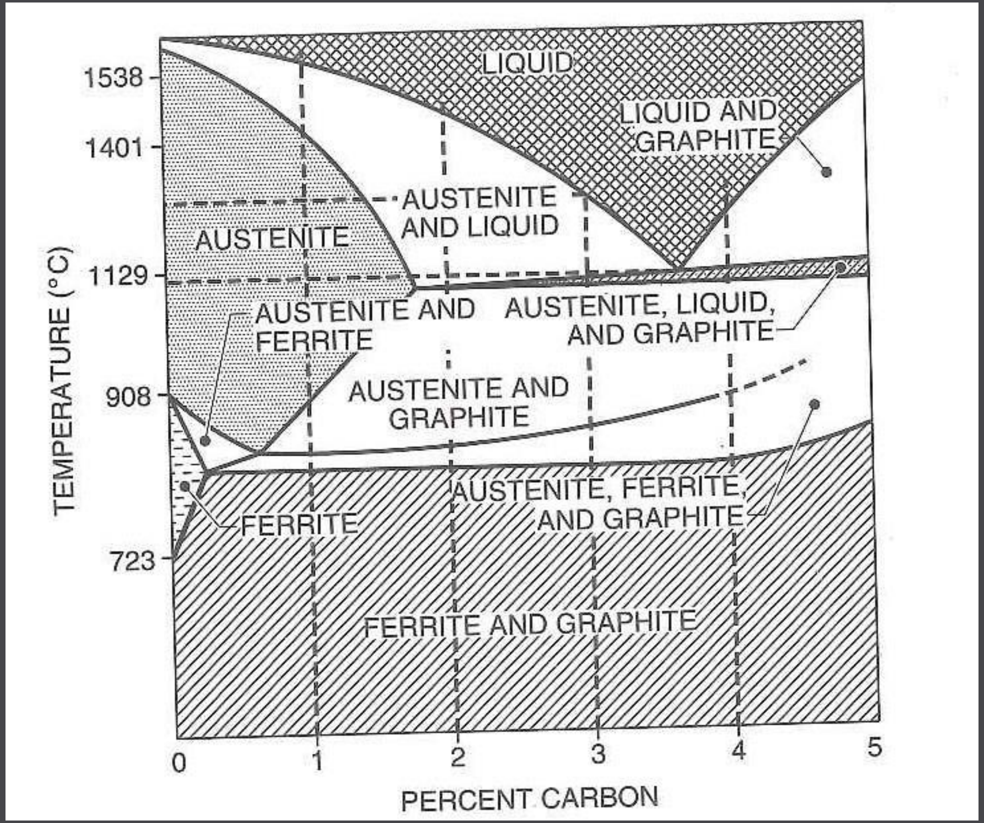
- Once enough salt has been added such that it will not dissolve no mater the vigor of mixing a slurry has been created

- A slurry is a saturated liquid solution with excess solid phase solute

- In general increasing the temperature of the solvent increases the amount of solute that can be dissolved into solution, up to a point

Solutions and Slurries

- Example Iron-Carbon-2% Silicon Phase diagram for Cast Iron
- Saturation occurs around 1.5 to 2% C
- Multiple solid phases are possible, e.g. Austenite, Ferrite and precipitated graphite
- The iron solid phases of austenite and ferrite are crystalline



Iron into Steel

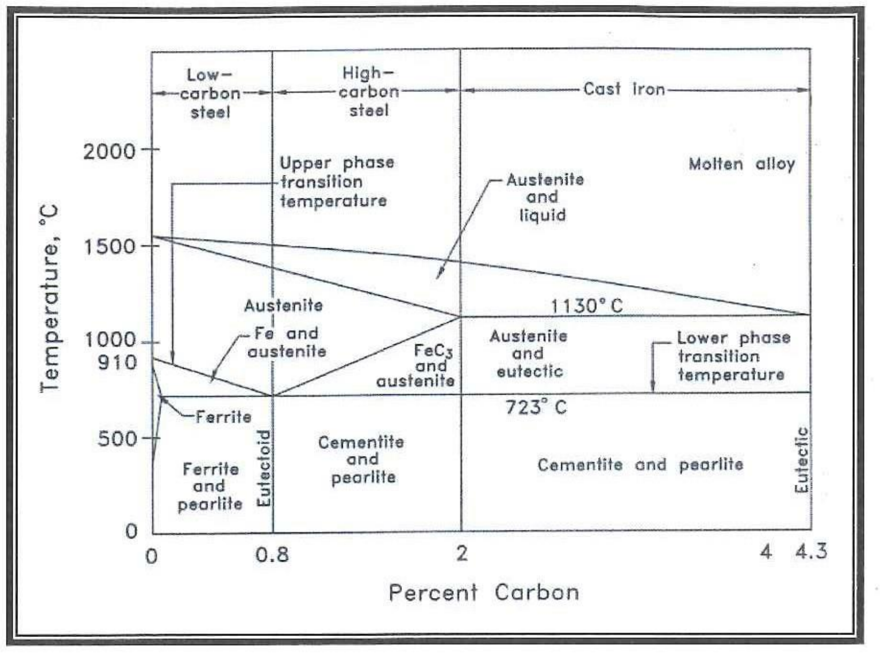
- Cast iron is a mixture in of Fe, C, and Si
- When in liquid form it is a slurry of Fe and C with Fe being the solvent and C being the solute
- More carbon is present than can be dissolved by the iron
- Excess carbon forms graphite and carbides which weaken the tensile strength and reduce ductility in most cases
- Steel does not have this extra carbon nor appreciable amounts of Si

Making of Steel

- Taking cast iron and further reducing and refining it until the carbon content is less than 1 ½% and removing other elements to near zero steel is made
- When steel is in liquid form it is not saturated with carbon which occurs near 2% carbon 98% Fe
- Typical structural steels have 0.05 to 0.30% carbon
- Tool steels have higher carbon up to 1.2%
- Higher carbon can lead to higher strength and lower ductility

Iron-Carbon Phase Diagram

- Steel has less than 2% carbon
- Melting temperature is near 2800 F
- Multiple solid phases are possible all of which are crystalline
- The graph is for slow cooling
- Slow cooled to room temperature yields pearlite which is a particular microstructure of steel often found in structural steel
- Fast cooling (quenching) can have a huge effects on the type of steel microstructure you end up with

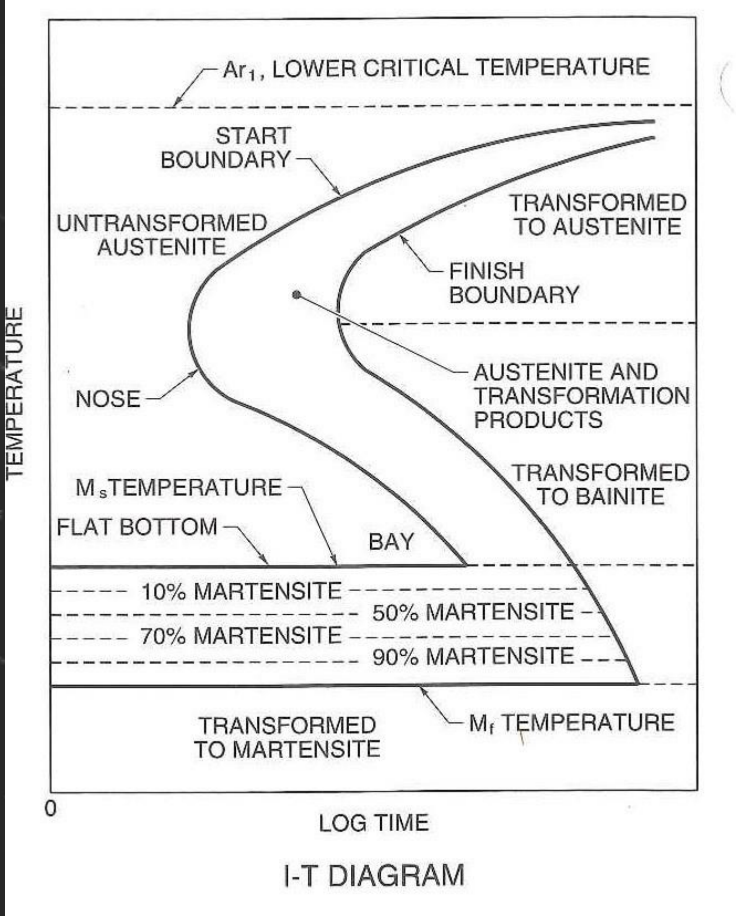


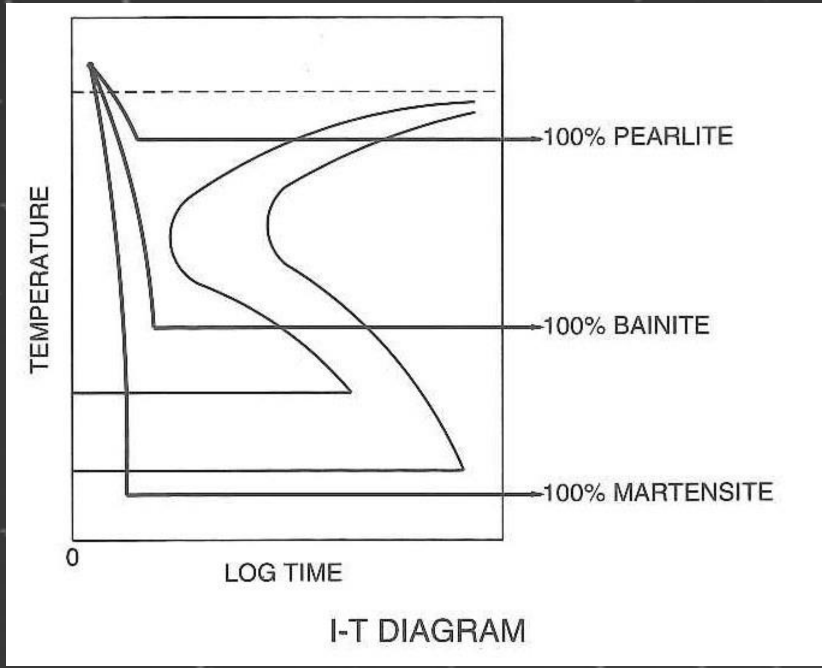
Effects of Carbon Content on Steel

Steel Type	Carbon Content %	Typical use
Low carbon	Less than 0.20	Modest strength high ductility Structural, ease of welding
Medium carbon	0.2 to 0.6	Higher strength with retained ductility machine parts
High carbon	0.6 to 1.5	High strength, very heat treatable, low ductility tools and cutters

- Carbon addition from 0% to 1.5% in iron has a significant effect on the strength properties of the steel
- Adding carbon alone and allowing to solidify slowly increase strength and lowers ductility
- More importantly the added carbon responds to rapid cooling by forming different microstructures when solidified at service temperatures
- In general an increase in strength causes a decrease in ductility.
- Fancy alloys other than carbon can obtain both high strength and ductility

Time-Temperature Transformation





Heat treatment of Steel

- By choosing the appropriate carbon content and heat treatment of steel the material properties can have a very large range
- Heat treatment usually involves heating the steel up to a critical temperature (typically 1400 F in carbon steels) which turns the solid crystalline microstructure from ferrite, pearlite, cementite, etc into austenitie.
- Austenite is non magnetic which is one way to tell you are at temperature, also red-orange in color
- The carbon content and cooling rate will determine the resulting microstructure

Heat treating steel

- Ferrite and pearlite are common structural steel microstructures which have moderate strength and good ductility. Low carbon steels often result in this type of microstructure reguardless of quench rate

- Martensite is common for high strength steels. It is very brittle as quenched and must be tempered (post heat treatment) to restore some ductility.

- Untempered martensite is very brittle and notch sensitive. It is to be avoided. Welding high carbon steels have leave such microstructures

Summary of Steel

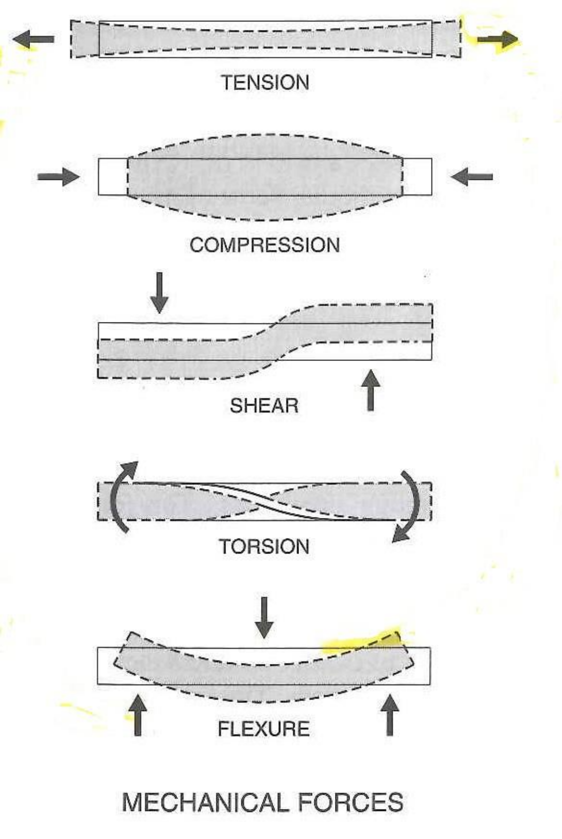
- A low carbon (less than 2%) solid solution of iron and carbon
- Often heat treated to alter strengths
- Huge range of strengths available   30 to 300 ksi tensile strength
- Huge range of ductility   1% to 25%
- Excellent fatigue strength including an endurance limit
- Generally easy to fabricate with

Engineering Properties of Steel

- Steels are typically characterized by physical testing of representative specimens

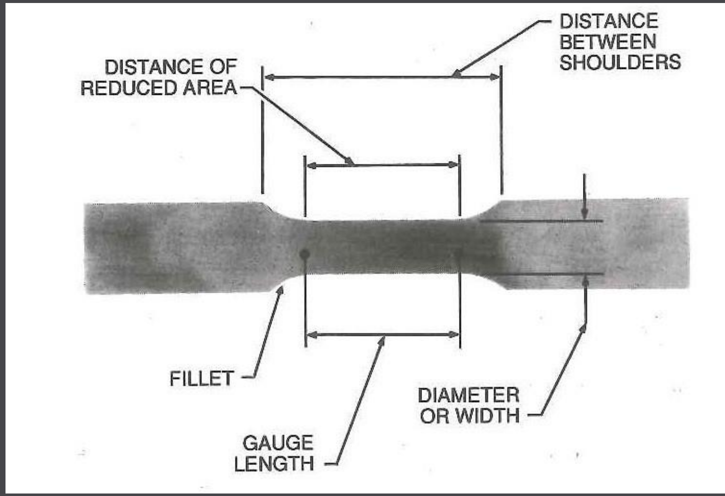
- Import tests are tensile, toughness, hardness, chemistry

General Mechanical Loadings

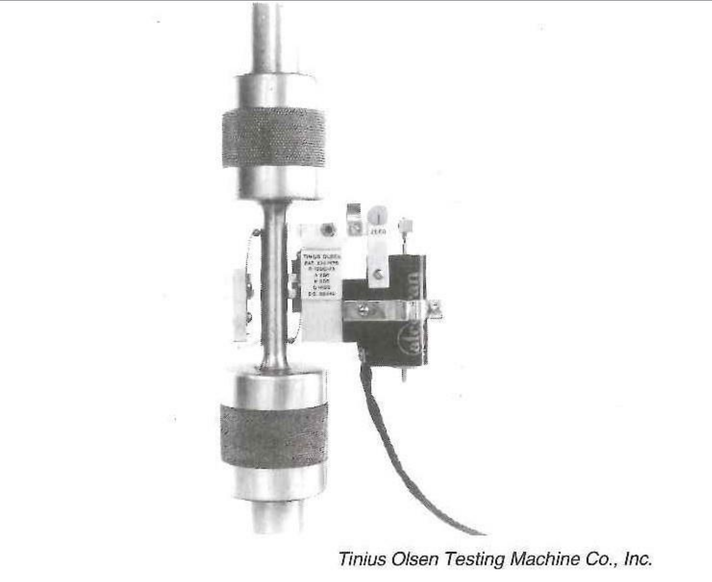


Tensile Testing is most common

Test specimen



Tensile Testing Machine



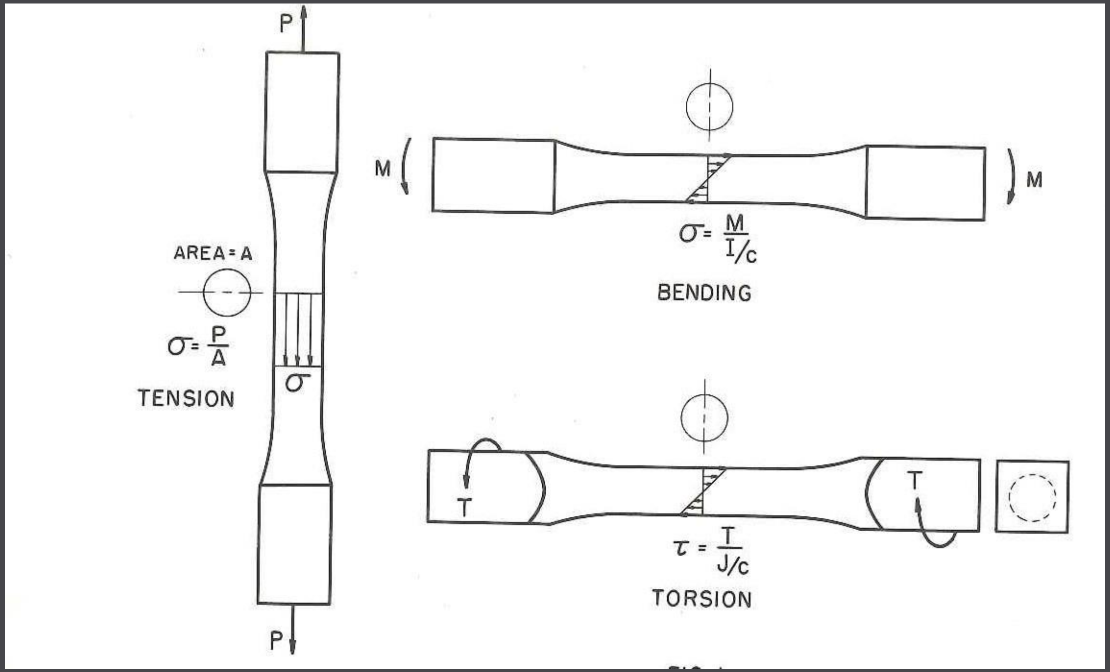
Data presentation: Stress vs. Strain

Force on test specimen

- The test machine applies a precisely measured tensile force to the specimen
- Engineering **Stress** is defined as the applied force divided by the reference area of specimen, typically the reduce cross sectional area

Elongation of the test speciment

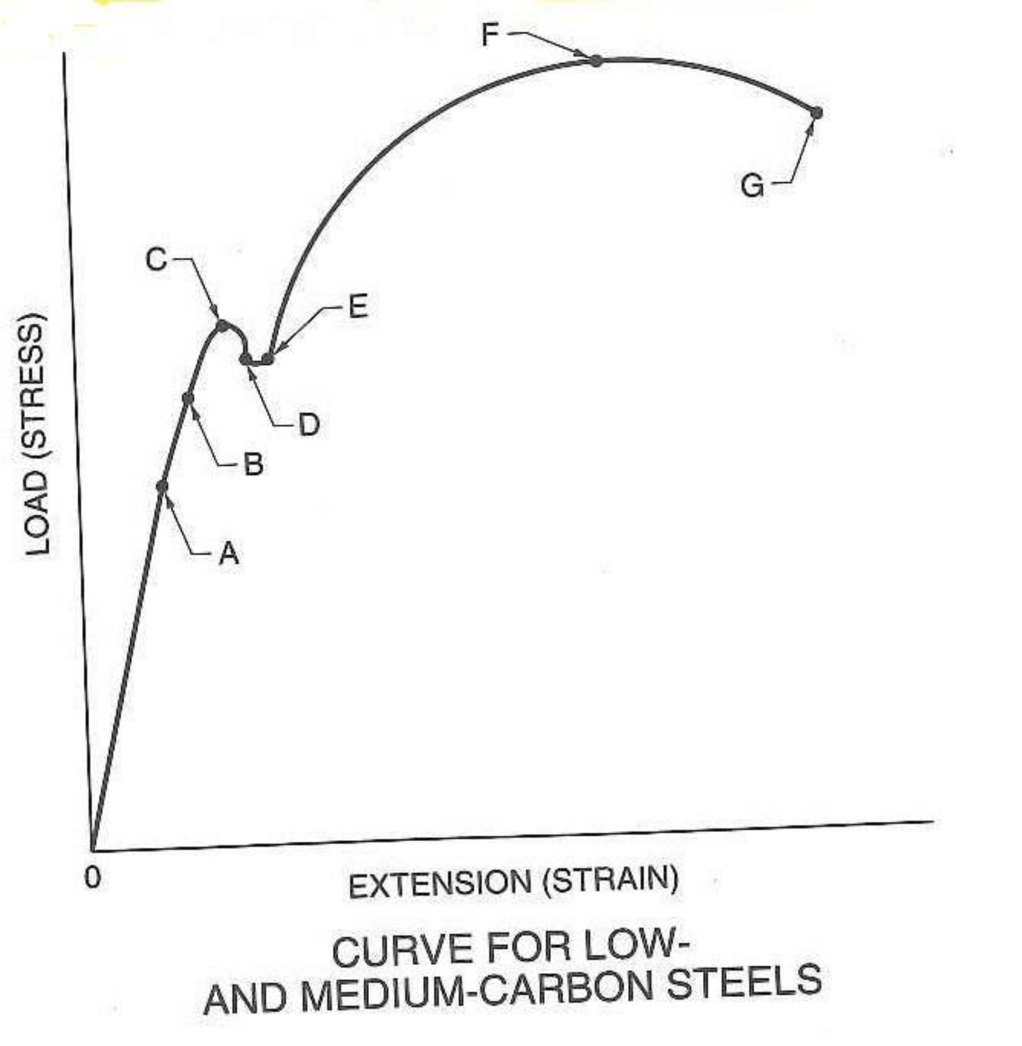
- The loaded test specimen stretches (elongates) and is elongation over a reference gage length is precisely measured
- Engineering **Strain** is defined as the measured stretch divided by the unloaded reference gage length



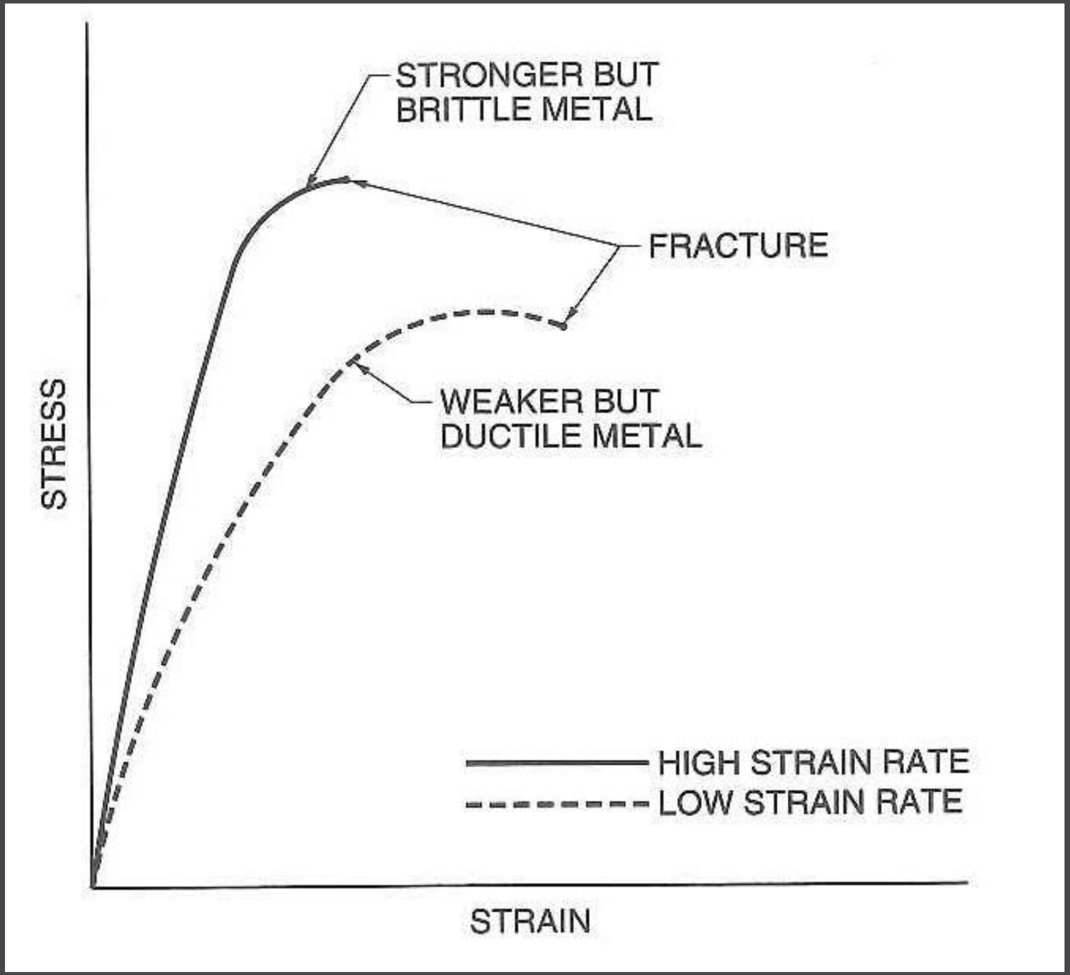
Common Stresses

Typical Tensile Test Results for Ductile Steel

- A- Proportional limit
- B- Elastic limit
- C- Yield Point
- E- Lower yield point
- F- Ultimate tensile strength
- G-Point of Failure



High strength steel behaves differently

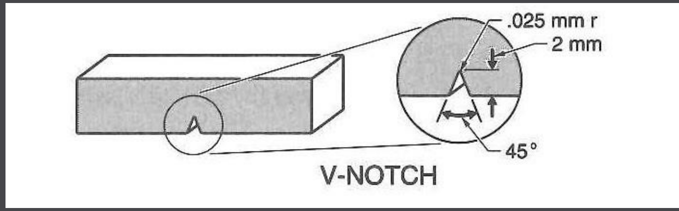


Strength range of common carbon steels

Steel type	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)
Low carbon ASTM A36	36 to 40	58-80	22-25
Medium Carbon SAE 1045	70 to 180	85 to 265	< 11%
High Carbon SAE 1090	100-150	185-220	< 5%

Toughness Testing

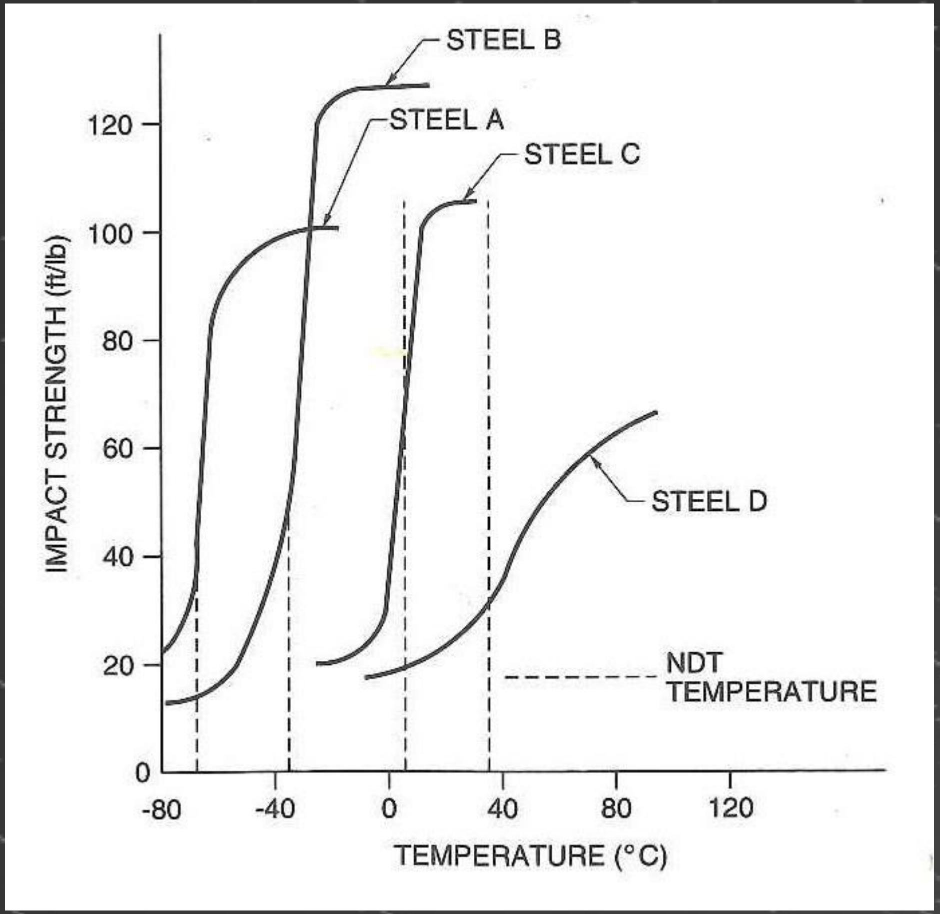
Specimens are tested at different temperature



Impact loading with falling hammer

Charpy V-notch toughness test results

- Carbon steels have a Body-Center-Cubic BCC crystalline structure which leads to a loss of ductility at low temperatures
- Ductile steels can behave in a brittle manner at low temperatures and/ or high loading rate
- CVN toughness is measured in energy absorbed (ft-lbf) at a given test temperature

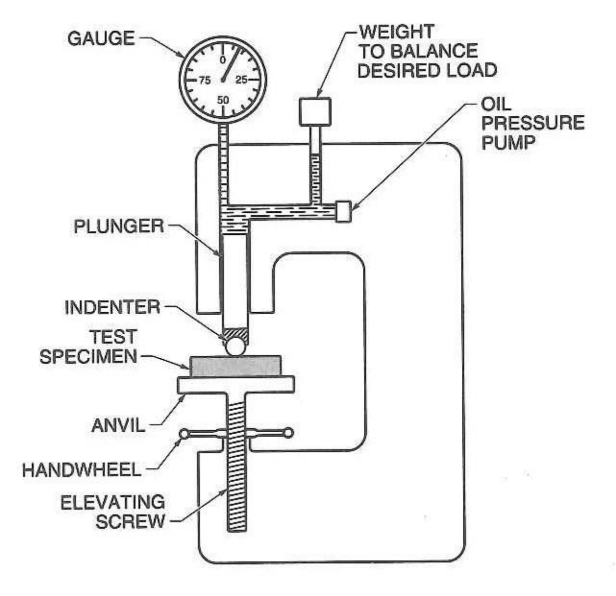


Hardness Testing

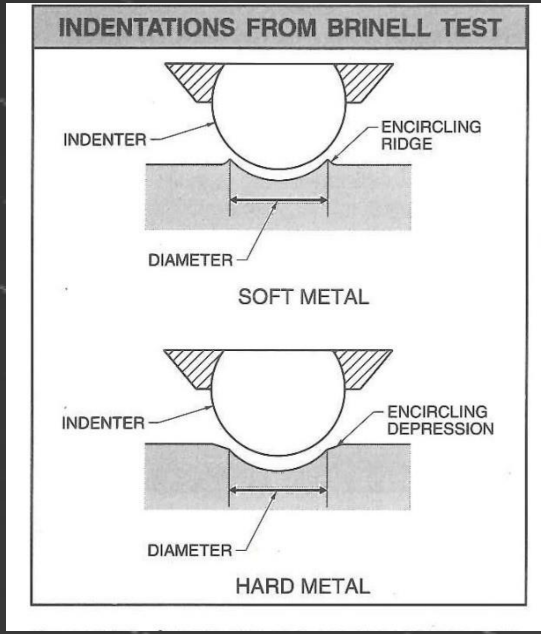
- Hardness testing is used to quickly assess the tensile strength of steel, especially following heat treatment
- A test machine applies a controlled load on a pointed indentor which produces a dimple in the test specimen.
- The softer the steel, the larger the indent
- Many scales exists for harness testing depending on the material being tested
- Common hardness scales used for testing steel are Rockwell B and C, Vickers and Birnell

Hardness Testing

- Schematic of test machine



- Deformation details of indent



Chemical Analysis of Steel

- The chemical content of steels is commonly provided with the materials certifications when purchased
- The AWS steel welding code provides a simple equation to calculate the hardenability of steel using the Carbon Equivalent
- Steel with C.E. > 0.45 needs special care when welding (usually preheat) to prevent brittle behavior of the welded joint
- For common structural steels weldability is typically not a problem
- If in doubt add 200 to 300 F preheat before welding

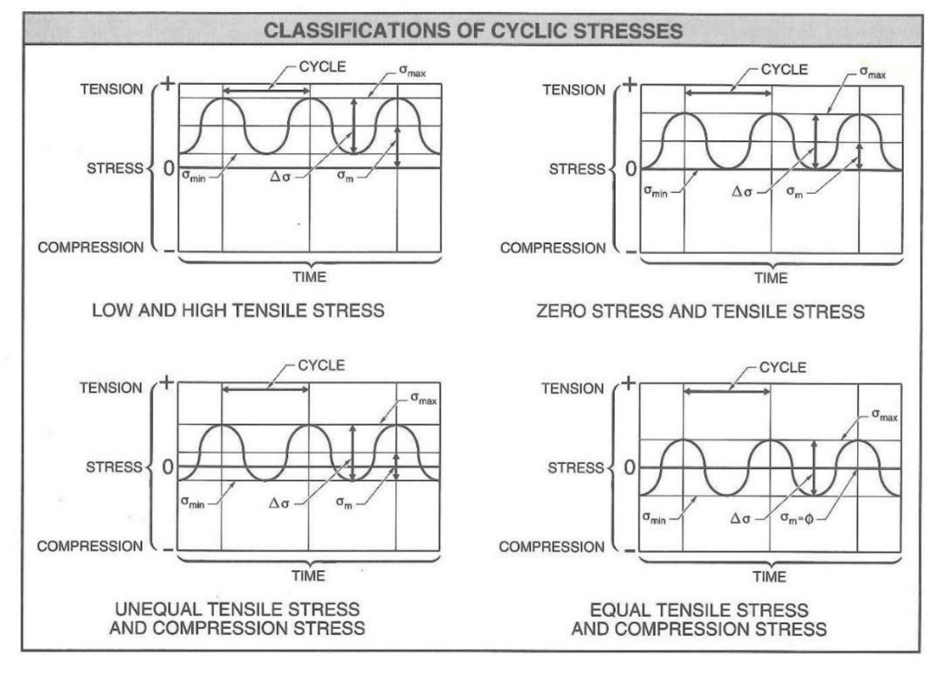
Fatigue Performance of Steel

- Metal fatigue is cumulative damage from repetitive alternating stress cycles

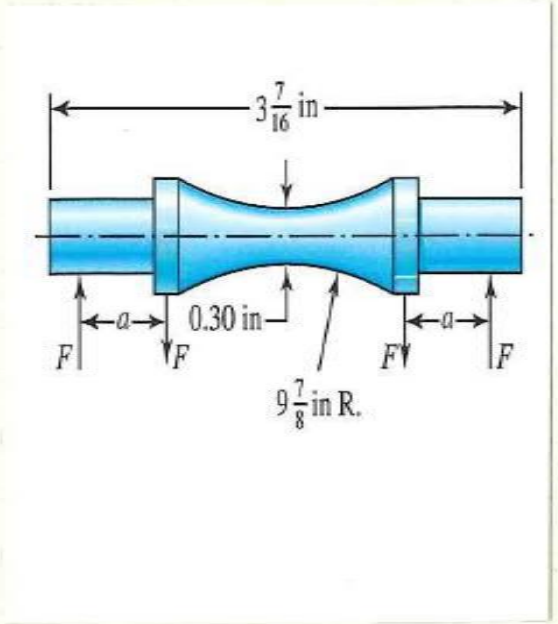
- The amplitude of the alternating stress is of primary importance

- The stress ratio (max / min) has a secondary effect

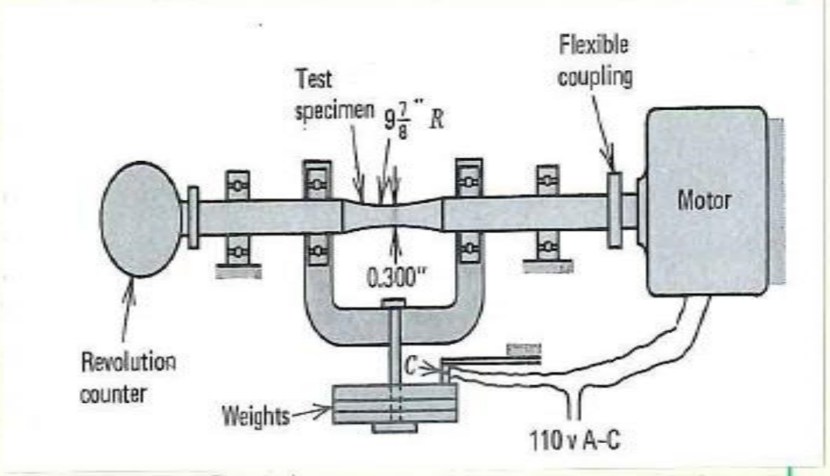
- Fatigue failures can occur at relatively low stress ranges compared to tensile strengths



Moore Rotating Fatigue Test Machine

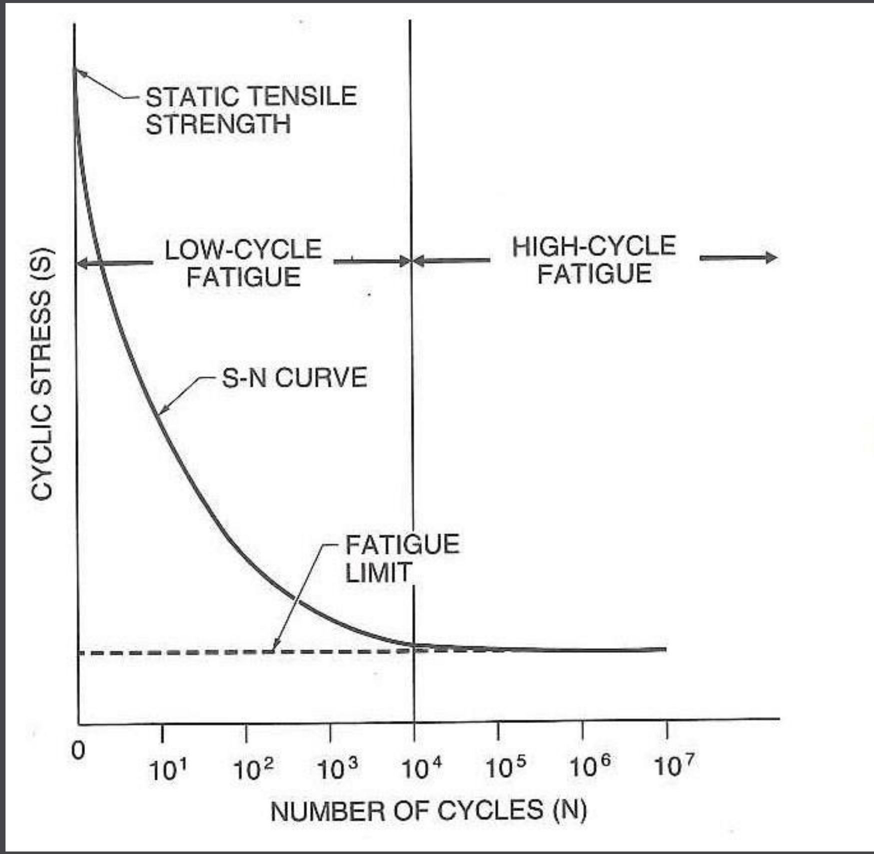


Test Sample



R.R. Moore Fatigue test Machine

Stress –Life (S-N) Fatigue Test Data

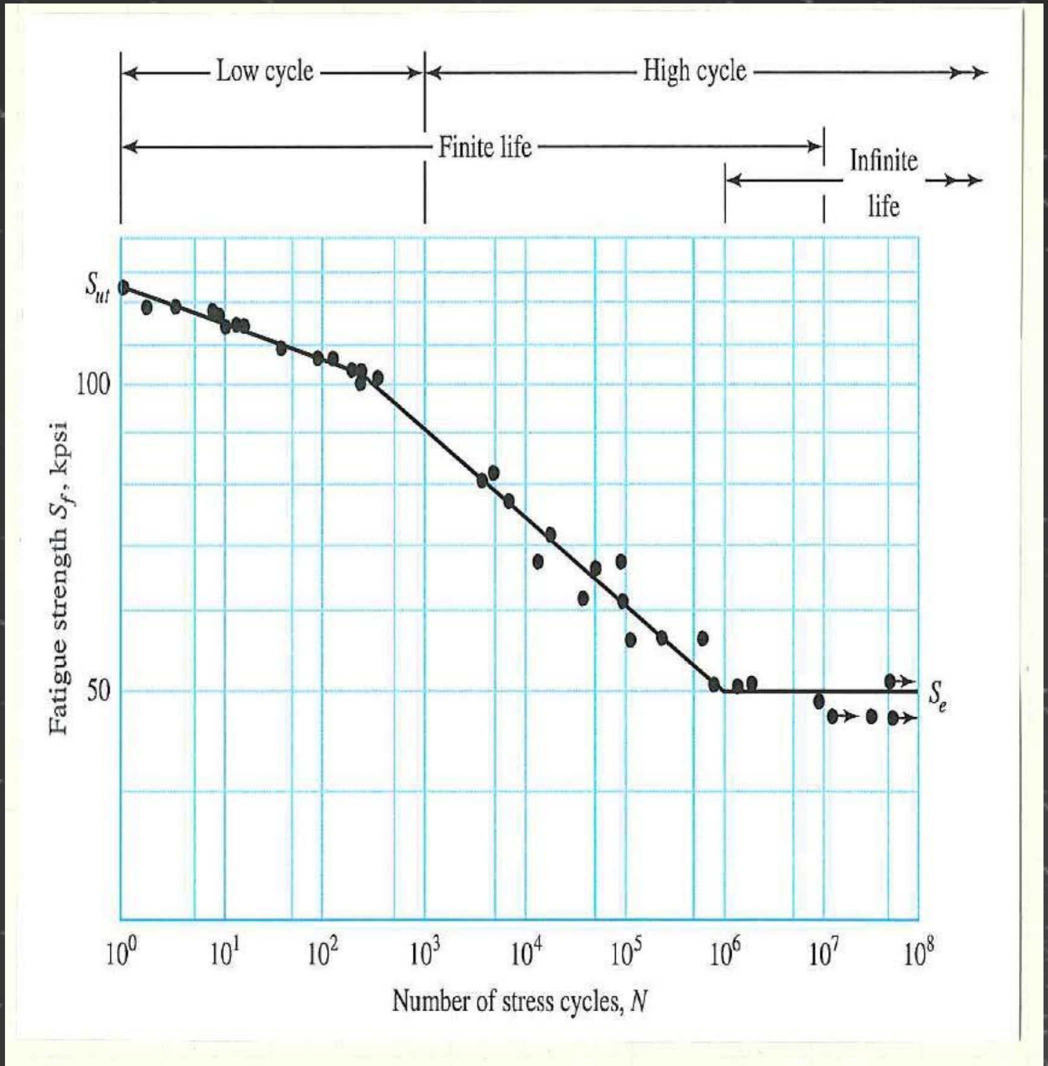


The S- N diagram

- Very high stress ranges produce short fatigue lives (N < 1000 cycles) called low cycle fatigue

- Moderated stress ranges produce a finite fatigue life (1000 < N < 1,000,000 cycles) called high cycle fatigue

- Stress ranges below the endurance limit will yield infinite fatigue life (N = infinite)

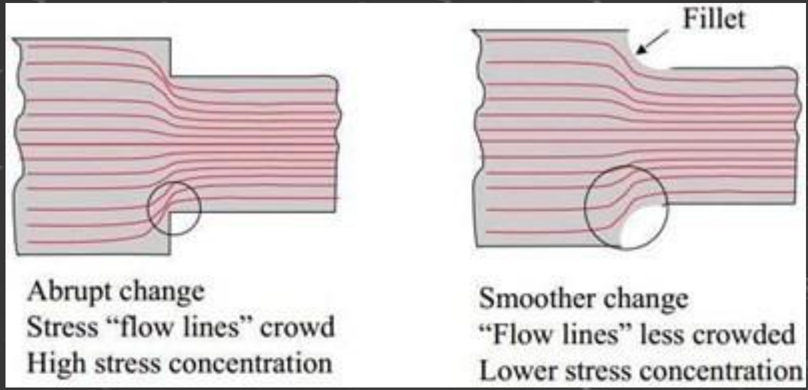


The Endurance Limit

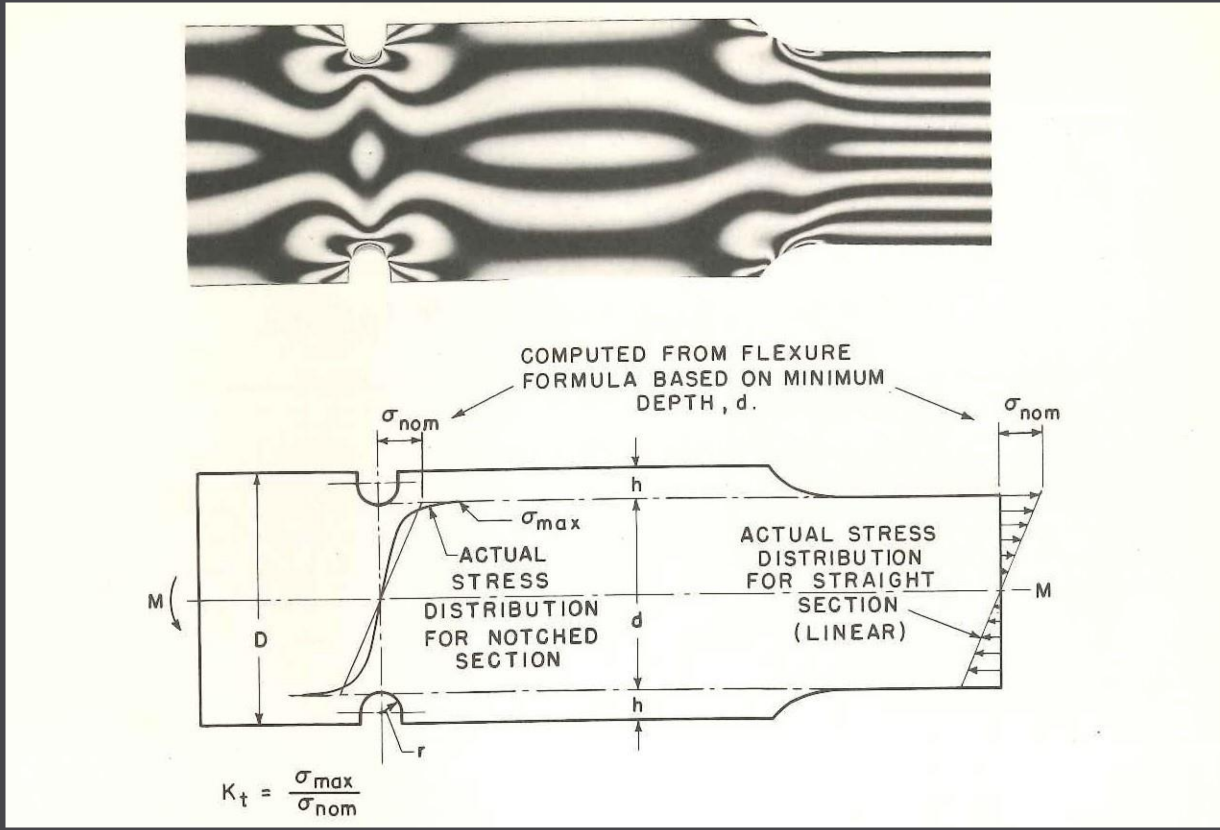
- Steel is one of the few engineering materials that exhibits an endurance limit with respect to cyclic loading
- It is common to design steel components to have an infinite fatigue life
- Notches, cracks and other geometric defects can make the endurance limit disappear and cause a shortened service life
- The endurance strength of a steel is approximately 40% of the tensile strength. Higher strength steels have a higher endurance limit in general.

Notches, sharp corners and holes

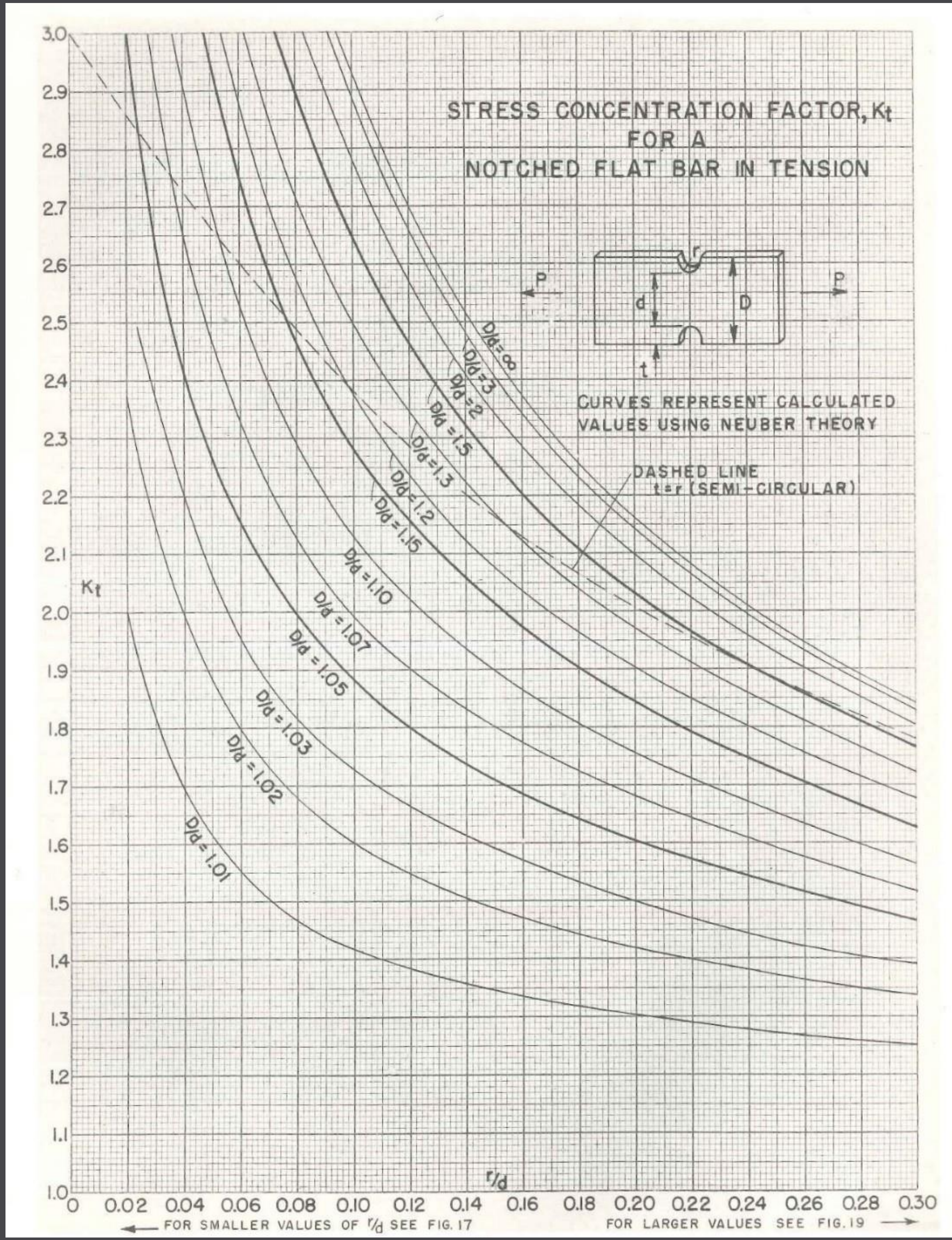
- Geometric defects such as sharp notches, corners, changes in section cause a stress concentration
- The stress field is locally magnified by these defects
- Most fatigue and brittle failure originate as these types of defects



Example Stress Concentration

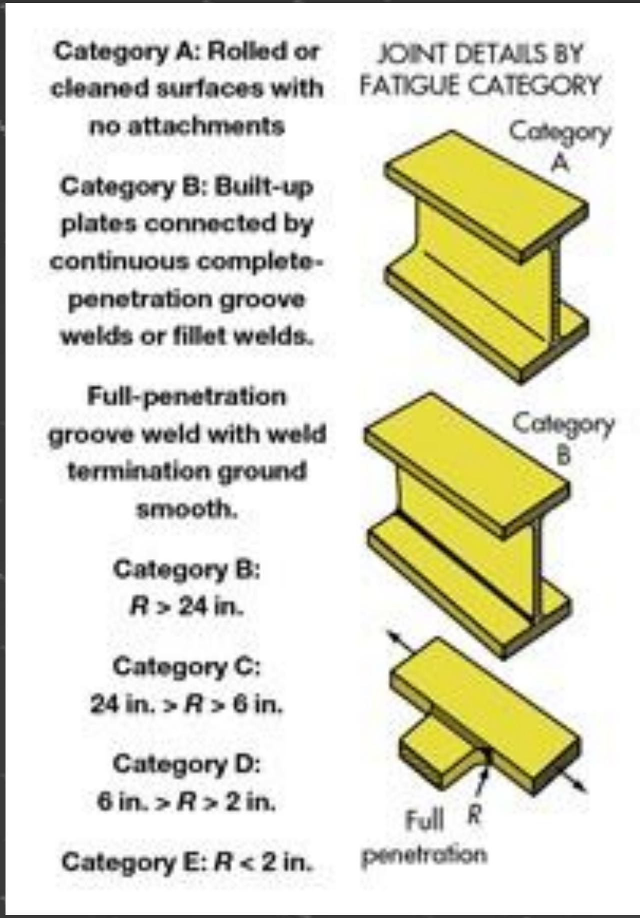


$K_t = 2$ to 3

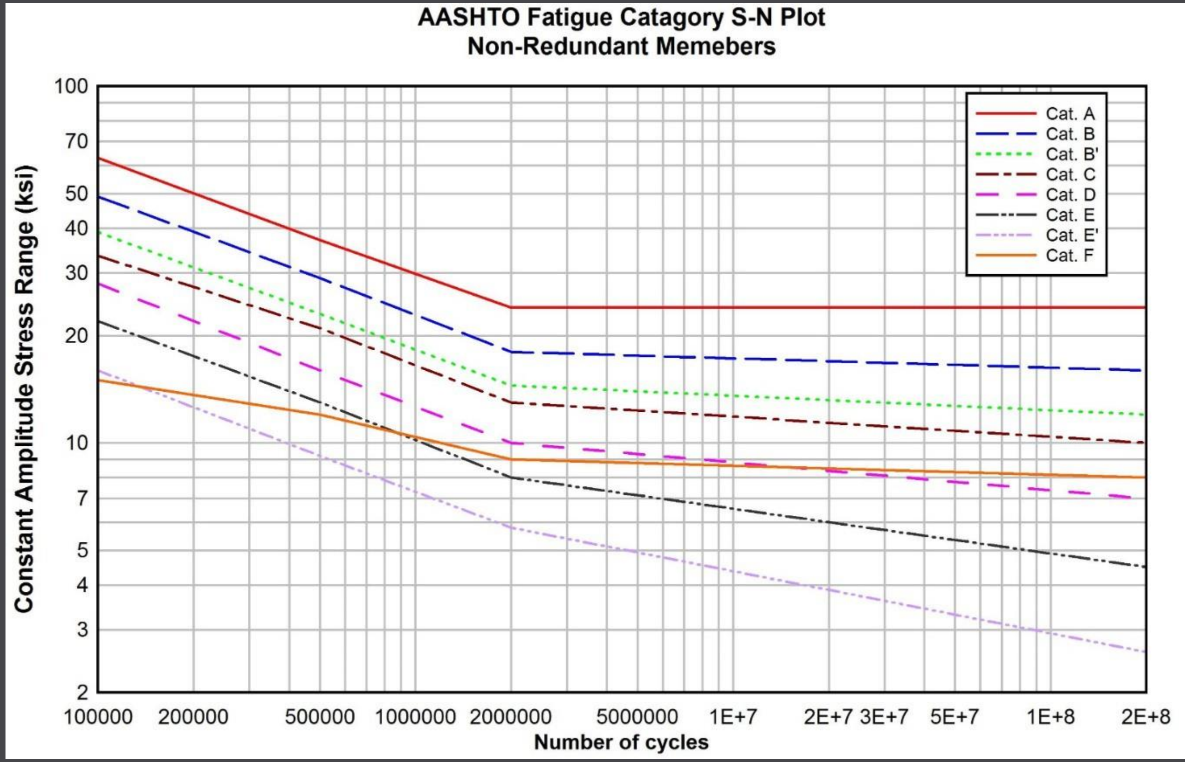

STRESS CONCENTRATION FACTOR, Kt
FOR A
NOTCHED FLAT BAR IN TENSION
CURVES REPRESENT CALCULATED VALUES USING NEUBER THEORY
DASHED LINE
t=r (SEMI-CIRCULAR)
Kt
r/d
D/d=∞
D/d=3
D/d=2
D/d=1.5
D/d=1.3
D/d=1.2
D/d=1.15
D/d=1.10
D/d=1.07
D/d=1.05
D/d=1.03
D/d=1.02
D/d=1.01
FOR SMALLER VALUES OF r/d SEE FIG. 17
FOR LARGER VALUES SEE FIG. 19

Welding Affects Fatigue

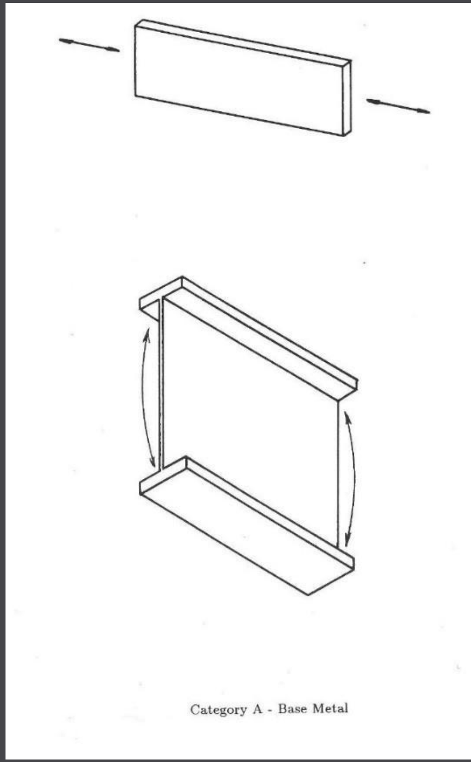
- Welds typically aggravate the fatigue problem by adding sharp geometric features and high residual stress
- The fatigue strength of common welded details has been well tested and documented
- The tensile strength of the welded steel has little effect on the fatigue strength



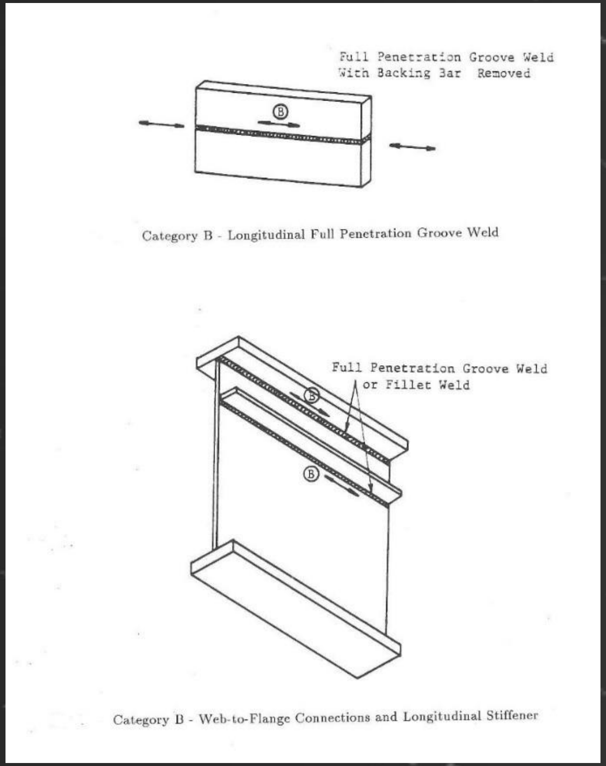
The higher the stress concentration the shorter the fatigue life

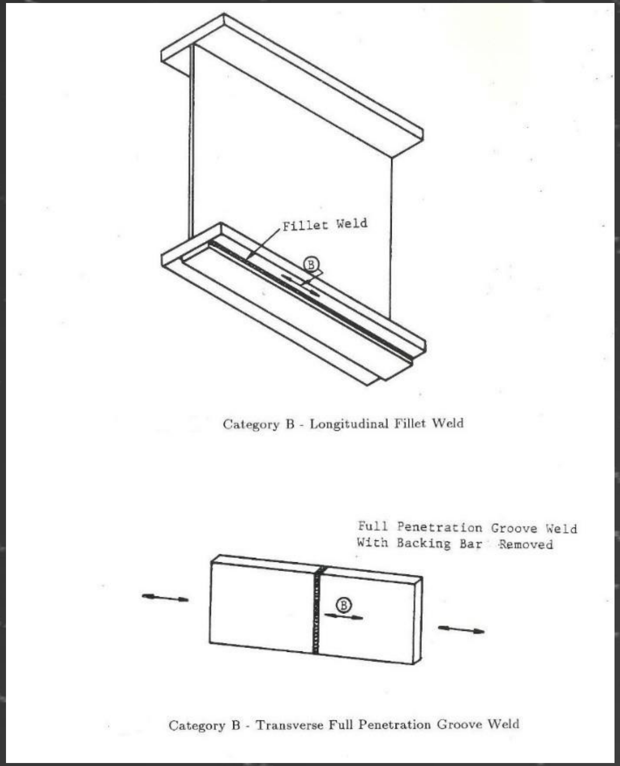


Example Category A
(No stress concentrations or welds)

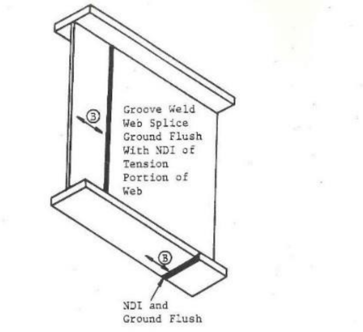


Example Category B details

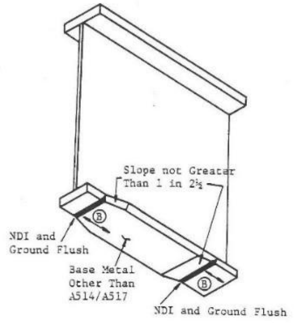




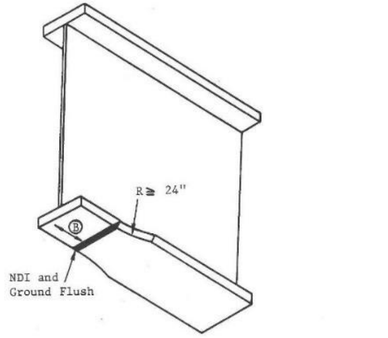
Example Category B details



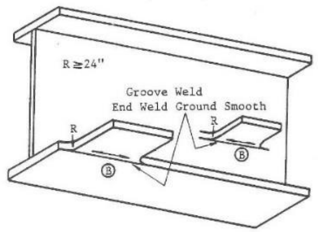
Category B - Traverse Groove Weld, NDI and Ground Flush



Category B - Transverse Groove Weld, Straight Transition

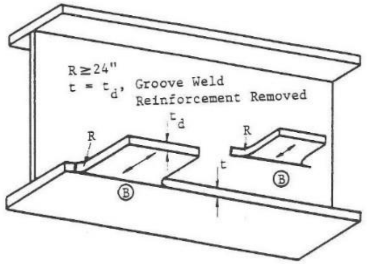


Category B - Transverse Groove Weld, Curved Transition

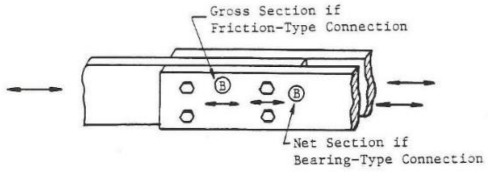


Category B - Groove-Welded Attachment, Weld Parallel to Stress

Example Category B details

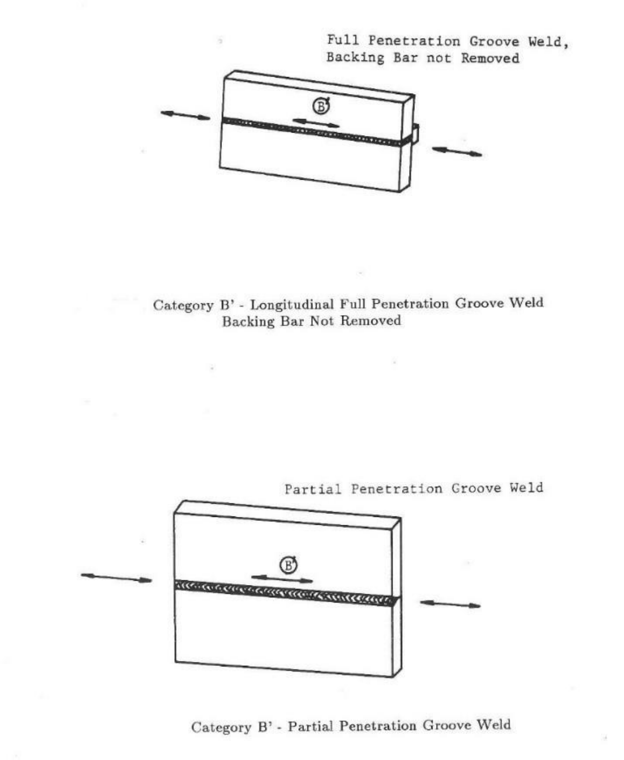


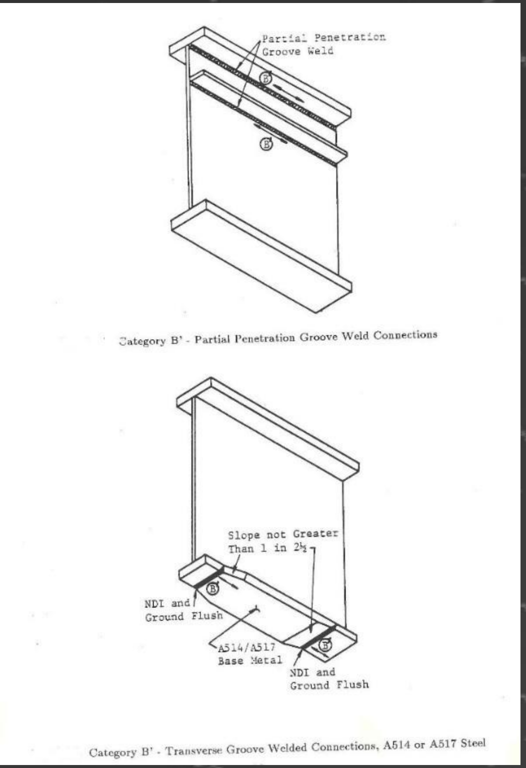
Category B - Groove-Welded Attachment, Weld Transverse to Stress



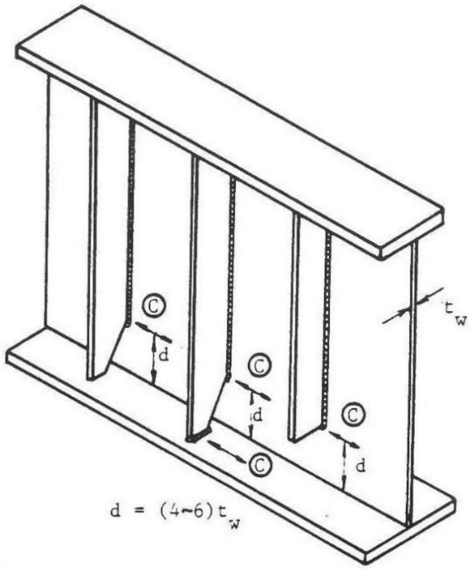
Category B - Bolted Connection

Example Category B/details

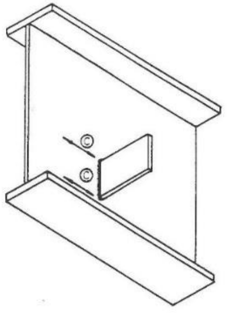




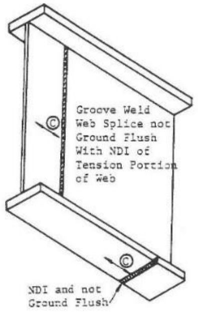
Example Category C details



Category C - Transverse Stiffeners on Web

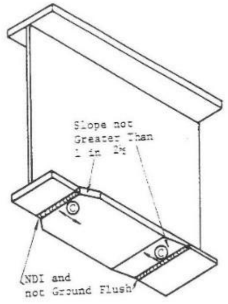


Category C - Transverse Gusset Plate on Web

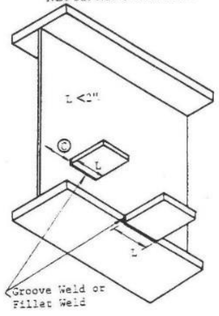


Category C - Transverse Groove Welded Splice, NDI but Not Ground Flush

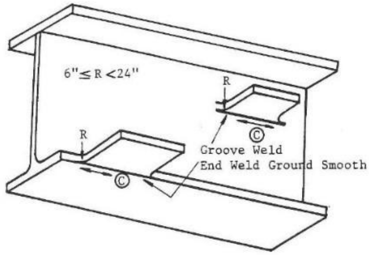
Example Category C details



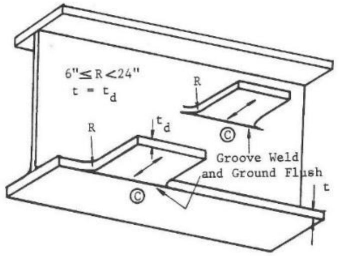
Category C - Transverse Groove Welded Flange Splice, NDI but Not Ground Flush



Category C - Groove or Fillet Welded Short Attachment

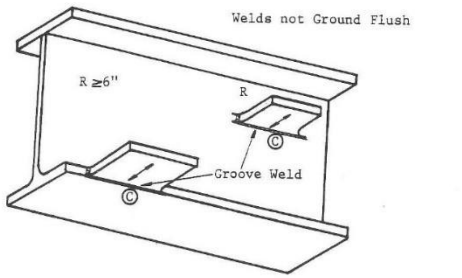


Category C - Longitudinal Groove Welded Attachment Intermediate Transition Radius

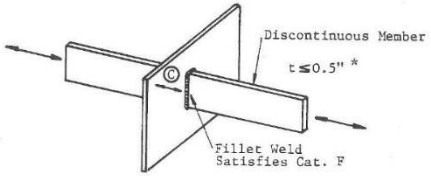


Category C - Transverse Groove Welded Attachment, Intermediate Transition Radius

Example Category C details

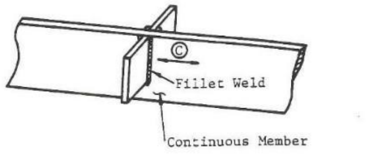


Category C - Transverse Groove Welded Attachment, Weld Not Ground Flush

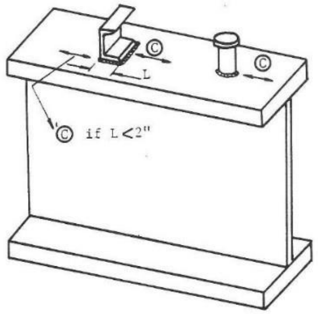


* Reduction of fatigue strength if t > 0.5"

Category C - Fillet Welded Connection (Load Carrying)

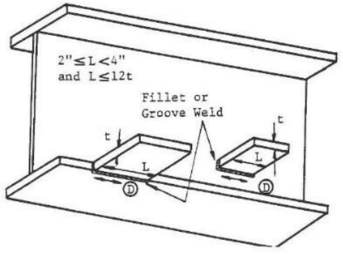


Category C - Fillet Welded Connection (Non Load Carrying)

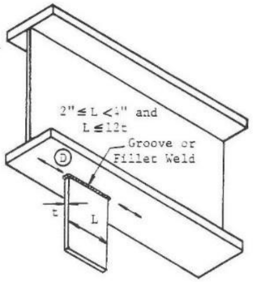


Category C - Stud Shear Connectors

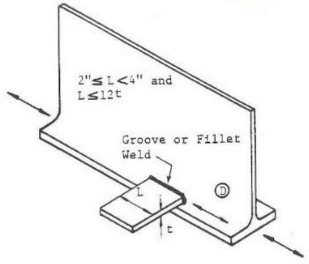
Example Category D details



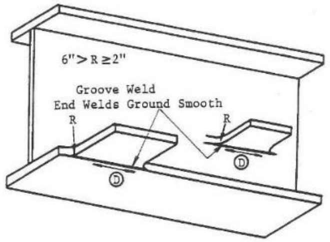
Category D - Groove or Fillet Welded Attachment, Intermediate Length



Category D - Welded Gusset Plate, Intermediate Length

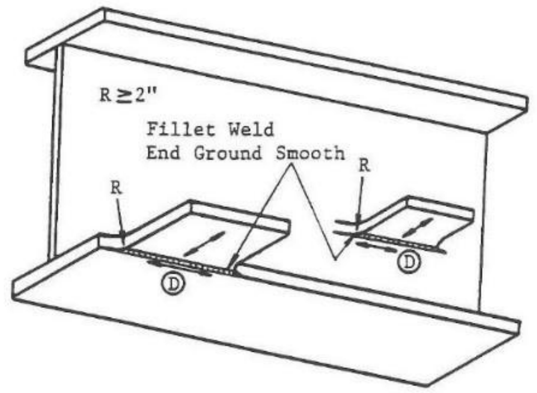


Category D - Welded Gusset Plate on Rolled Shape, Intermediate Length

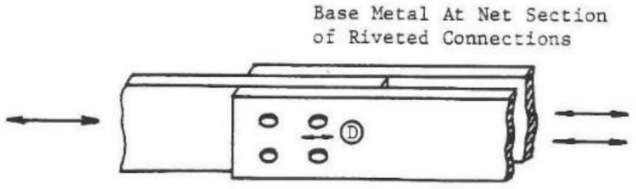


Category D - Longitudinally Welded Attachment, Short Transition Radius

Example Category D details

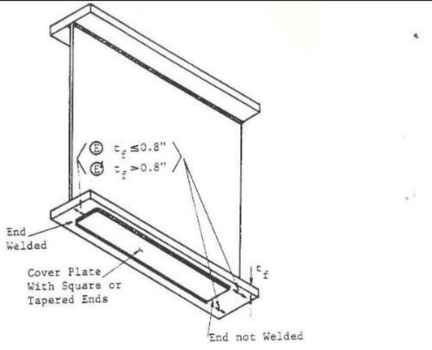


Category D - Fillet Welded Attachment,
Transition Radius 2" or More

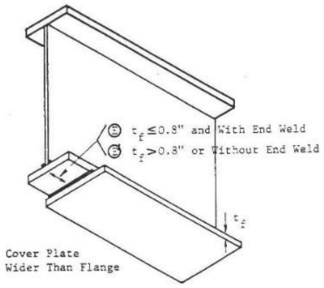


Category D - Riveted Connections

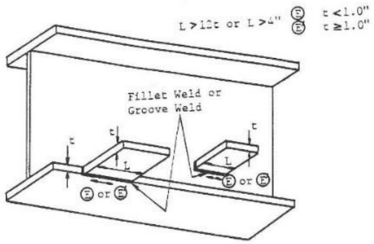
Example Category E and E/ details



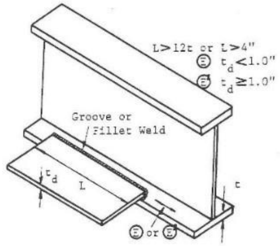
Category E or E' - Ends of Welded Cover Plate



Category E or E' - Ends of Wider Cover Plate

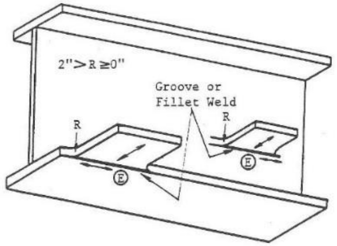


Category E or E' - Longitudinal Welded Attachment

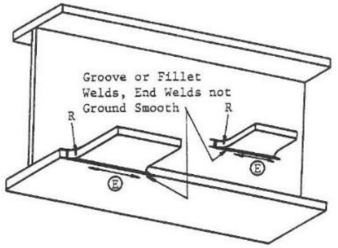


Category E or E' - Longitudinally Welded Attachment (Lap Joints)

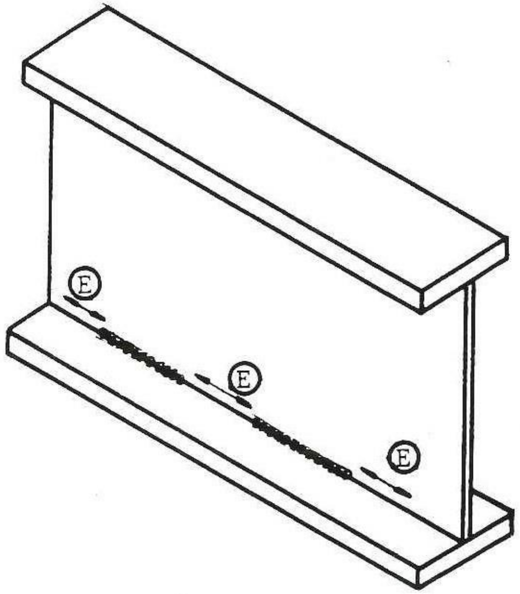
Example Category E and E′ details



Category E - Welded Attachment,
Very Short Transition Radius

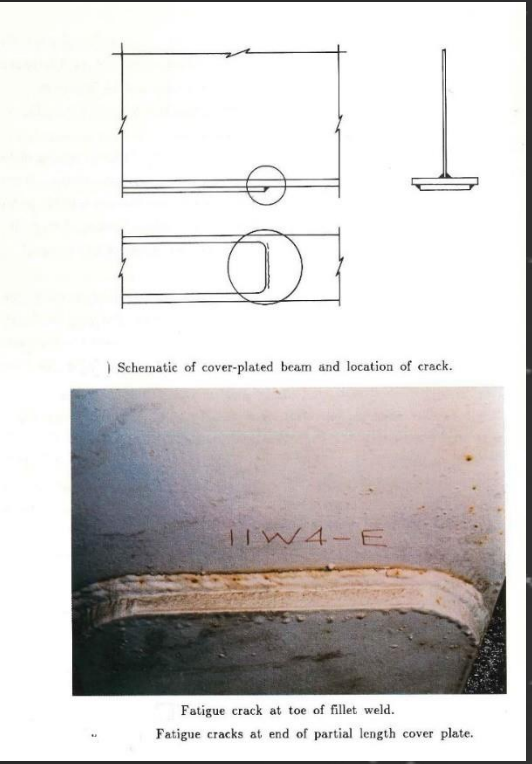


Category E - Longitudinally Welded Attachment,
Any Transition Radius



Category E - Intermittent Fillet Welds

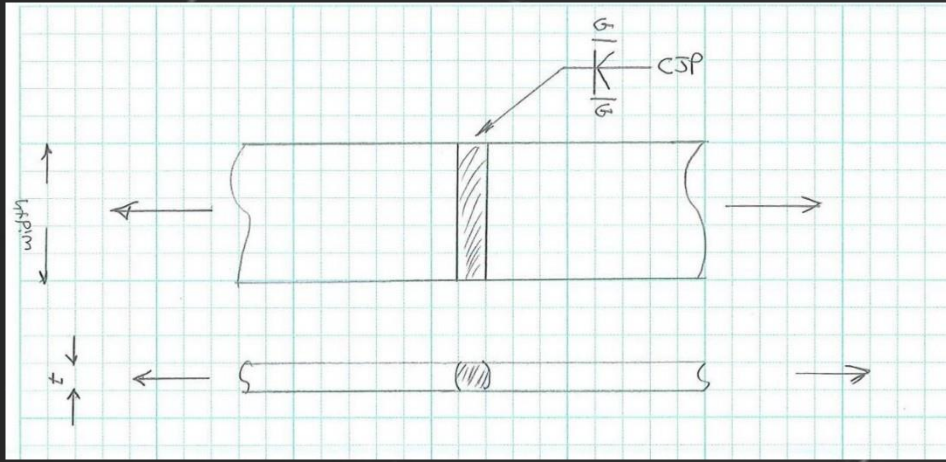
Example Category E and E' details



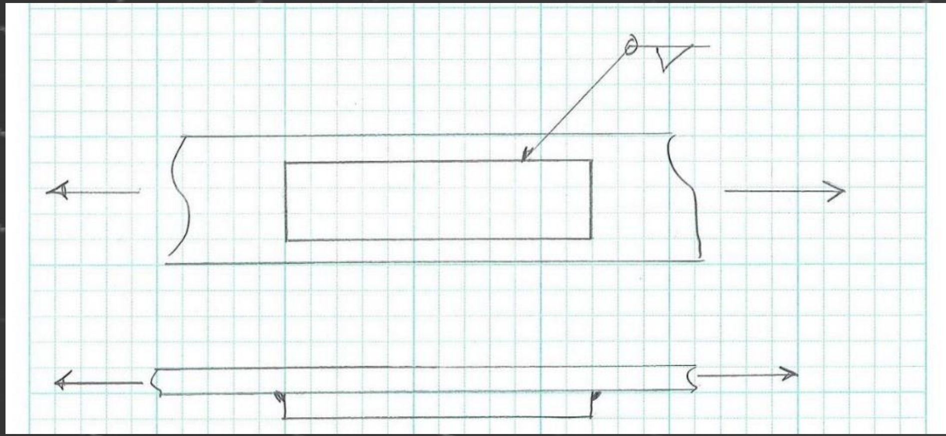
- Under direct stress loading only E and E' details are likely to develop cracks under common service loading

Best and worst welded fatigue details

- Category B CJP butt weld, ground smooth



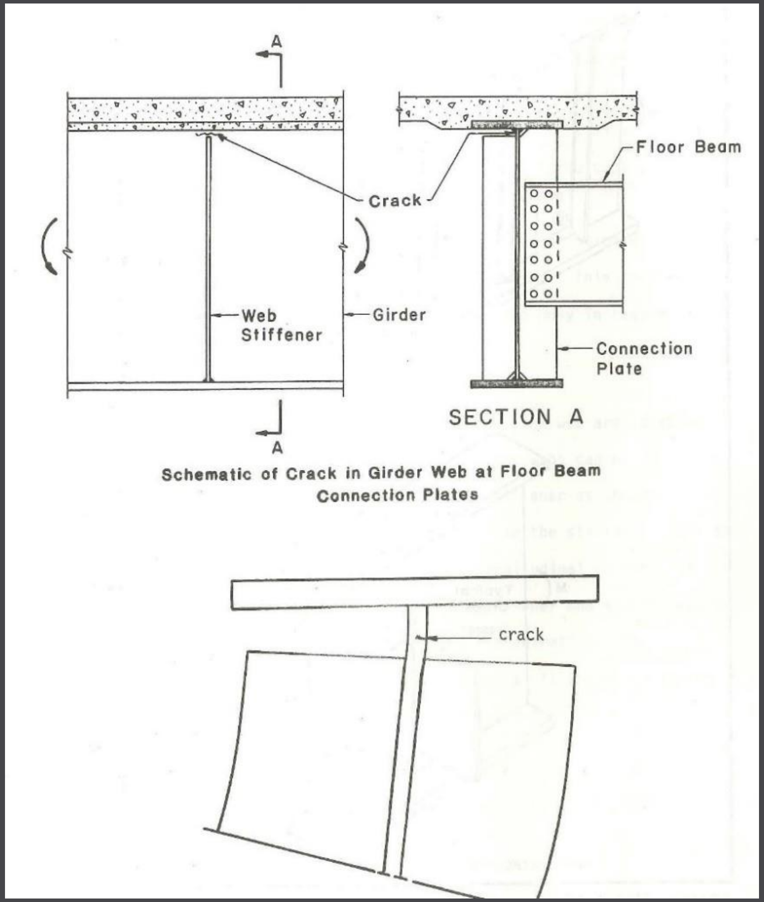
- Category E' Added cover plate



Welded Structure Summary

- Welding when properly designed and installed will match the strength and ductility of the parent structure
- Poor design or installation practices can greatly reduce the strength and ductility of welded structures
- Most bridge and structural steels are very weldable provided good design and workmanship are included
- If the carbon content of the steel is unknown, preheat is always your friend when welding

Distortion induced fatigue is far more common than direct loading induced fatigue

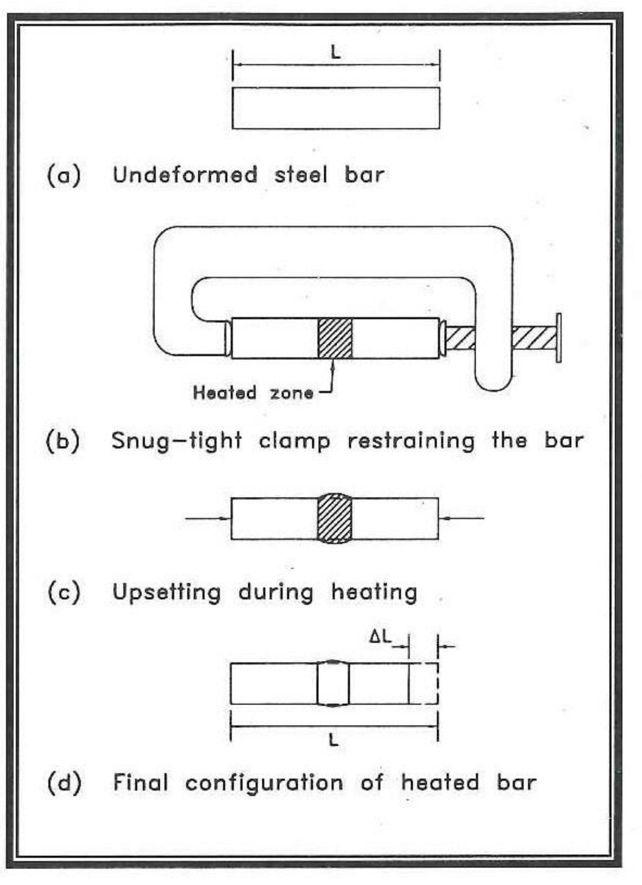


Heat Straightening of Steel Structures

How to get this straight again?

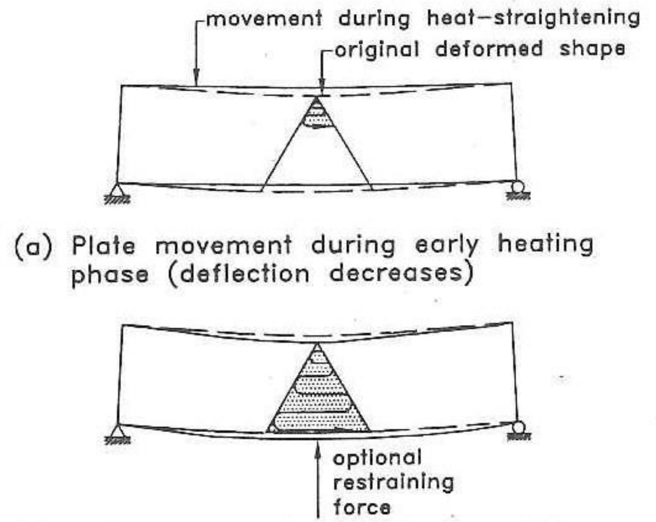
Thermal expansion induced yielding

- Steel will elongate when heated if it is not constrained
- If it is prevented from elongating, compressive stresses build
- If yielding occurs, the part will shorted when cooled



Basic heating pattern for a bent beam

- Overload caused top flange to compress and bottom flange to stretch
- Heat pattern will reverse this deformation (bottom flange is heated in a strip shape)
- Optional restraining force expedites the movement per heat cycle



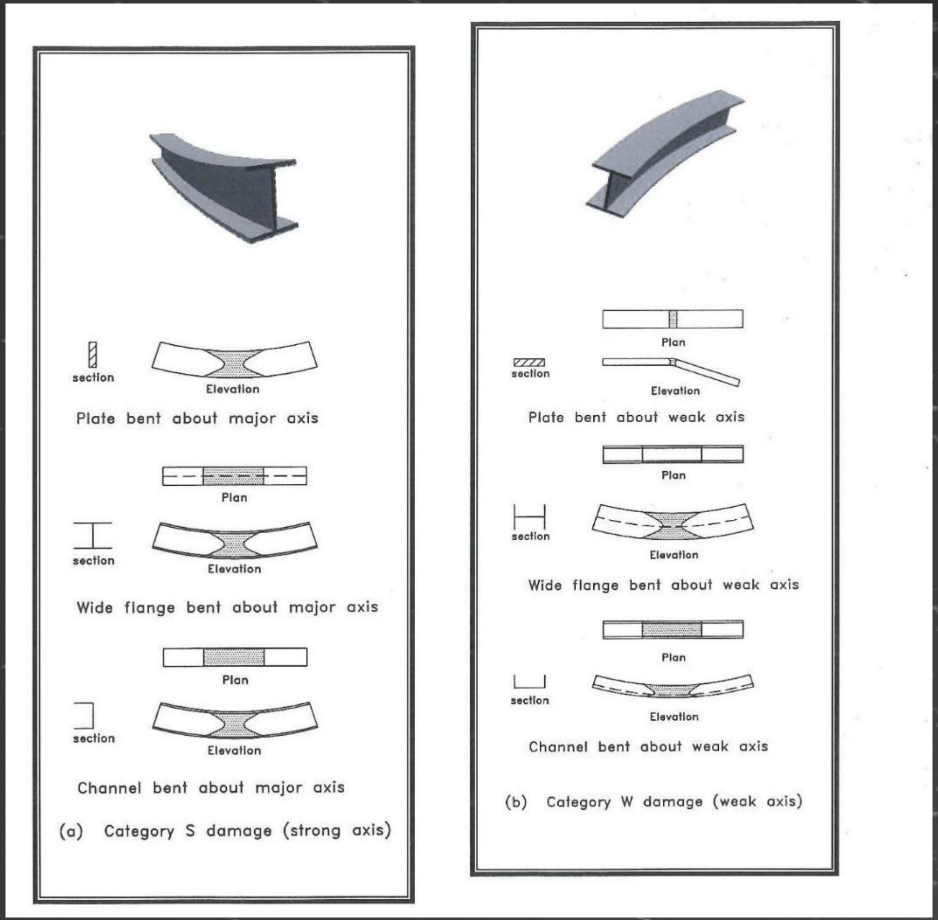
(a) Plate movement during early heating phase (deflection decreases)

(b) Plate movement near the completion of heating (deflection increases)

(c) Final position after cooling (deflection decreases)

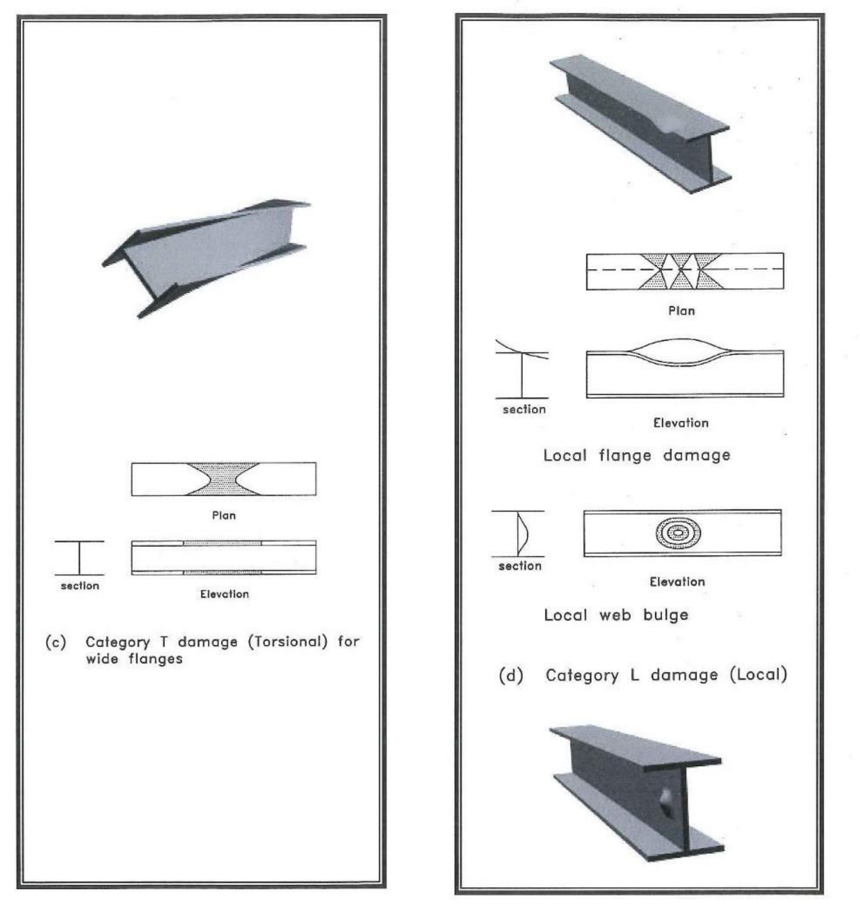
Strong and Weak Axis Repairs

Both V and Strip heat patterns are applied is successively overlapping regions



Torsional Axis and Localized Dimpling Repairs

V, Strip and circular heat patterns are used



FHWA has published useful guides for heat straightening

Heat-Straightening Repairs of Damaged Steel Bridges

A technical Guide and Manual of Practice

FHWA-IF-99-004

October 1998

Guide for Heat-Straightening of Damaged Steel Bridge Members

FHWA-IF-08-999

August 2008

FHWA and Texas DOT have sponsored studies on the effects of heat straightening bridge members multiple times

EFFECTS OF BENDING AND HEAT ON THE DUCTILITY AND FRACTURE TOUGHNESS OF FLANGE PLATE

FHWA/TX-10/0-4624-2

March 2012

Hot Working versus Heat Straightening

Hot working

- Steel is heated above the transition temperature (1400 F)
- At high temp yield strength goes down and ductility goes up
- Mechanical force is used to move the steel
- Does not rely on thermal expansion

Heat straightening

- Steel is heated below the transition temperature (1200 F maximum)
- Strength is also reduced and ductility increased but to a smaller degree
- Applied forces are low and are intended to only apply constraint
- Constrained thermal expansion is used to move the steel

Proper Heat straightening requires patience and skill

- Constraining forces (jacks, chains, hoists and struts) are carefully applied to the member before heating in many cases
- Heat patterns are often marked out on the member as a guide
- Oxy/fuel rosebuds are used to apply localized heating
- Temperatures are typically control by experience and subtle changes in the color of the heating steel. Temp crayons and FLIR are used by novices and inspectors.
- Heats are applied and allowed to cool and then applied again and again to different areas (5 to 10 heats is not uncommon).

Hot working is sometimes used

- Very localized deformations such as flange gouge can be straightened with localized hot working

- Mostly used for cosmetic repairs after the major straightening is complete

- Hot working is not used for major straightening unless a significant strength reduction in the finished member is acceptable

Scottsburg bridge Hit April 2017

Driver walked away after being cut out of the cab

Tractor frame is bent into a U shape

The bridge is shut down until repairs are made

Two Stages of Repairs

- Compression post L0-U1 is severally damaged and close to buckling under dead load only

- I have straightened this particular member 4 times since 1996 so the integrity of the steel is in question and the probability of another strike or three is not small.

- After heat straightening the member must be reinforced to maintain sufficient reliability

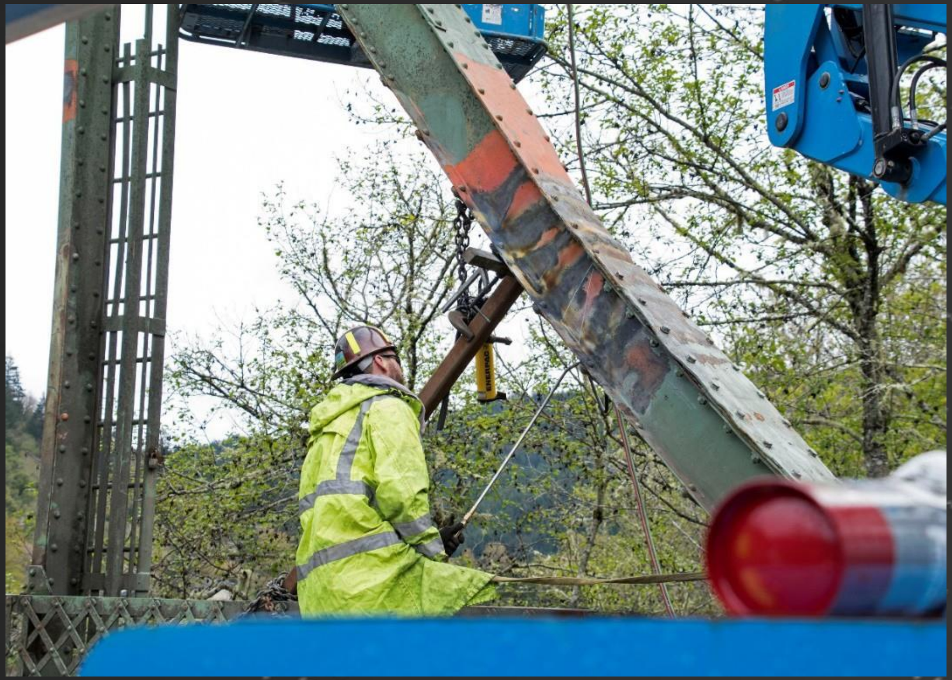
- In 28 years of this kind of work, this is by far the closest to collapse I have witnessed

First Straighten, then strengthen

Myself and Darrel Thomas discussing his approach to the repairs

Adding bracing with small jacks for restraint

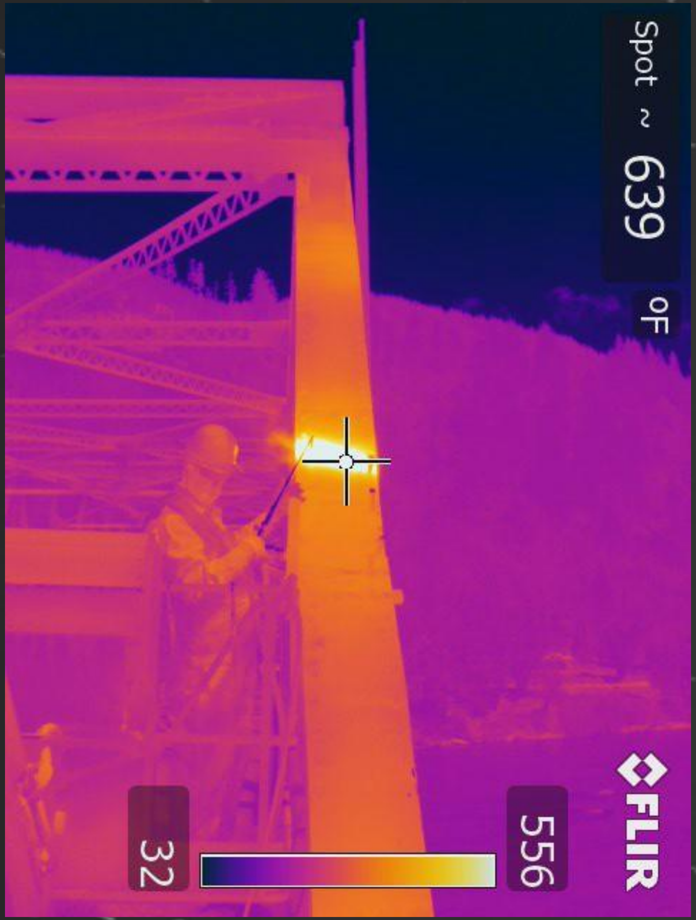
Applying V heat to the webs and strip heats to the top flange



Cool to hand touch after heat application

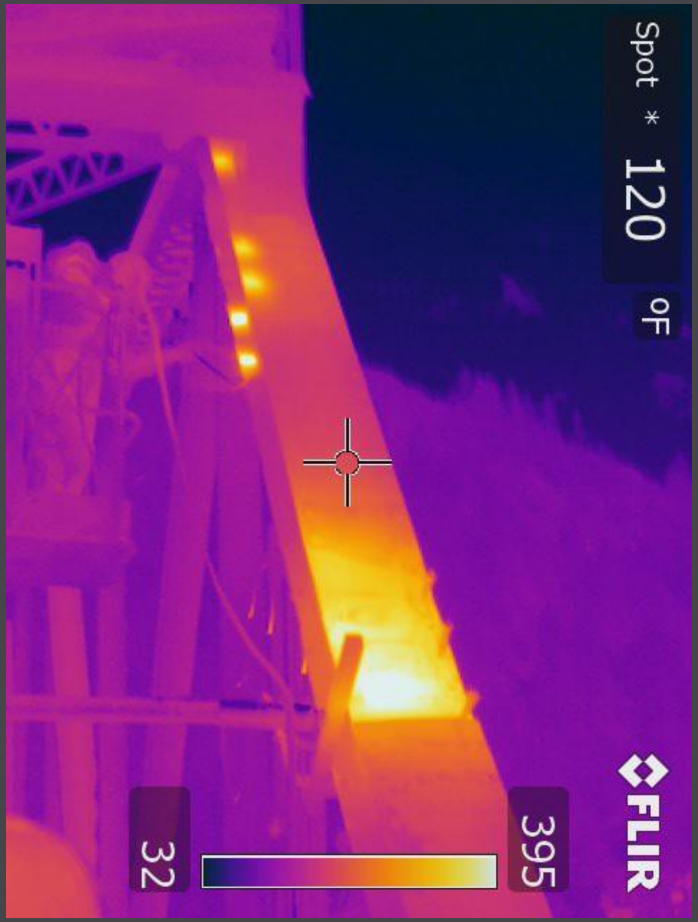
Working upper connection

Thermal Camera View of Heat Straightening



1220 F is the highest temperature I witnessed

Lower end cools while they start on the top



Repaired and Strengthened

Replace battens with slotted plates

A previous hit September 2014

Another previous hit September 2006

Other notes of interest

- Riveted steel bridge members are extremely tough and damage tolerant
- Many engineers like to get very worried about fracture critical members
- That worry may or may not be warranted when compared to the loss of a non-redundant compression member
- Compression members can act like tension members if called upon to do so
- The same cannot be said of a typical tension member under compression