FCP Short Course

Fracture Case Studies

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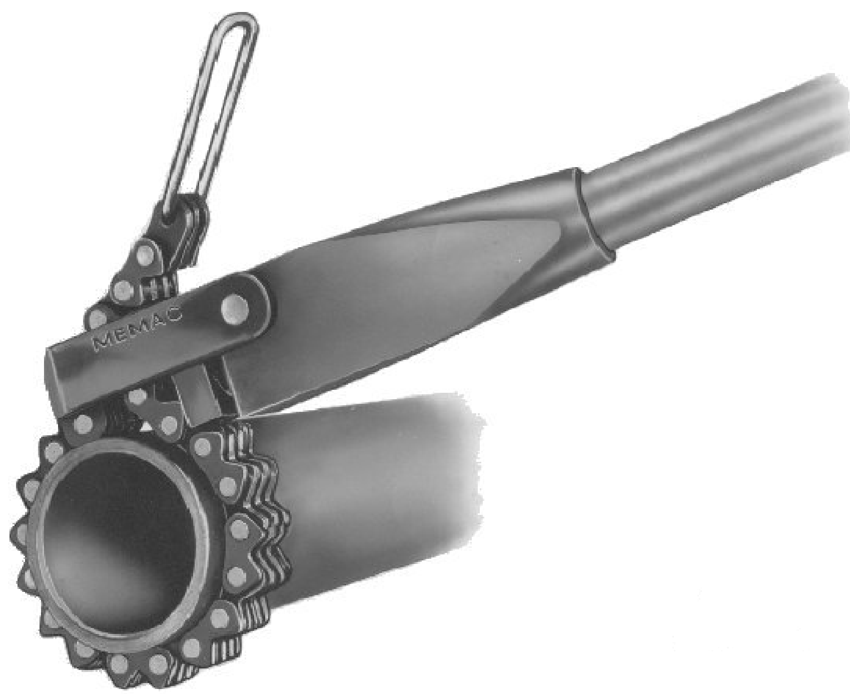
Mechanical Science and Engineering

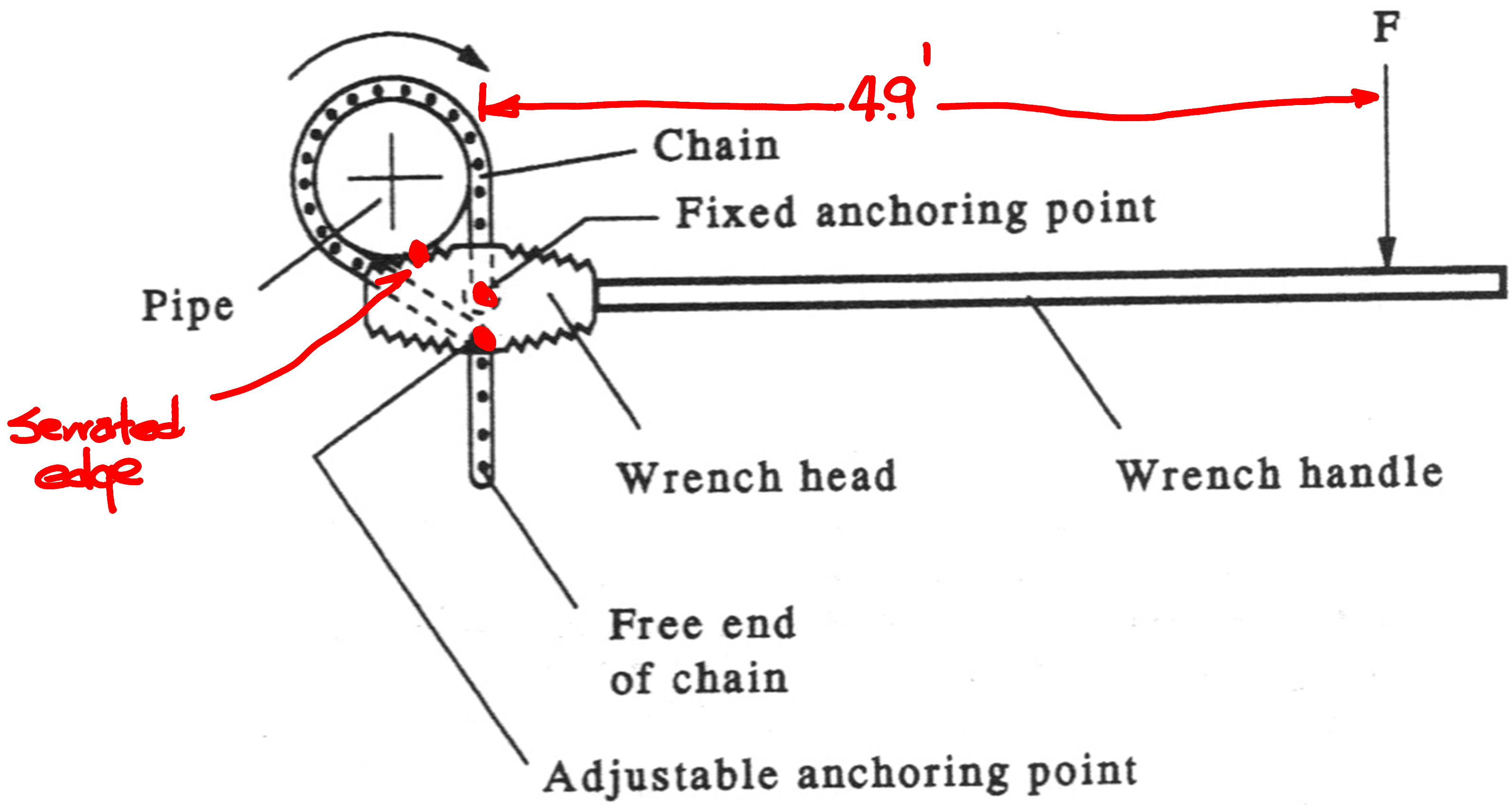
Agenda

- Pipe Wrench Failure
- Truck Steering Shaft
- Ammonia Pressure Vessel
- Silver Bridge

Chain Wrenches



Chain Wrench In Use



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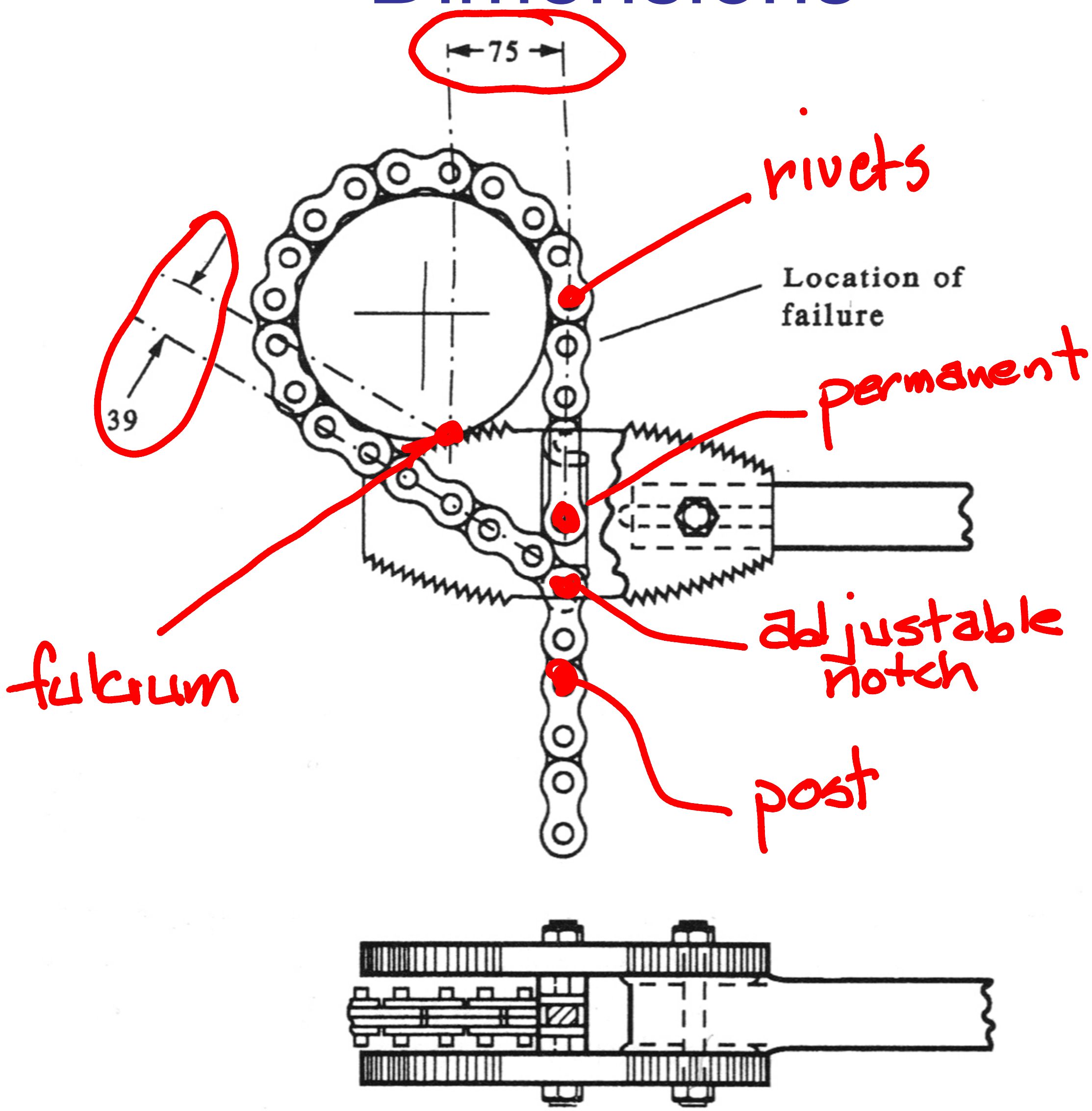
Info

- Length: 1.5 meters
- Weight: 25 kilograms
- Pipe Diameter: 160 mm
- Broke during use
- Injured Worker
- Identify Cause
  - Defective Part?
  - User Overload?

Dimensions



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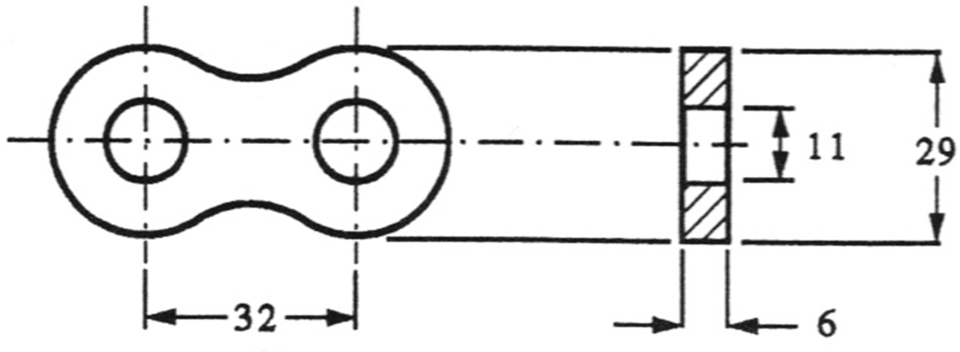
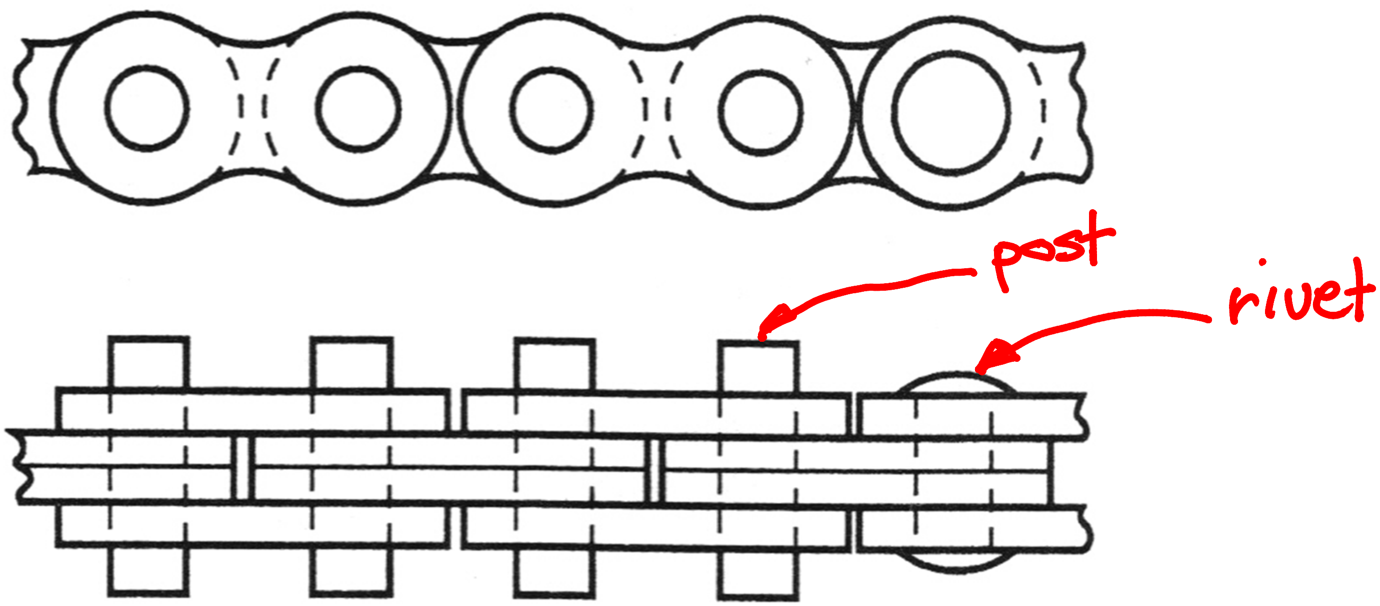
Dimensions





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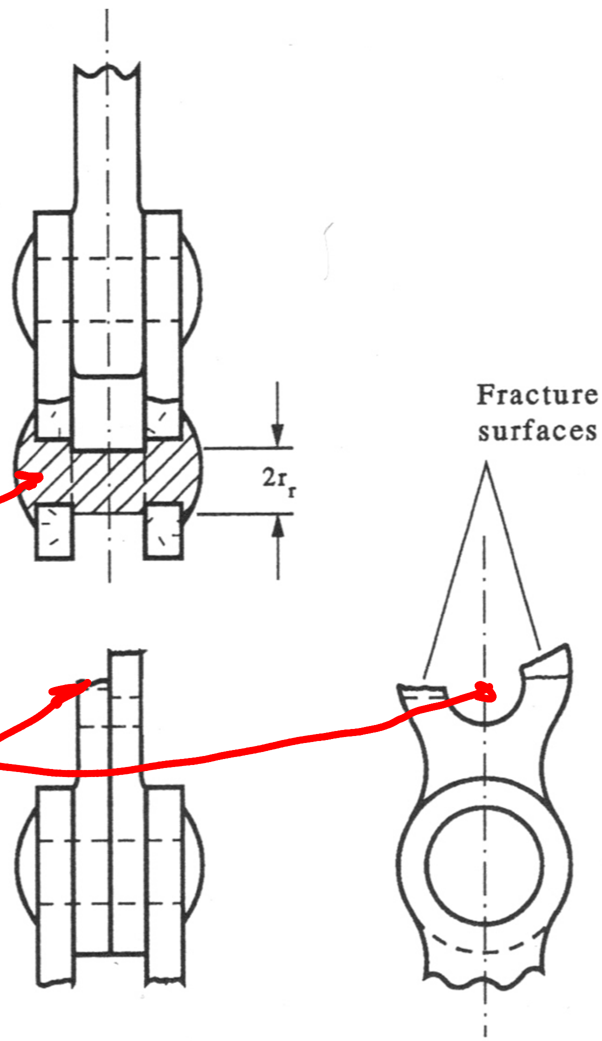
Failures – Link and Pin

Two failures

Double shear of rivet

Link Fracture



Overload

- fibrous / ductile
- small reduction in area
- hardened / tempered
- no apparent defects

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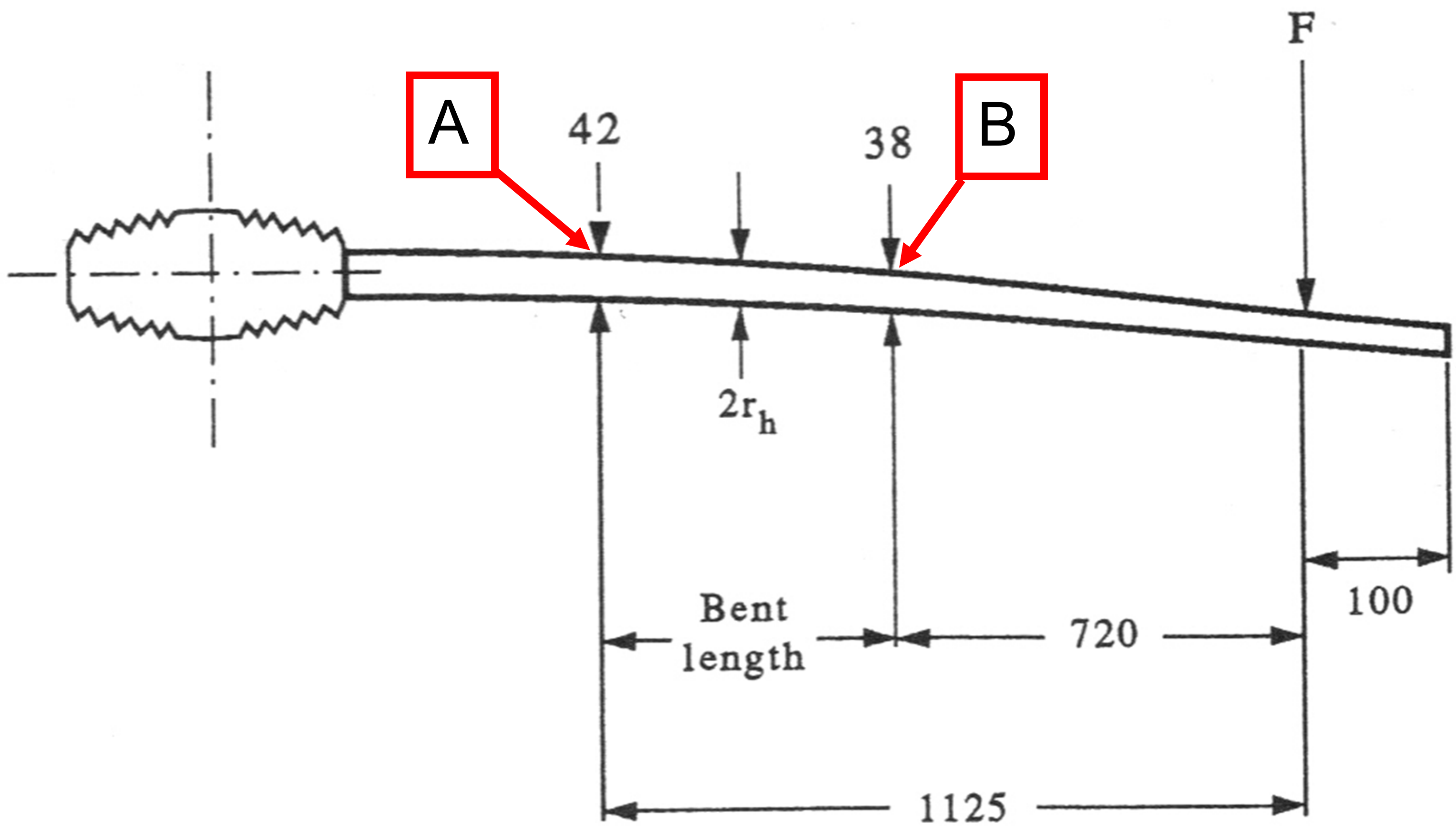
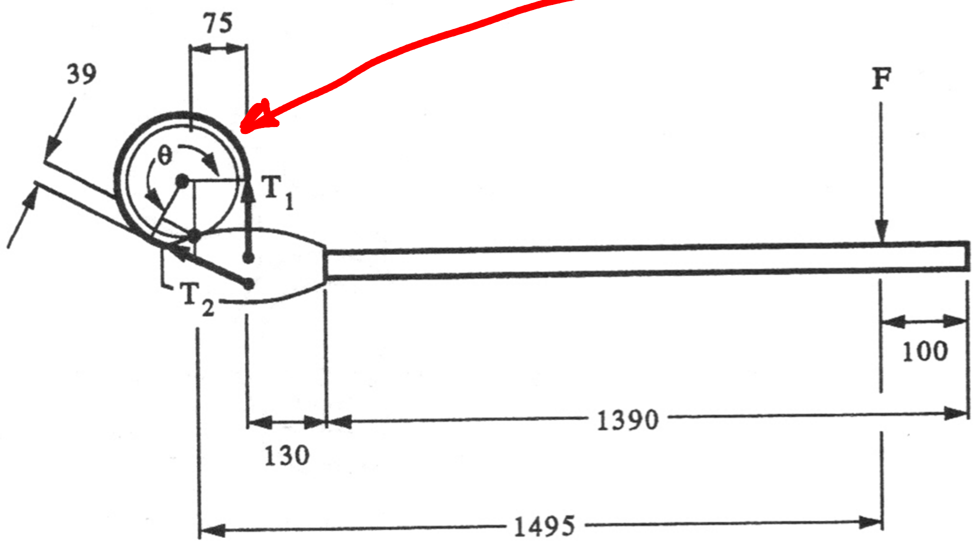
Failure - Handle



Force Equations



Band Brake / Belt – Pulley

$$\frac{T_1}{T_2} = e^{\mu\theta} \qquad T_1 = T_2 e^{\mu\theta}$$

$\theta = 245° = 4.3$ rad

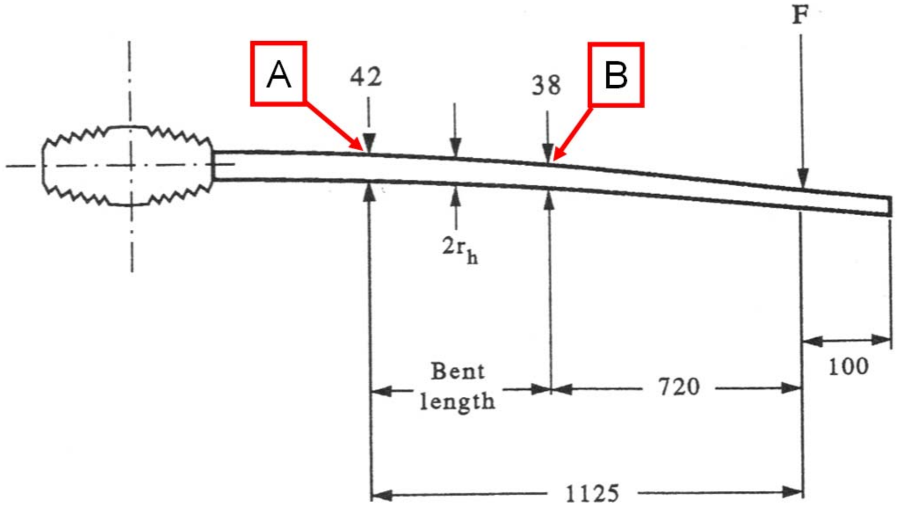
$\mu = .5$ hard steel on soft steel

$$T_2 = 0.116\, T_1$$

$$\Sigma M_{fulcrum} = 0 \Rightarrow F(1495) + T_2(39) = T_1(75)$$

$$T_1 = 21\, F$$

Bending the Handle



Elastic $\sigma = \frac{Mc}{I} = \frac{4M}{\pi r^3}$

$M_e = \frac{\pi r^3 \sigma_y}{4}$ $M_o = \frac{4 \sigma_y r^3}{3}$

$\frac{M_o}{M_e} = \frac{16}{3\pi} = 1.7$

What is σ_y?

Hardness Reading

Vicker HV = 185 ± 2 ⇒ σ_{uts} (MPa) ≅ 3.2 HV = 590 MPa

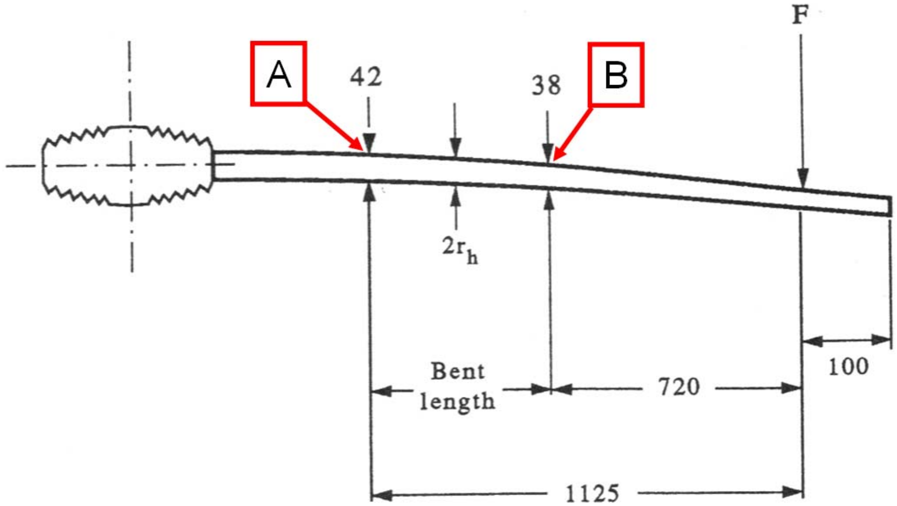
Plain carbon steel – manganese – .36% C

Smithells

$\sigma_{uts} = 590$ MPa

$\sigma_y = 435$ MPa

Bending the Handle



$$(M_o)_A = \frac{(4)(435\ \text{MPa})(21)^3}{3}$$

$$= 5370\ \text{Nm}$$

$$(M_o)_B = 3980\ \text{Nm}$$

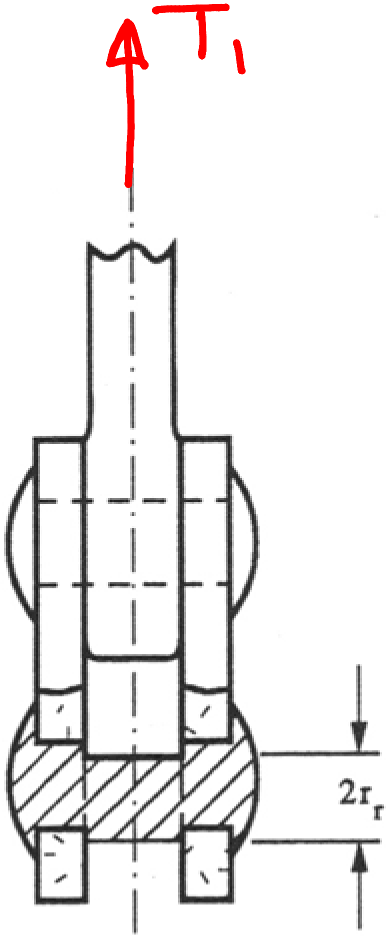
$$(M_o)_A = F(1125) \Rightarrow F = 4.77\ \text{kN}$$

$$(M_o)_B = F(720) \Rightarrow F = 5.53\ \text{kN}$$

average $F = 5.15\ \text{kN}$

$$T_1 = 21\,F = 21(5.15) = \underline{108.2\ \text{kN}}$$

Shearing the Rivet



$T_1 = \tau_{uts}\, 2\pi r^2$

τ_{uts} ?

Rivet Hardness HRC = 30 ± 3

Convert To Vickers $HV = \frac{HRC}{.1} = 300 \pm 30$

Strength $\sigma_{uts} \cong 3.2\, HV = 960 \pm 96$

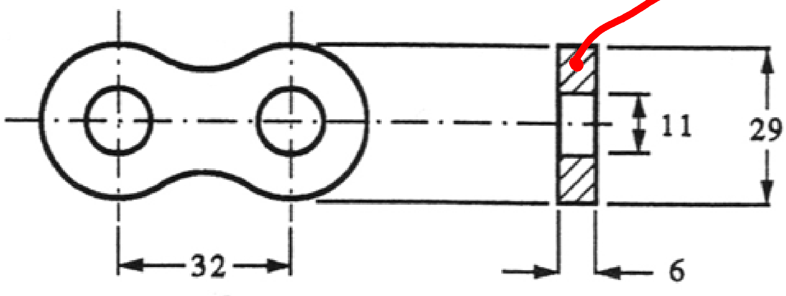
Shear Strength $\tau_{uts} = \frac{\sigma_{uts}}{\sqrt{3}} \cong \frac{\sigma_{uts}}{1.6} = 600 \pm 60$ MPa

$T_1 = \tau_{uts}\, 2\pi r^2 = (600 \pm 60)(2\pi)(5.5)^2$

$T_1 = 114 \pm 11.4$ kN

Compare To 108 kN from bent handle

Fracturing the Link



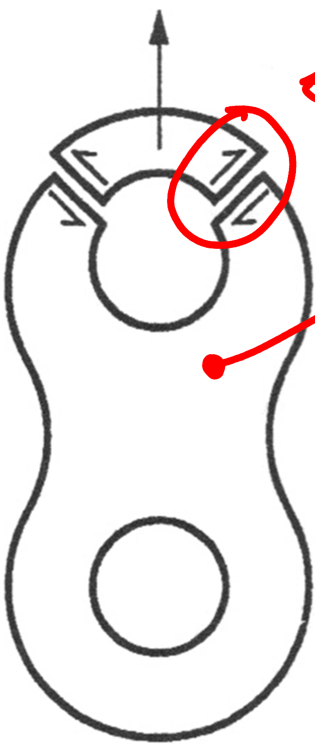
$A = (29-11)(6) = 108\ mm^2$

Two Fractures

$A_t = 216\ mm^2$

$\sigma_{uts} = 3.2(250) = 800\ MPa$

$T_1 = \sigma_{uts} A_t = 173\ kN$



shear

$HV = 250$

$\tau_{uts} = \frac{\sigma_{uts}}{1.6} = 500\ MPa$

$T_1 = \tau_{uts} A_t = 108\ kN$

108 Handle

114±11 rivet

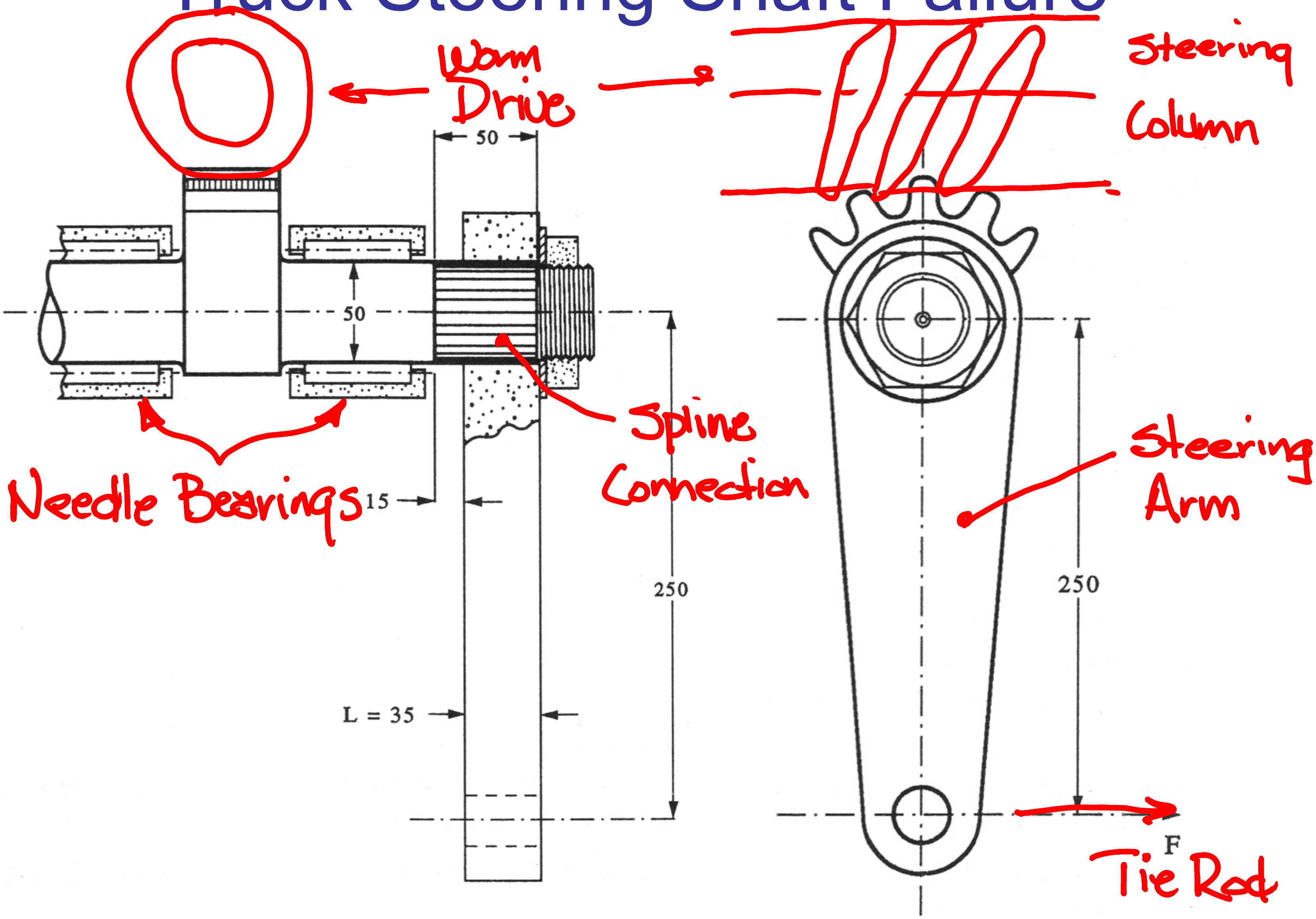
Diagnosis

- Defective?
  - No defects seen in fracture micrographs
  - Link hardness of 250 HV consistent with good quench and temper
- Overload?
  - Force (5.15 kN) to bend the handle 5.8 times 200 lb man
  - Double handle length and stand 3 men on the end
  - Slip long pipe over handle to increase leverage

Agenda

- Pipe Wrench Failure
- **Truck Steering Shaft**
- Ammonia Pressure Vessel
- Silver Bridge

Truck Steering Shaft Failure



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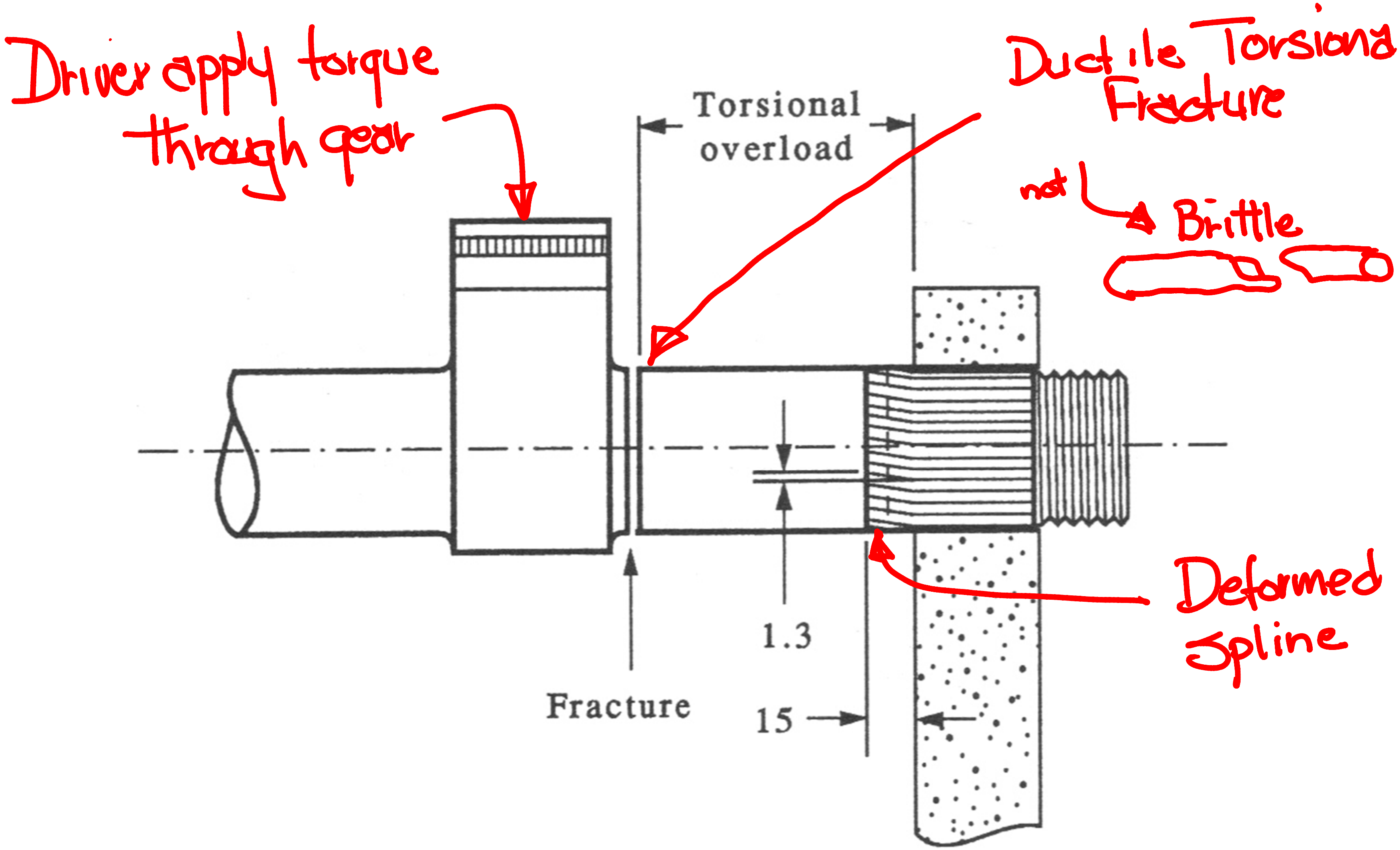
Question

Did shaft failure cause accident?

or

Did accident cause shaft failure?

Steering Shaft Failures



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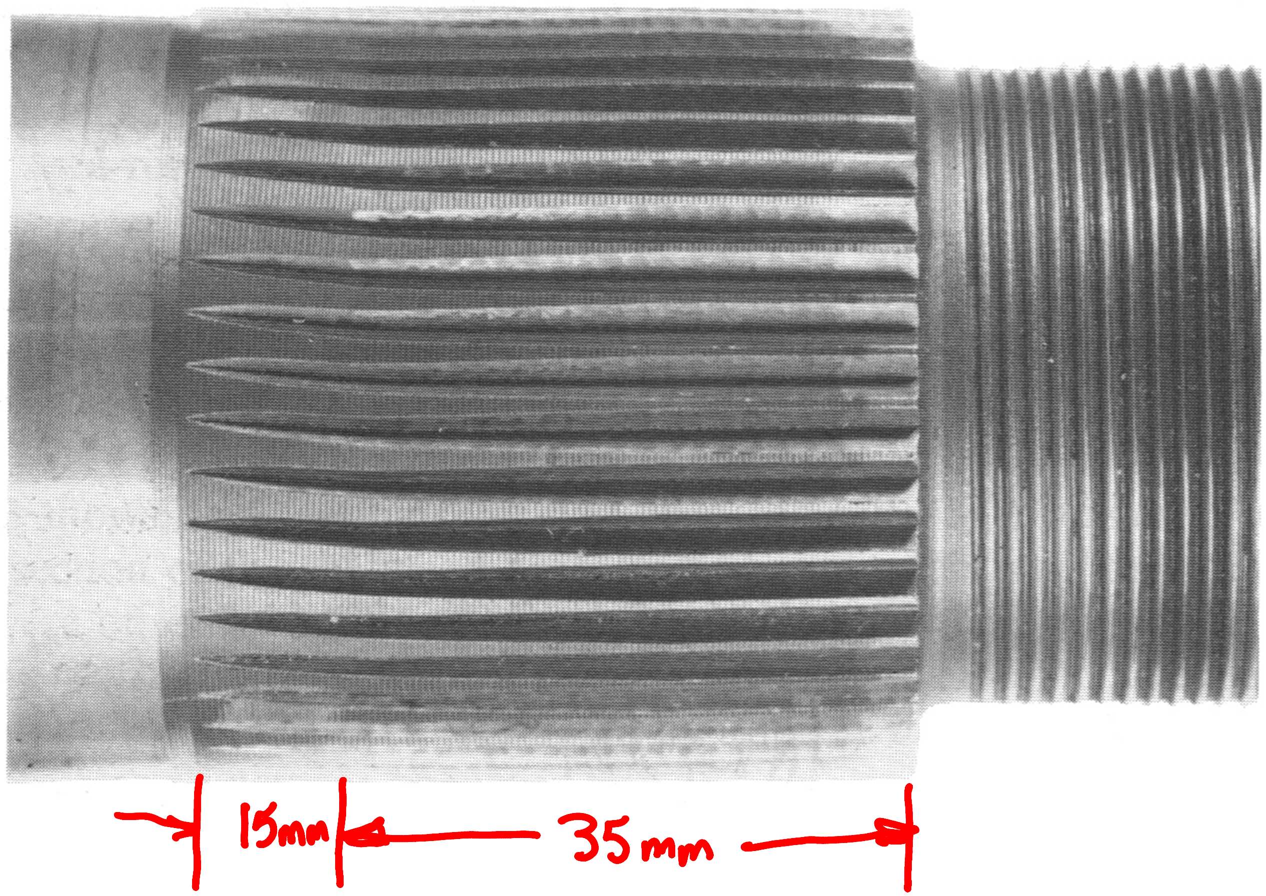
Deformed Splines



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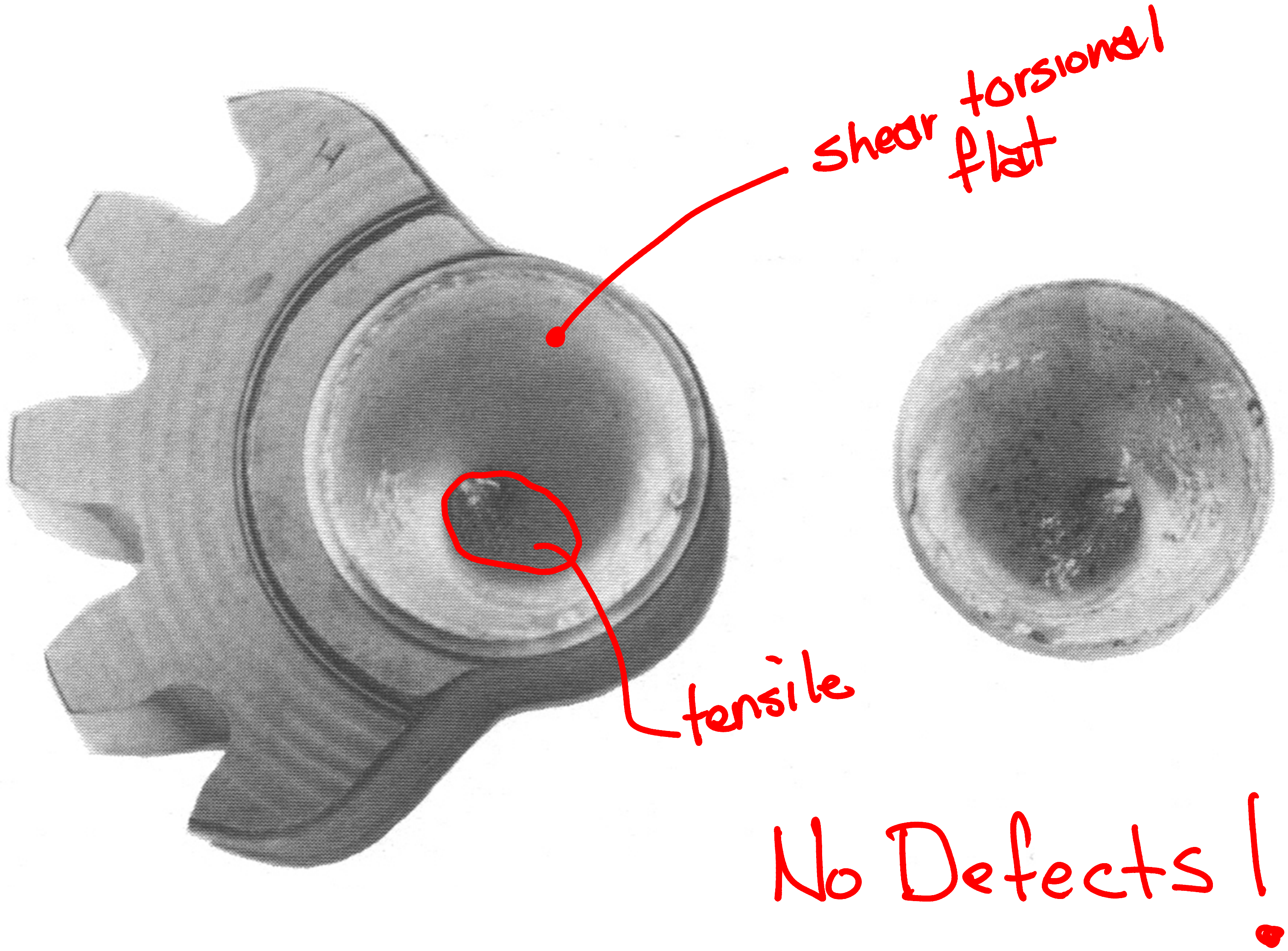
Matching Fracture Surfaces



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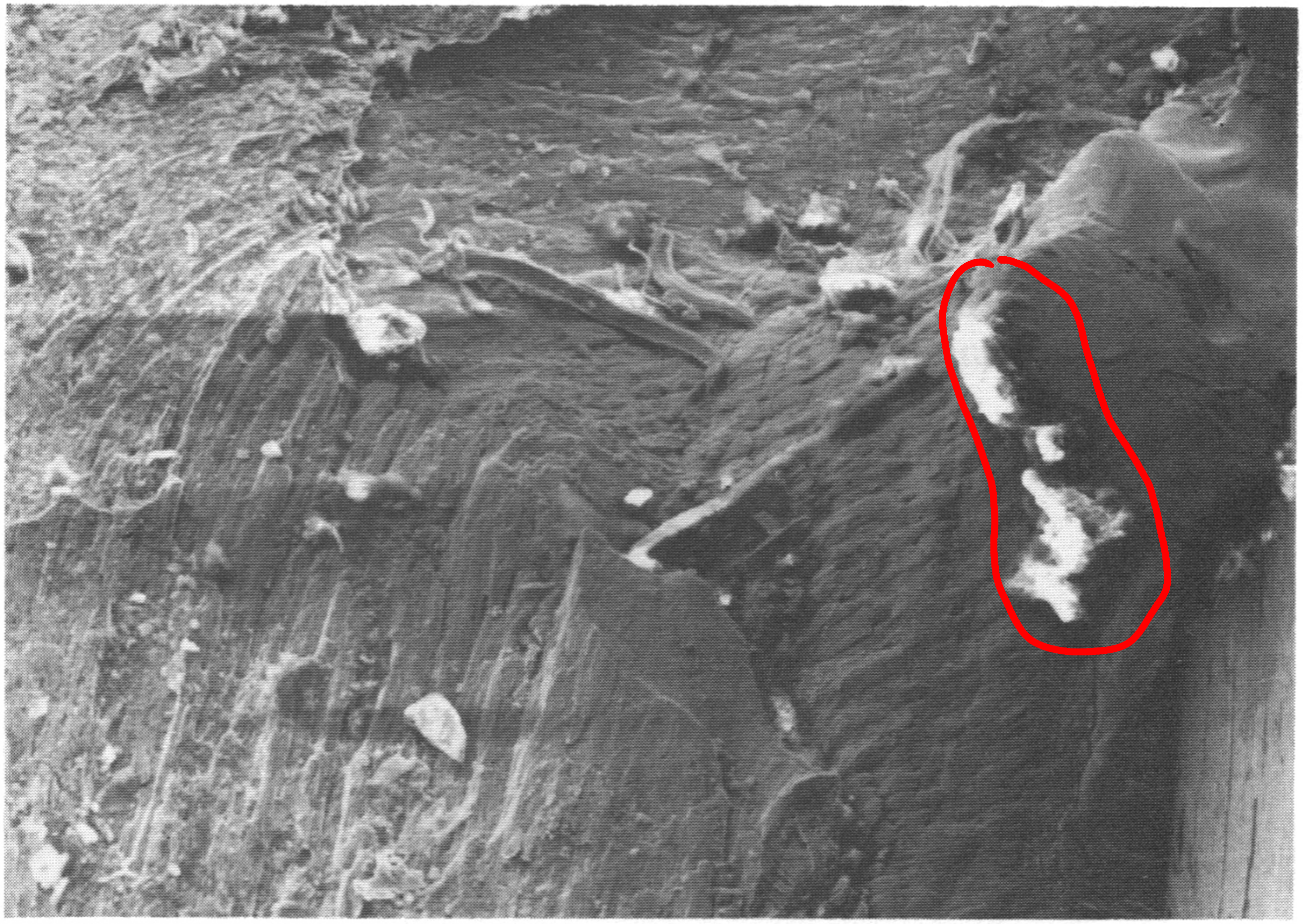
Shear Failure Surface



rubbing
smearing

Magnification x170

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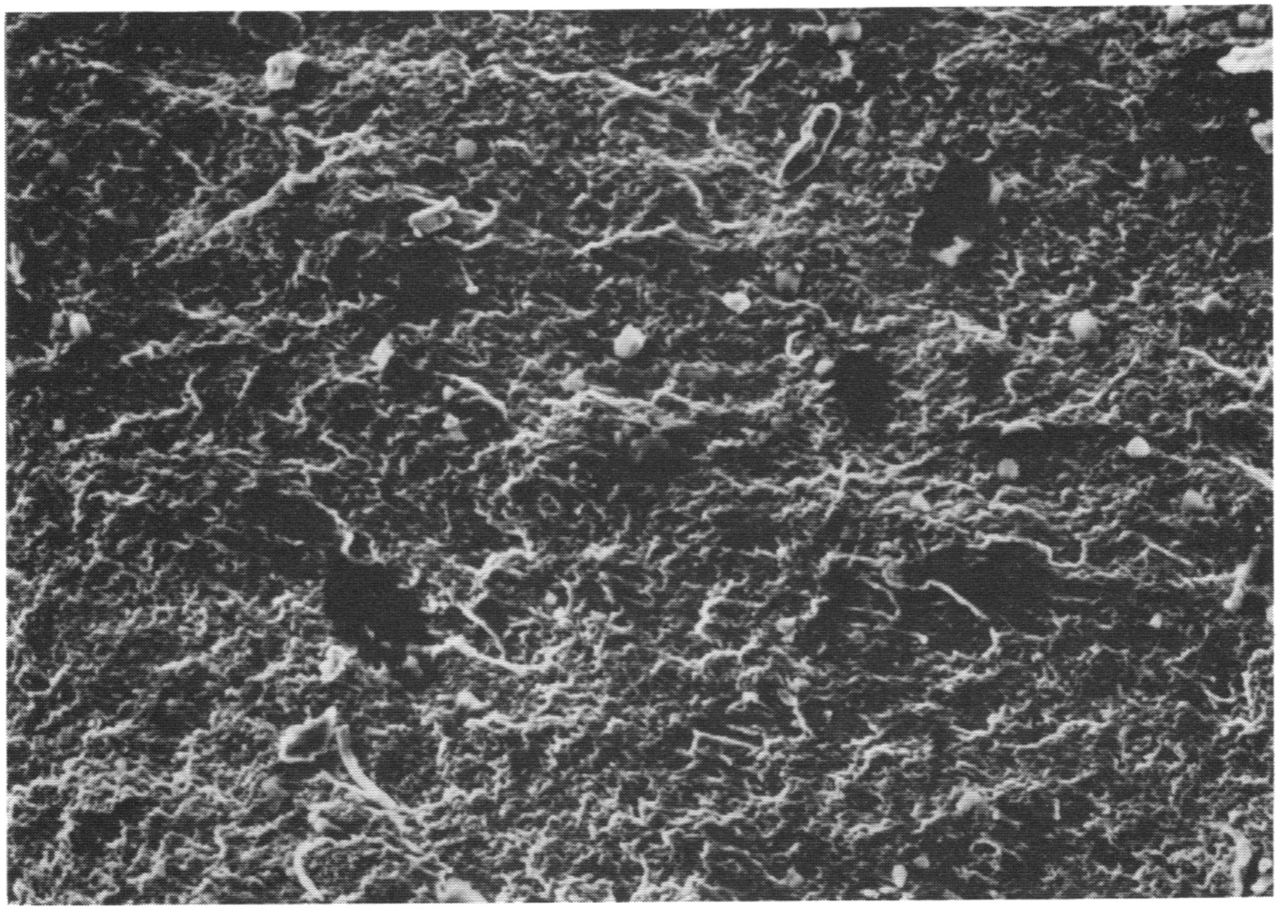
Fibrous Tensile Fracture



fibrous
ductile

Magnification x325

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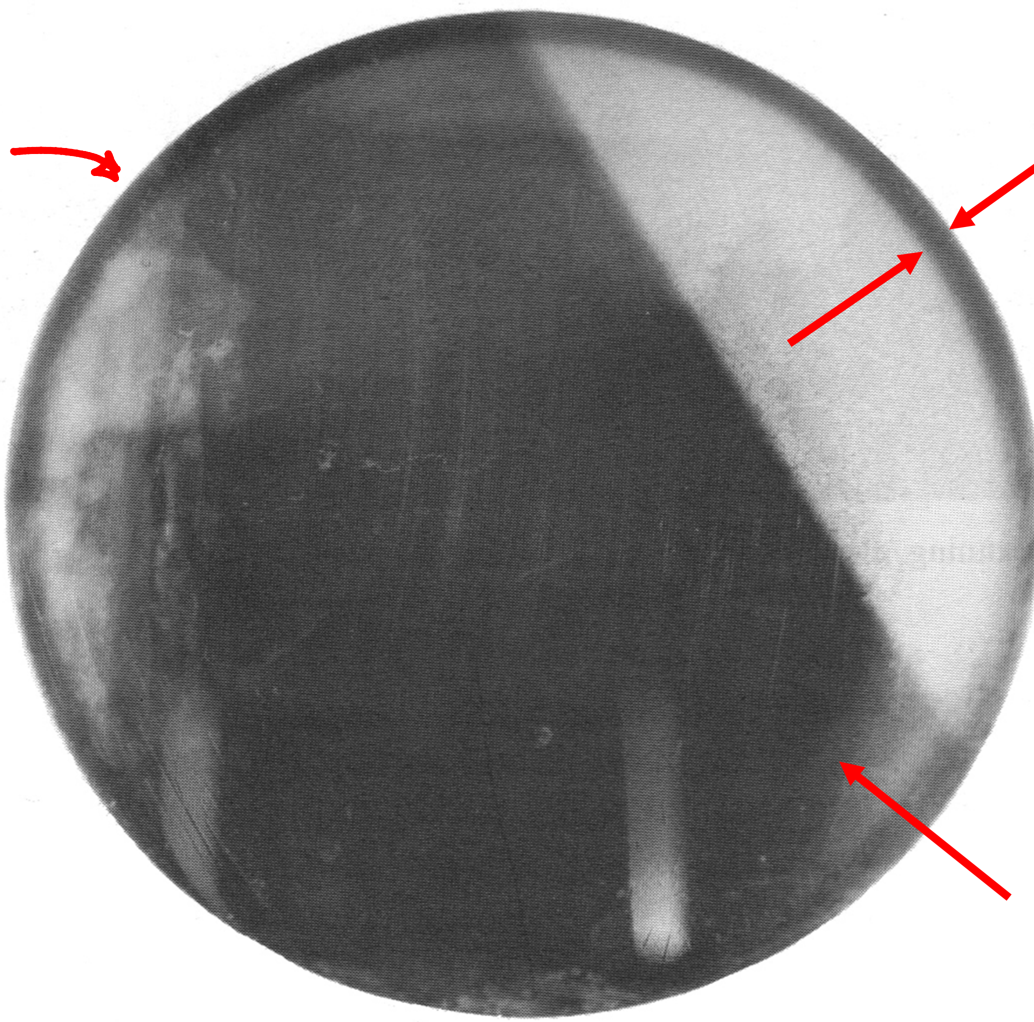
Polished Cross-Section

Thin Slice

- high speed abrasive cutter
- coolant
- Ground & Polished



1.5 mm case hardened

Etched 2% nital

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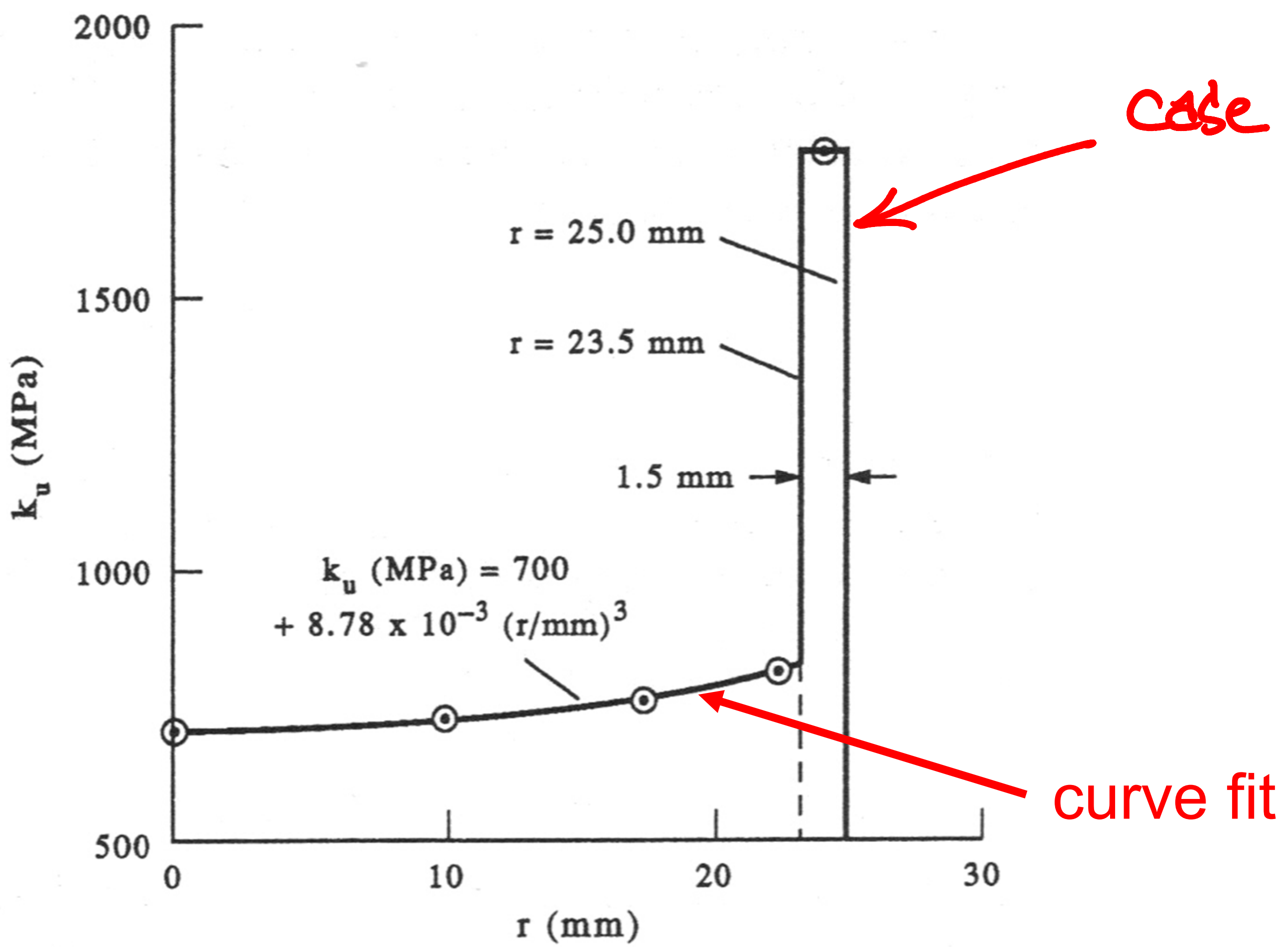
Hardness vs. Radius

$\sigma_u \hat{=} 3.2 HV$ $\tau_u = \frac{\sigma_u}{1.6}$

r(mm)	HV	σ_u(MPa)	τ_u (MPa)
0	350	1120	700
10	360	1152	720
17.5	375	1200	750
22.5	400	1280	800
Case	880	2816	1760

Steering Shaft



Shear stress vs. radial distance from shaft center

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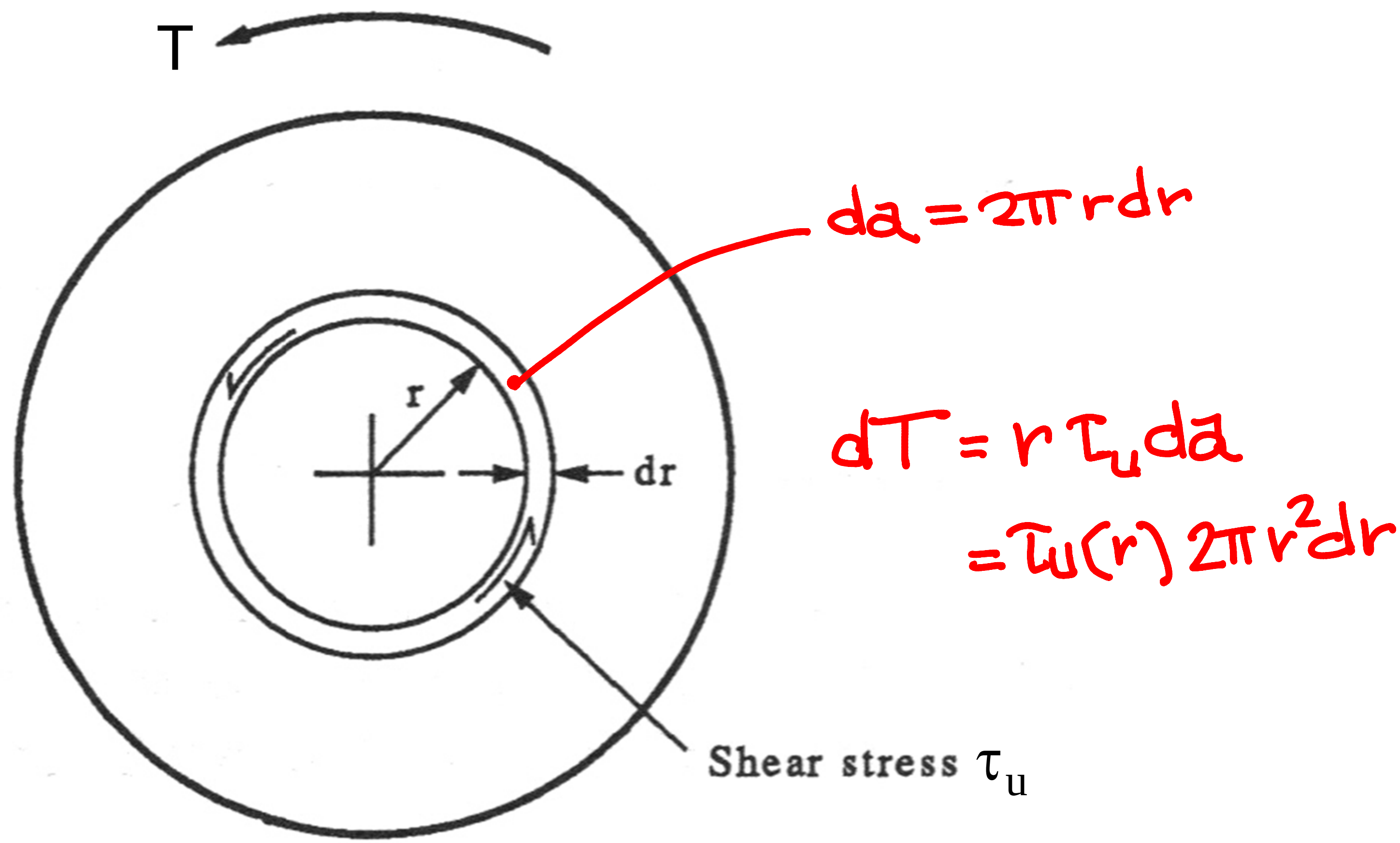
Steering Shaft



Calculating the torsional moment

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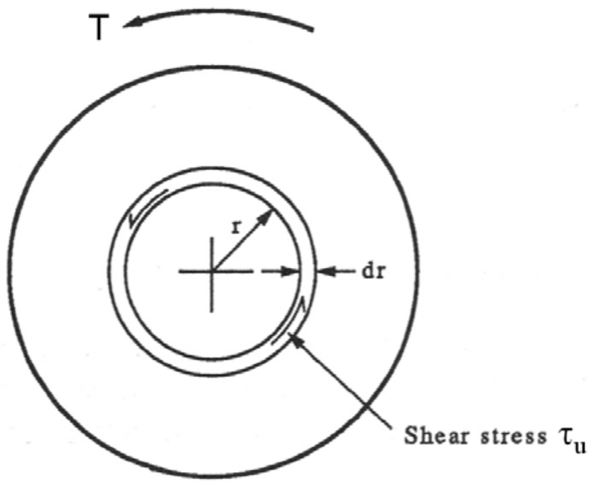
Steering Shaft



$$dT = 2\pi \tau_u r^2 dr$$

$$T = 2\pi \int_0^R \tau_u r^2 dr$$

$$T_{total} = T_{core} + T_{case}$$

Core

$$\tau_u = 700 + 8.78 \cdot 10^{-3} r^3$$

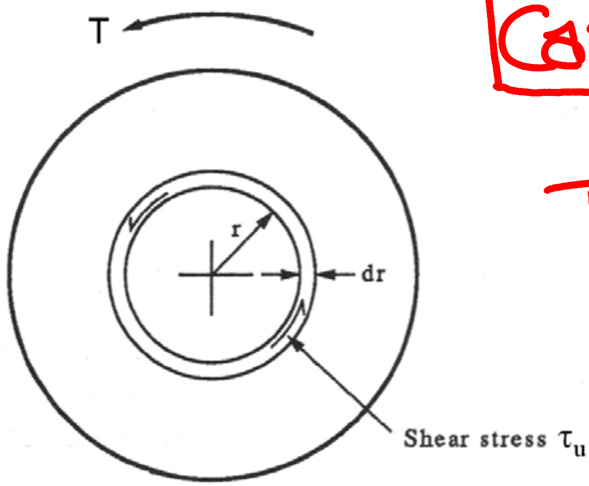
$$T_{core} = 2\pi \int_0^{23.5} (700 + 8.78 \cdot 10^{-3} r^3) dr$$

$$= 2\pi \left[\frac{700 r^3}{3} + \frac{8.78 \cdot 10^{-3} r^6}{6} \right]_0^{23.5}$$

$$= 2\pi \left[3.03 \cdot 10^6 + 0.25 \cdot 10^6 \right] = 2.06 \cdot 10^7 \text{ Nmm}$$

$$= \underline{20.6 \text{ KNm}}$$

Steering Shaft



Case

τ_u = const = 1760 MPa

$$T_{case} = 2\pi \int_{23.5}^{25} \tau_u r^2 dr = 2\pi \left[\frac{r^3}{3}\right]_{23.5}^{25}$$

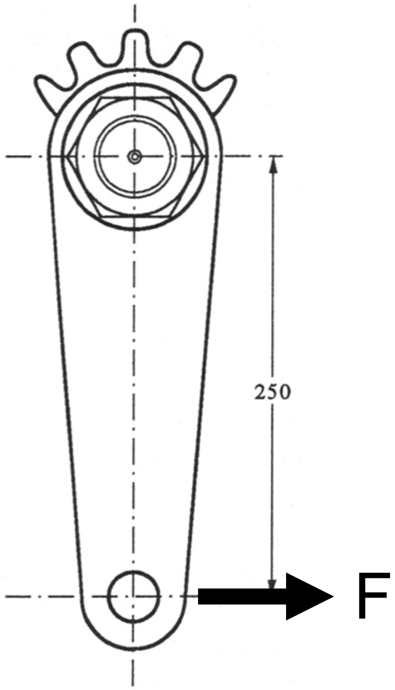
$$= \frac{2\pi}{3}(1760)\left[25^3 - 23.5^3\right]$$

$$= 9.8 \text{ kNmm}$$

$$T_{total} = 20.6 + 9.8$$

$$T = 30.4 \text{ kNm}$$

Caused By Collision?



- Steering Arm Force

$F \cdot 250mm = 30.4\ kNm$

$F = 122\ kN$ (27,500 lbs)

- Collision Force
  - 4 g's
  - truck mass = 20 metric tonnes

$F = ma = 20{,}000\ (9.81\ m/s^2)(4\ g's)$

$= 784\ kN$

6.5 times greater than force to fracture!

Meet Material Specs?

Nickel-chrome-moly steel

Element	Weight %	Element	Weight %
Carbon	0.17	Phosphorus	0.035 max
Silicon	0.25	Chromium	1.6
Manganese	0.5	Molybdenum	0.3
Sulphur	0.035 max	Nickel	1.55

1018

Yield stress = 736 MPa minimum OK

Tensile strength = 1079 to 1324 MPa

Core 1120 – 1280 OK

Elongation = 8% minimum

$\gamma_{spline} = \frac{1.3}{15} = 8.7\%$ $\varepsilon_y = \frac{\gamma}{\sqrt{3}} = 5\%$ low

Case hardness = 59 to 63 Rockwell C 680–780 HV

880 HV

Impact energy = 59 J/cm2 minimum

No evidence of brittle fracture!

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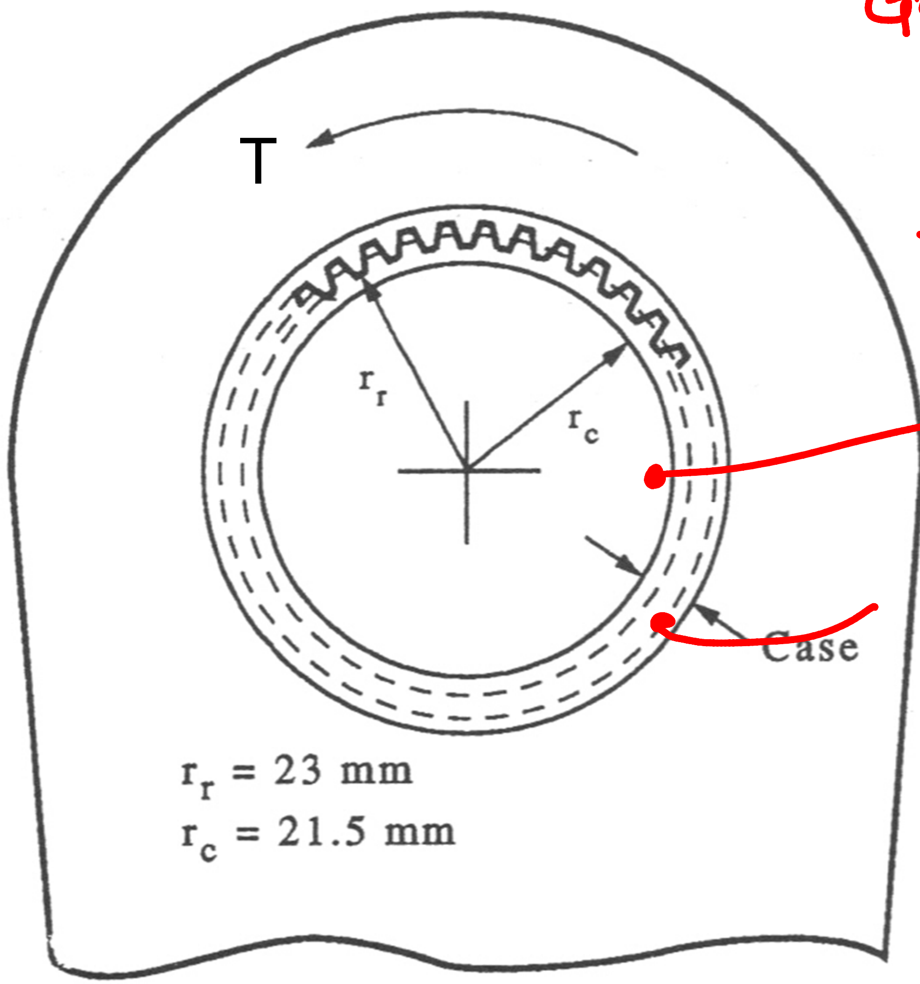
Spline Connections



Good For Large Torques!

Spline Length 35mm

Core Strength
$\tau_u = 800$ MPa

Case Strength
$\tau_u = 1760$ MPa

Dimensions of the splined section

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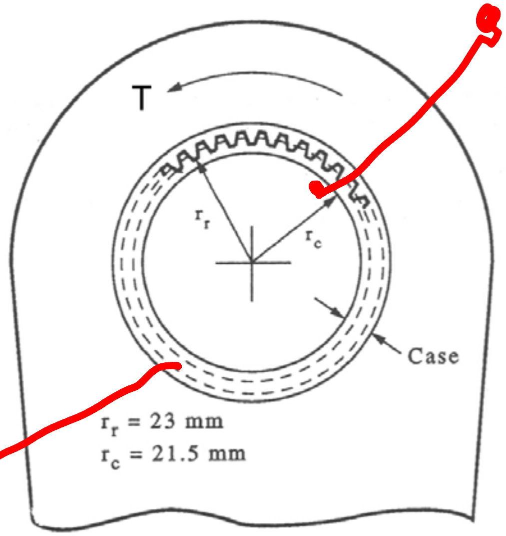
Spline Connections



Shear Core Just Under Case

$$T = \tau_u 2\pi L r_c^2$$

$$= (800)(2\pi)(35)(21.5)^2$$

$$= 81 \text{ kNm} > 30.4$$

Shear At Spline Root ($r = 23\text{mm}$, $\tau_u = 1760 \text{ MPa}$)

$$T \approx \frac{\tau_u 2\pi L r^2}{2} = 102 \text{ kNm}$$

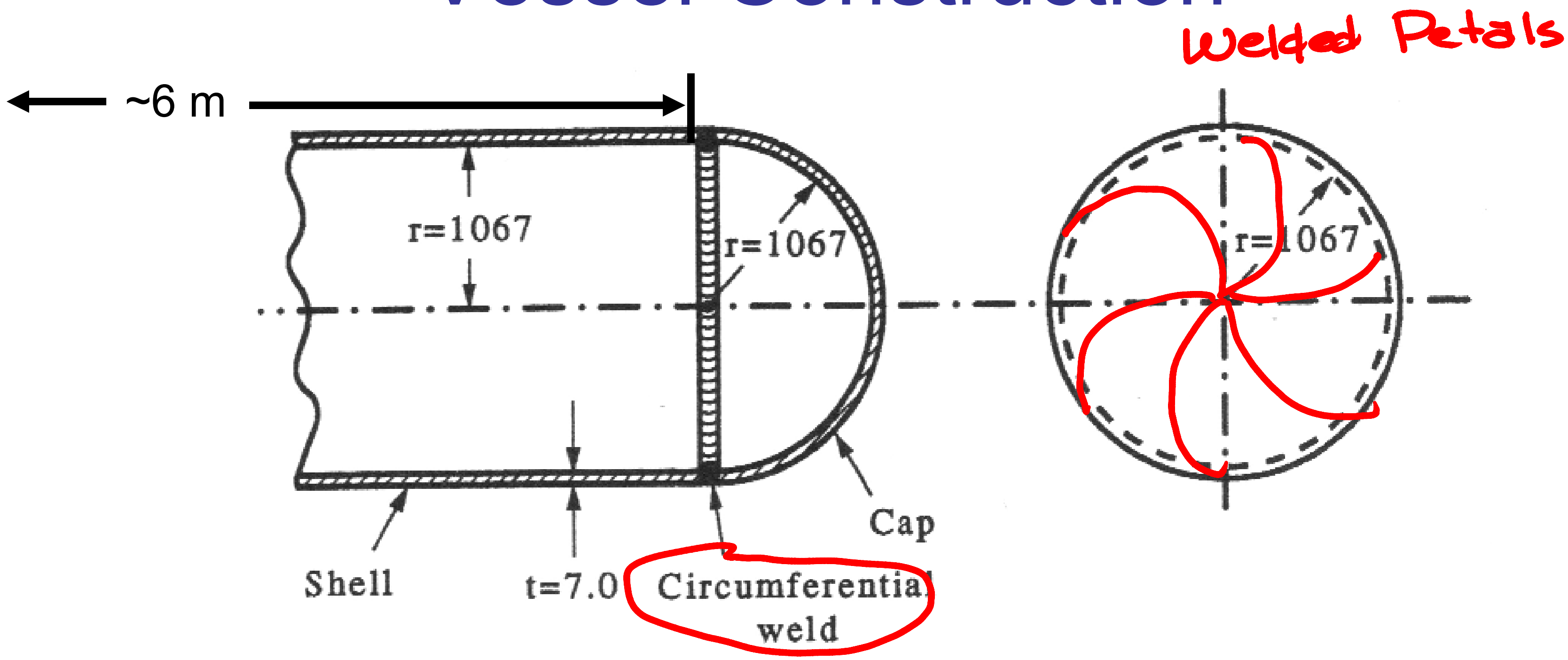
Spline 2.67 times stronger

Agenda

- Pipe Wrench Failure
- Truck Steering Shaft
- **Ammonia Pressure Vessel**
- Silver Bridge

Similar Tanker Truck

Vessel Construction



Weld between the shell and end cap of the pressure vessel

Saturation
20°C – 8.57 bars
50°C – 20.33 bars

Test Gauge Press. @ 50°C = 19.33 bars = 1.9 MPa
Max. Operating Press. = 2.07 MPa

50°C ≡ 122°F

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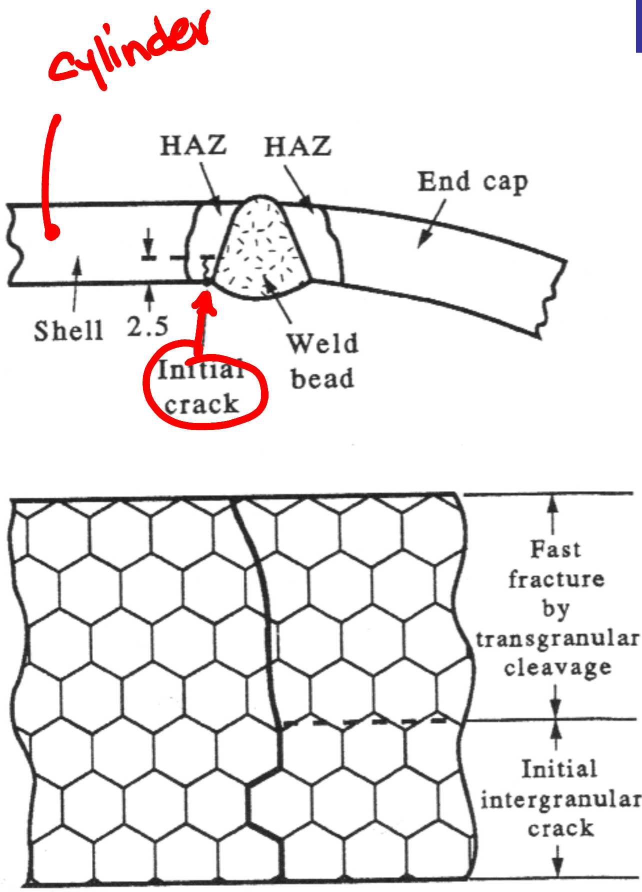
During Unloading

- Fast fracture in circumferential weld
- End cap blown off (serious mayhem)
- Unloading (decanting) process
  - Space above liquid is pressurized with ammonia gas with compressor
  - $P_{compressor}$ = 1.83 MPa
  - Safety valve set at 2.07 MPa

} should be safe

- Get materials data
- Understand mechanics
- Reasonable?

Fracture



Geometry of the failure

- Crystallographic
- No plastic deformation
- HAZ – low fracture toughness

ferritic steels prone to SCC (stress corrosion cracking) in presence of liquid anhydrous ammonia

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Materials Data

- ASTM A517 Grade E -HSLA steel
- Samples cut from failed tank

Parent Plate

$$\sigma_y = 712\,\text{MPa}$$
$$\sigma_u = 833\,\text{MPa}$$
$$\varepsilon_f = 22\%$$
$$\text{VH} = 280$$
$$\text{CVN} = 22\,\text{lb ft}\ (30\text{J})\ @\ -34^{o}\text{C}$$

Weld Bead

$$\text{CVN} = 8\,\text{lb ft}\ (11\text{J})\ @\ -34^{o}\text{C}$$
$$\text{CVN} = 10\,\text{lb ft}\ (14\text{J})\ @\ -3^{o}\text{C}$$

HAZ

$$\text{VH} = 300 \text{ to } 370\ \ (335)$$
$$\text{CVN} = 2\,\text{lb ft}\ (3\text{J})\ @\ -34^{o}\text{C}$$
$$\text{CVN} = 5\,\text{lb ft}\ (5\text{J})\ @\ -3^{o}\text{C}$$

HAZ Estimates

Corten-Sailors

$$K_{Ic} = 15.5(\text{CVN})^{1/2} = 35\ \text{ksi}\sqrt{\text{in}} = 39\ \text{MPa}\sqrt{\text{m}}$$

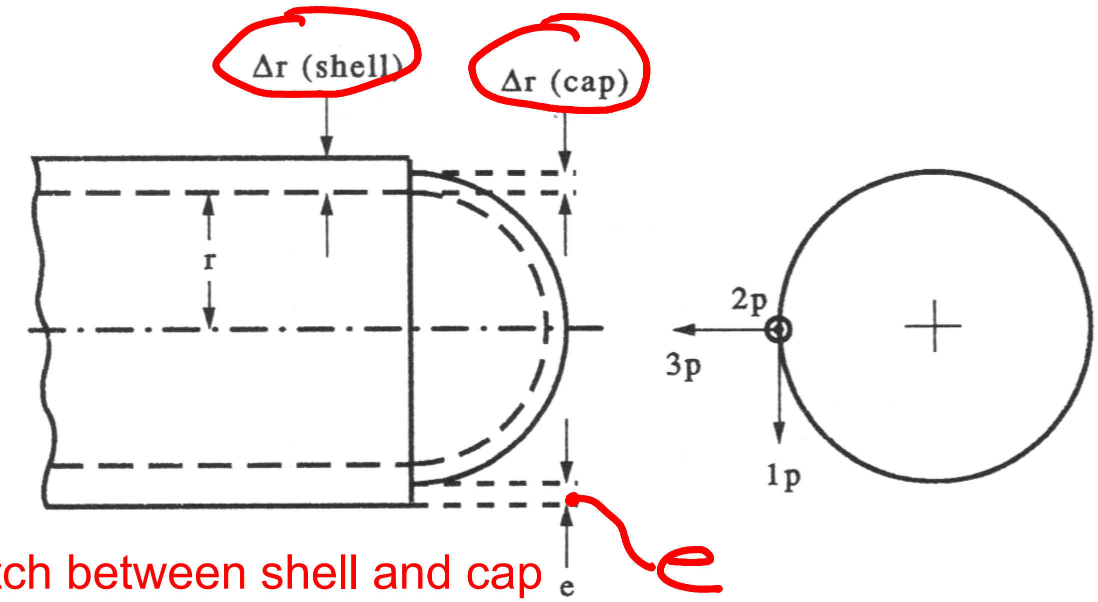
Ultimate Strength

$$\sigma_u(\text{MPa}) \approx 3.2\ \text{HV} \approx 1070\ \text{MPa}$$

Yield Strength $\quad \frac{\sigma_y}{\sigma_u} = \text{const.}$

$$\sigma_y = 1070\ \frac{712}{833} = 915\ \text{MPa}$$

Stresses Acting on Crack



Mismatch between shell and cap

Thin-walled Pressure Vessel – Closed Ends

$$\sigma_1 = \frac{pr}{t}, \quad \sigma_2 = \frac{pr}{2t}, \quad \sigma_3 = 0$$

Hemispherical Cap

$$\sigma_1 = \frac{pr}{2t}, \quad \sigma_2 = \frac{pr}{2t}, \quad \sigma_3 = 0$$

Axial Stress on Crack

$$\sigma_{axial} = \sigma_2 = \frac{pr}{2t} = \frac{(1.83\,MPa)(1067\,mm)}{2(7\,mm)} = \underline{\underline{140\,MPa}}$$

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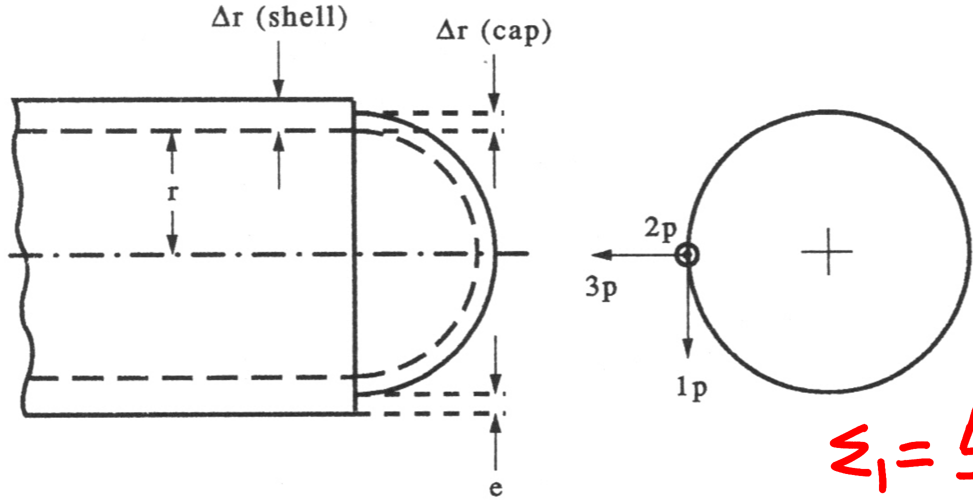
Bending Stress



Mismatch between shell and cap

Hoop Stress

$$(\sigma_1)_{shell} = 2\,(\sigma_1)_{end\ cap}$$

Radial Distortions - ε_1

$$\varepsilon_1 = \frac{\Delta r}{r} = \frac{\sigma_1}{E} - \nu\frac{\sigma_2}{E} - \nu\frac{\sigma_3}{E} \quad (\sigma_3 \rightarrow 0)$$

Shell

$$\varepsilon_1 = \frac{\Delta r}{r} = \frac{Pr}{tE}\left(1 - \frac{\nu}{2}\right)$$

Cap

$$\varepsilon_1 = \frac{\Delta r}{r} = \frac{Pr}{2tE}\left(1 - \nu\right)$$

Mismatch

$$\sigma_{axial} = 140\ \text{MPa}$$

$$e = \Delta r_{shell} - \Delta r_{cap} = \left(\frac{Pr}{2t}\right)\left(\frac{r}{E}\right) = (140)\frac{1067}{212{,}000} = .71\ \text{mm}$$

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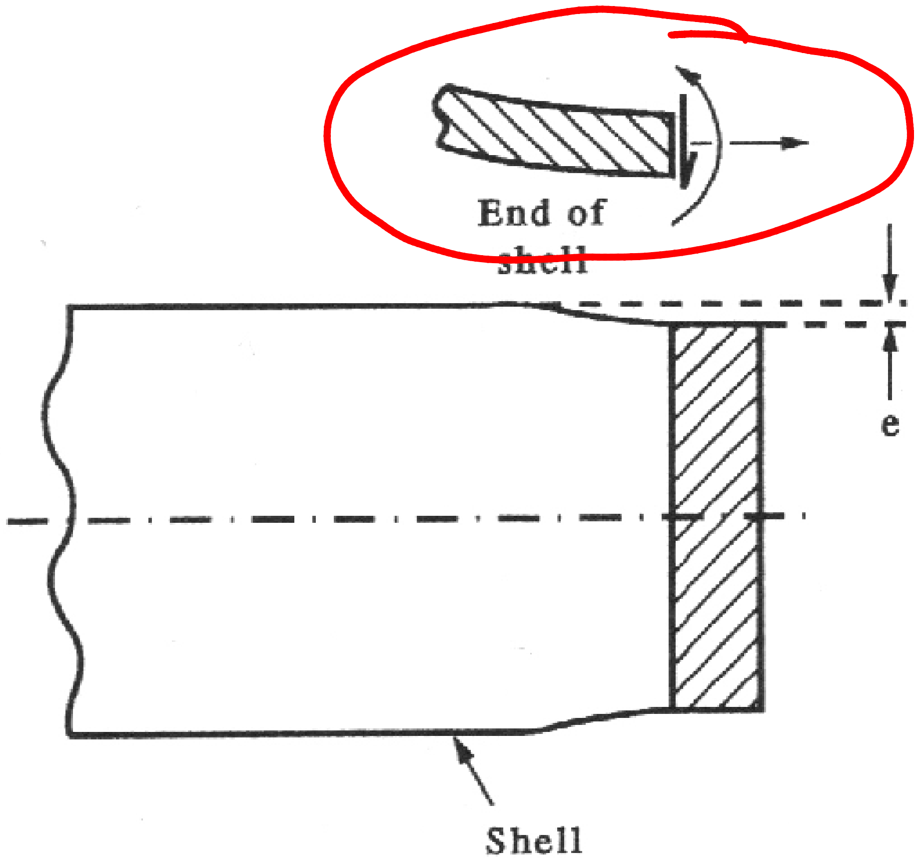
Stress State of Mismatch



All mismatch taken by shell

- Assume cap is infinitely stiff
- End of shell is subjected to bending moment and shear force in addition to membrane stress.
- Bending moment tries to open crack.
- What does shear do?

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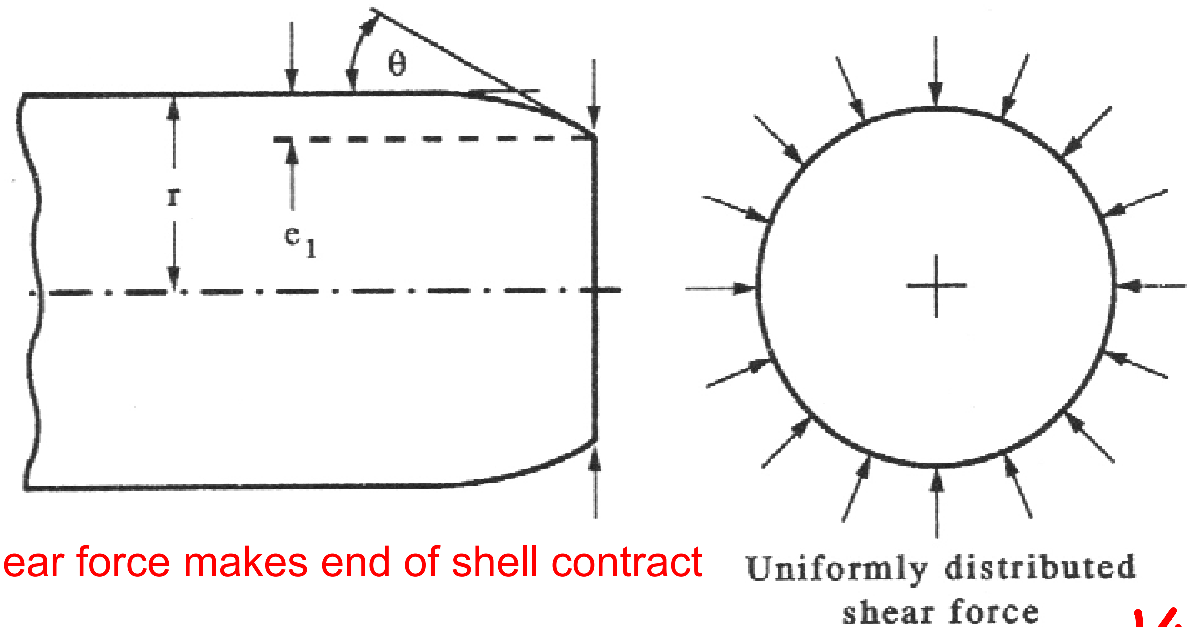
Effect of Shear



Shear force makes end of shell contract

Roark

$$e_1 = \frac{\theta}{\lambda}$$

$$\lambda = \left[\frac{3(1-\nu^2)}{r^2 t^2}\right]^{1/4} \text{ mm}^{-1}$$

$$\lambda = 0.0149 \text{ mm}^{-1}$$

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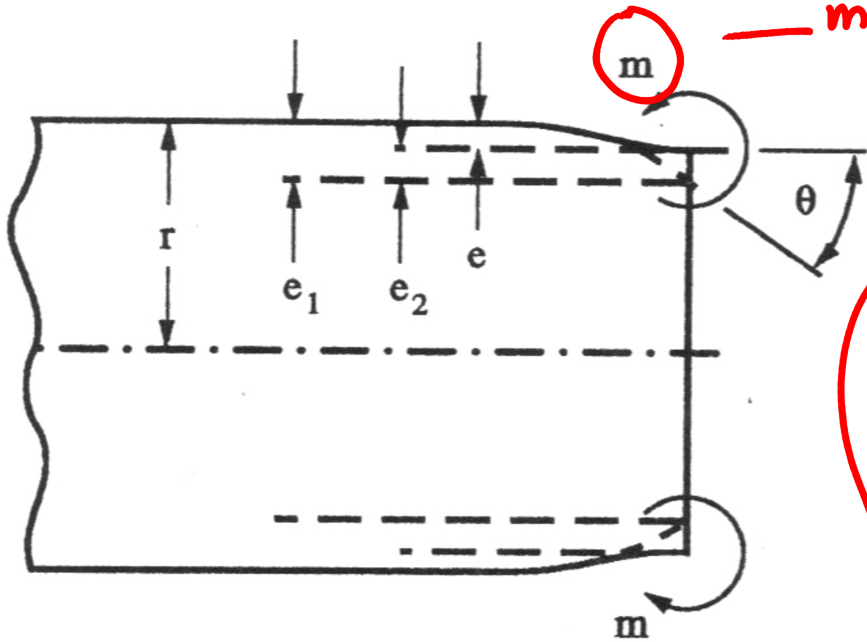
Effect of Bending



Bending moment makes end of shell expand

Roark

$m = \theta D \lambda \quad (N)$

$D = \frac{Et^3}{12(1-\nu^2)} \quad (Nmm)$

$= 6.16 \cdot 10^6 \ Nmm$

$m = 2eD\lambda^2$

$m = 2061 \ N$

Roark

$e_2 = \frac{\theta}{2\lambda}$

$e = e_1 - e_2 = \frac{\theta}{2\lambda} \Rightarrow \theta = 2e\lambda$

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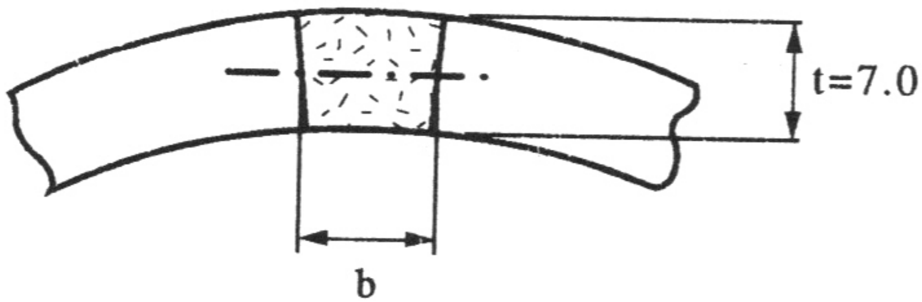
Maximum Moment and Stress



$M = mb$

$c = t/2$

$I = \frac{1}{12}bt^3$

$$\sigma = \frac{Mc}{I} = \frac{mb(t/2)}{bt^3/12}$$

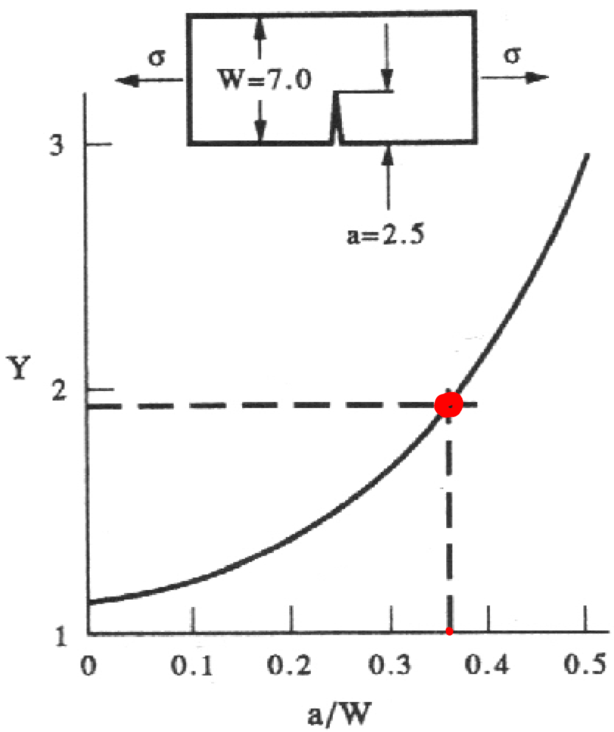
$$= \frac{6m}{t^2} = \underline{252\ \text{MPa}}$$

Do I believe this?

No! Take Half

$$(\sigma_{max})_{bend} = 130\ \text{MPa}$$

Stress Intensity (Tension)



$Y = 1.92$

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

$= (140\ \text{MPa})\sqrt{\pi(.0025)}\,(1.92)$

$= 24\ \text{MPa}\sqrt{m}$

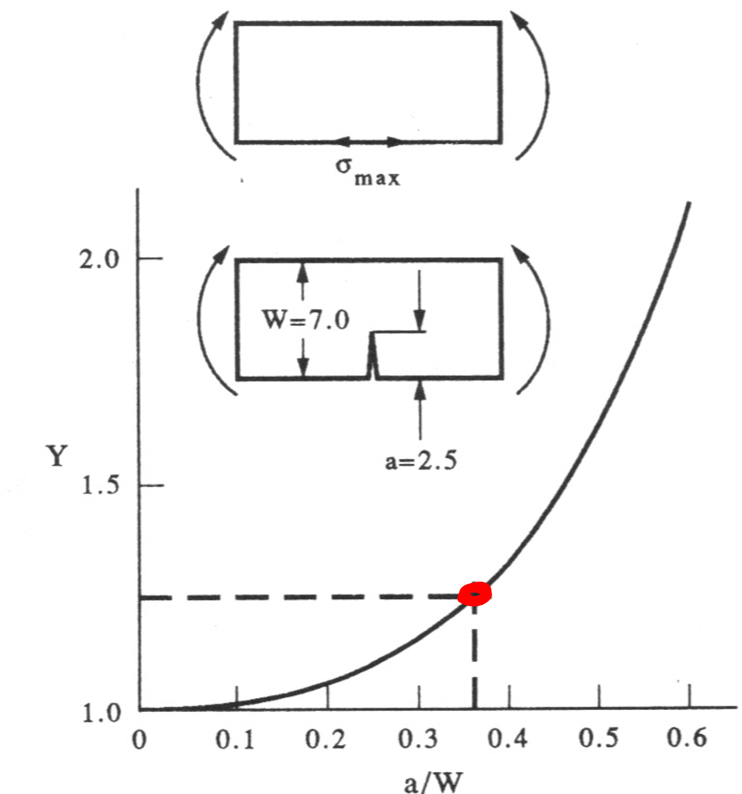
Less than $K_{IC} = 39\ \text{MPa}\sqrt{m}$

Stress Intensity (Bending)

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

$$= (130\,\text{MPa})\sqrt{\pi(.0025)}\,(1.25)$$

$$= 14\,\text{MPa}\sqrt{m}$$



$$Y = 1.25$$

$$K_{total} = K_{axial} + K_{bending}$$

$$= 38\,\text{MPa}\sqrt{m}$$

$$\approx K_{Ic} = 39\,\text{MPa}\sqrt{m}$$

Comments

Valid LEFM?

$$2.5\left(\frac{K_{IC}}{\sigma_y}\right)^2 = 4.5\text{ mm}$$

a little shy!

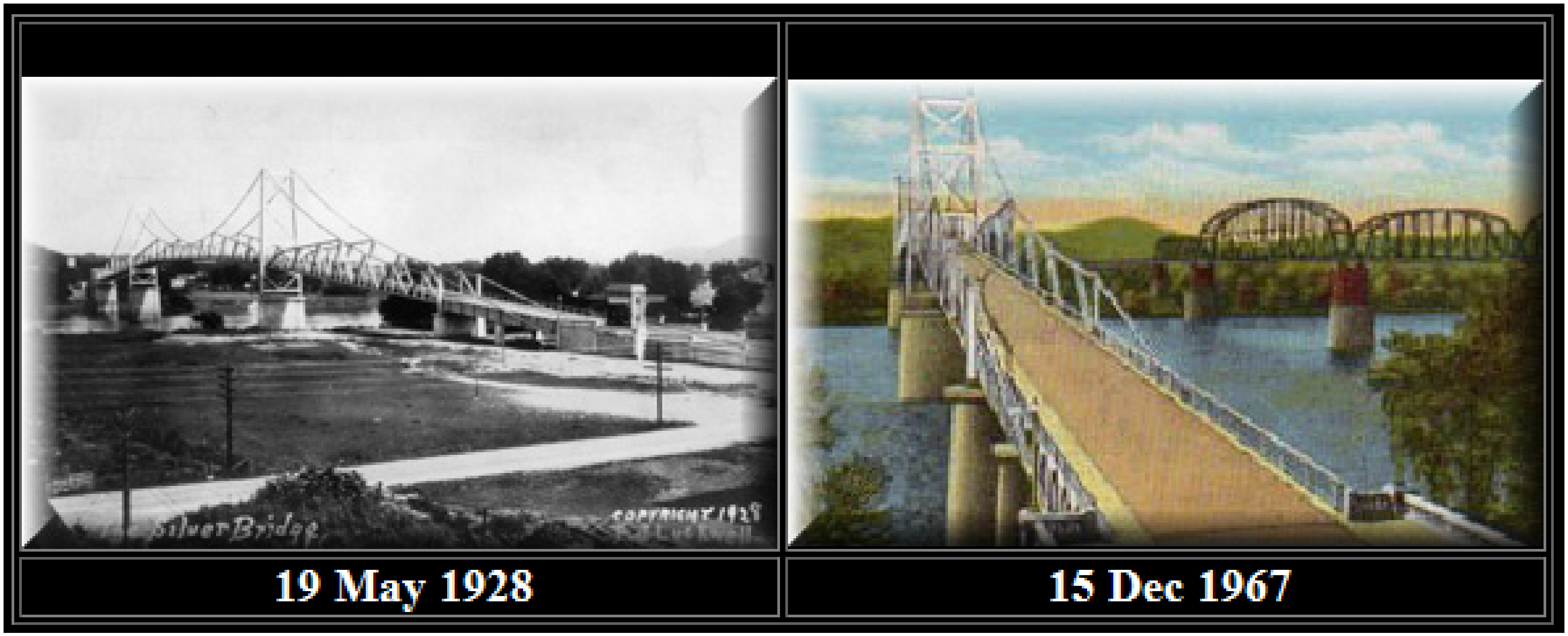
- Toughness HAZ wrecked by welding
- SCC endemic in ferritic steel under anhydrous ammonia.

Coat Tank!

Agenda

- Pipe Wrench Failure
- Truck Steering Shaft
- Ammonia Pressure Vessel
- **Silver Bridge**

Silver Bridge



Statistics

- Completed 19 May 1928
- Connects
  - Huntington, VA to Middleport, OH
  - Charleston, VA to Dayton, OH
- Major east-west connection for US Route 35
- Two lanes of automobile traffic
- 1750 feet in length
- Steel Eyebar Suspension Bridge
- Aluminum Paint (“Silver Bridge”)

Ohio River


NORTH
SOUTH
WEST
EAST
MapPoint
Milwaukee
Madison
WISCONSIN
MICHIGAN
Grand Rapids
Flint
Lansing
London
Sarnia
ONTARIO
St. Catharines
Buffalo
CANADA
Lake Michigan
Rockford
Kalamazoo
Battle Creek
Ann Arbor
Detroit
Lake Erie
Erie
NEW YORK
Olean
IOWA
Clinton
Davenport
Chicago
Toledo
South Bend
Cleveland
St. Marys
Sandusky
Warren
Galesburg
Fort Wayne
Findlay
Youngstown
Clearfield
Peoria
Akron
PENNSYLVANIA
Macomb
Bloomington
Wabash
Lima
Mansfield
Canton
Pittsburgh
Kokomo
Lafayette
Anderson
Muncie
OHIO
Newark
Wheeling
Johnstown
Champaign
Danville
ILLINOIS
Springfield
Cambridge
Cumberland
INDIANA
Columbus
Springfield
Charleston
Indianapolis
Dayton
Fairmont
MD
Terre Haute
Columbus
Athens
Clarksburg
Effingham
Bloomington
Cincinnati
Parkersburg
Ohio
Portsmouth
Vincennes
Washington
WEST VIRGINIA
St. Louis
Mount Vernon
UNITED STATES
Huntington
Charleston
Harrisonburg
Jasper
Louisville
Morehead
Staunton
Evansville
Lexington
CUMBERLAND PLATEAU
Beckley
Carbondale
Owensboro
Lynchburg
MISSOURI
Madisonville
KENTUCKY
Paducah
Somerset
Bluefield
Roanoke
Poplar Bluff
Sikeston
Hopkinsville
Bowling Green
VIRGINIA
Danville
Kennett
Clarksville
Kingsport
Morristown
Winston-Salem
Dyersburg
Nashville
Cookeville
Durham
ARK.
Crossville
Knoxville
High Point
Raleigh
Murfreesboro
Jackson
Columbia
Asheville
Athens
BLUE RIDGE
NORTH CAROLINA
Memphis
TENNESSEE
NANTAHALA NATIONAL FOREST
Charlotte
Savannah
Lawrenceburg
Cleveland
Spartanburg
Fayetteville
Florence
Huntsville
Chattanooga
MISSISSIPPI
GEORGIA
Greenville
Lumberton
ALABAMA
SOUTH CAROLINA
©2006 Microsoft Corp.
88°
86°
84°
82°
80°

4:58 PM December 15, 1967

SILVER BRIDGE TUMBLES, TOLL, 7 DEAD, 41 MISSING

SPECIAL EDITION

Point Pleasant Register

Mason County's Daily Newspaper

Vol. XXXIII NO. 303 Point Pleasant, W. Va. SATURDAY, DEC. 16, 1967 Price 5c

'I Couldn't Understand Why I Made It'

Five Survivors Give Accounts

Eye Witnesses Tell Of Tragedy

Divers Begin Search For Untold Loss

The toll is not yet told, and may not be for some time.

At presstime this afternoon there were 7 bodies recovered, 41 reported missing and 11 injured. There may be more.

It was right at 5 o'clock last night. Rush-hour traffic was heavy.

What happened is not yet clear. But the giant Silver Bridge, a gateway to to the west along the Ohio River at Point Pleasant, shivered, toppled, and sank.

With it went an untold numbers of cars, trucks, and lives.

Of the bodies recovered, four have been identified and three have not. The dead listed by State Police, which is not releasing a list of the missing, include:

Melvin Cantrell, Gallipolis Ferry.

Cecil Counts, Gallipolis Ferry.

George McManis, South Point, O.

Leo Blackman, Richmond, Va.

Pleasant: Mrs. Margaret Cantrell, Gallipolis Ferry; Mrs. Charles Wood, Gallipolis; William Edmonson, King, N. C.; William Needham Jr., Ashboro, N. C.; Paul Scott, Middleport; Della Boggs address unknown; Howard Boggs, Porter-Bidwell, O.; Frank Nunn, Winston-Salem, N. C.; Sam Ellis, Winston-Salem.

Shortly before noon today a car was pulled from the river, but it was unoccupied. Two barge derricks from M. T. Epling Company were scouting the river, one just opposite Fourth Street.

Register Staff Writer Jean Warner communicating from the scene said one skin diver had gone into the water, and one blue buoy could be spotted from the shore.

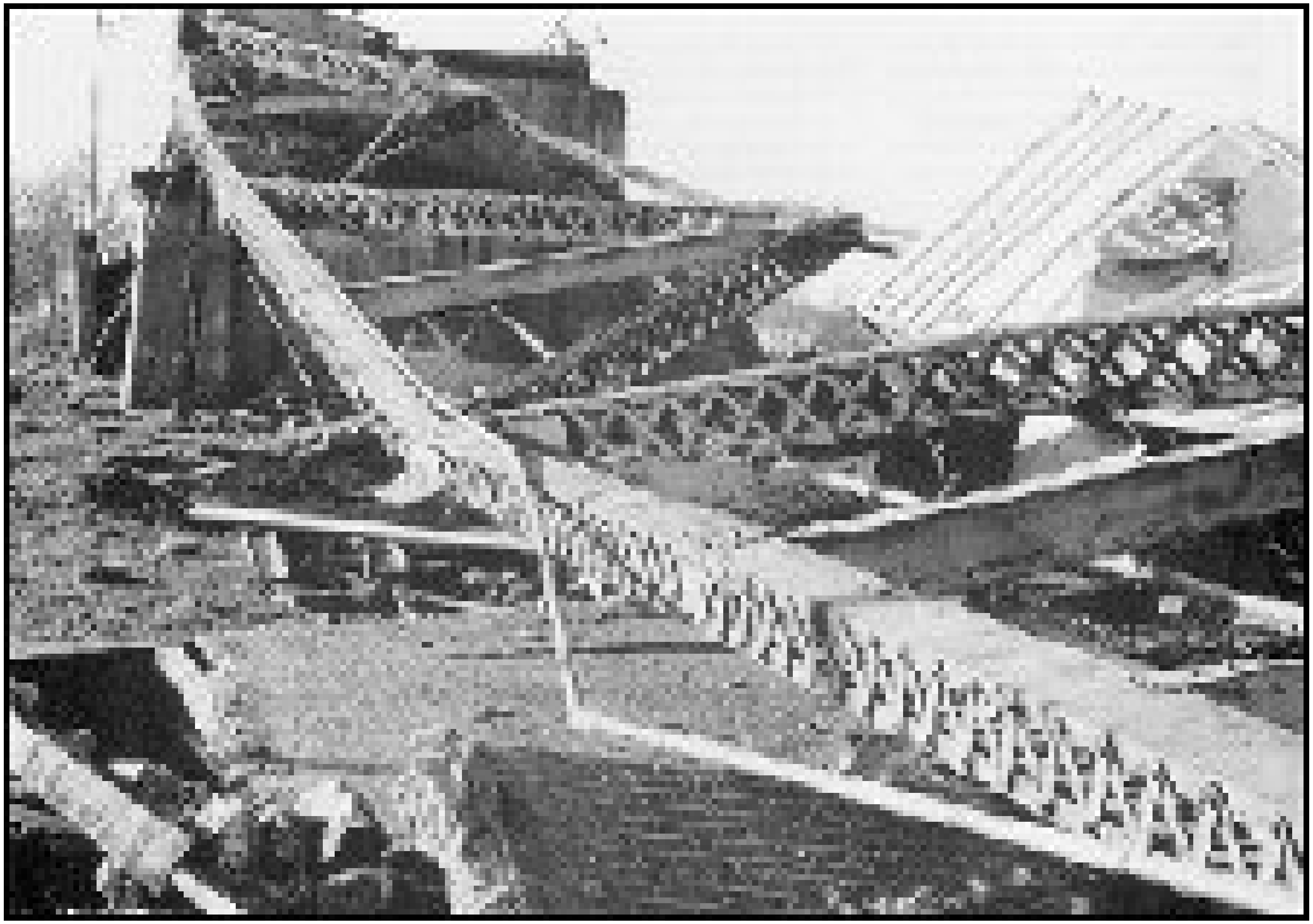
Reports said three Goodyear employes, several teachers and some prominent Point Pleasant residents were among the missing.

Bodies of the deceased had been taken to Malone Funeral Home in, Graceland, Ky.; Crow-Hussell Funeral Home here and Miller Funeral Home in Gallipolis.

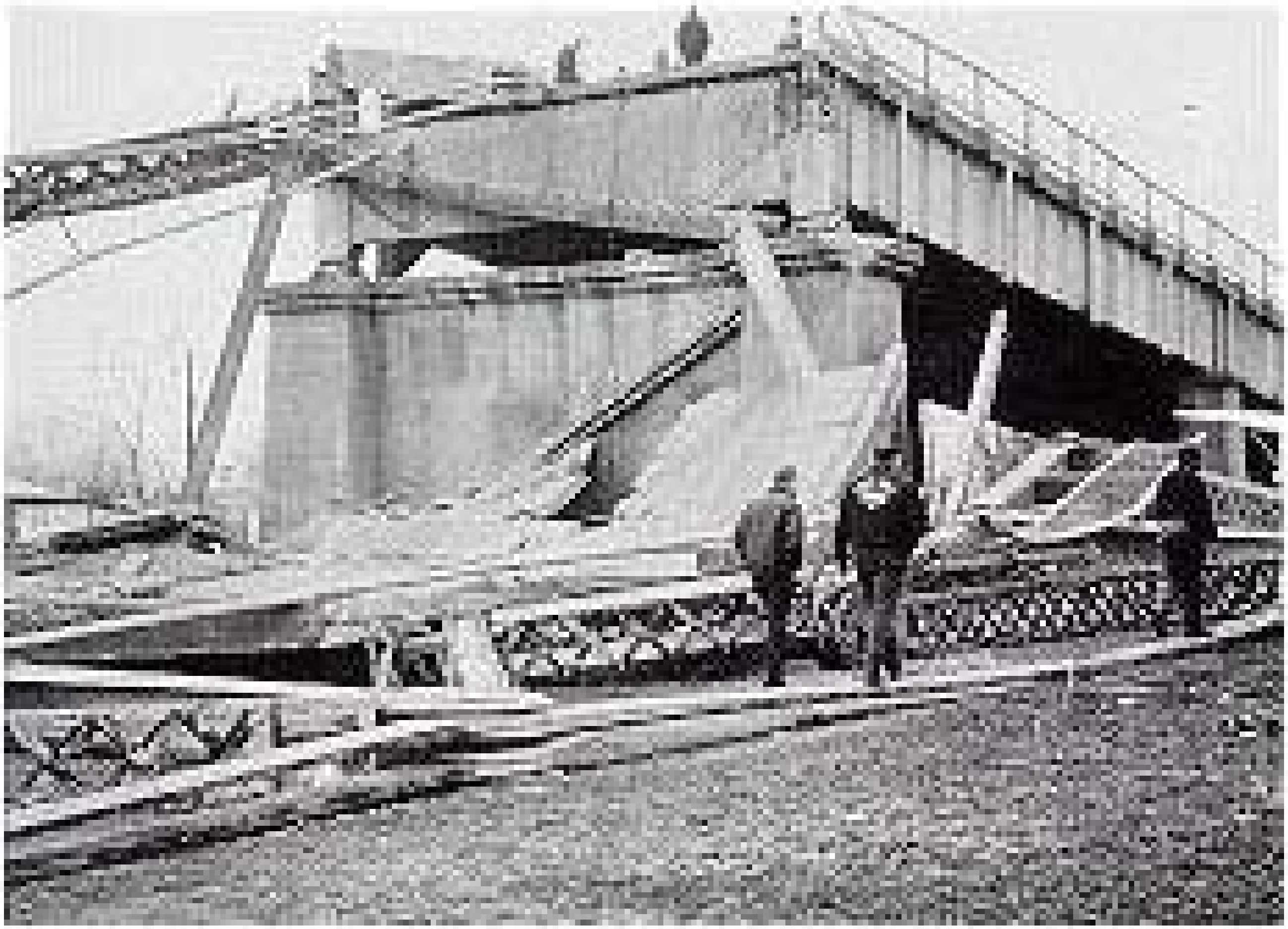
Disaster

- Second most deadly U.S. bridge disaster
- 64 hit the water
- 18 rescued
- 46 dead or missing
- 31 vehicles on the bridge

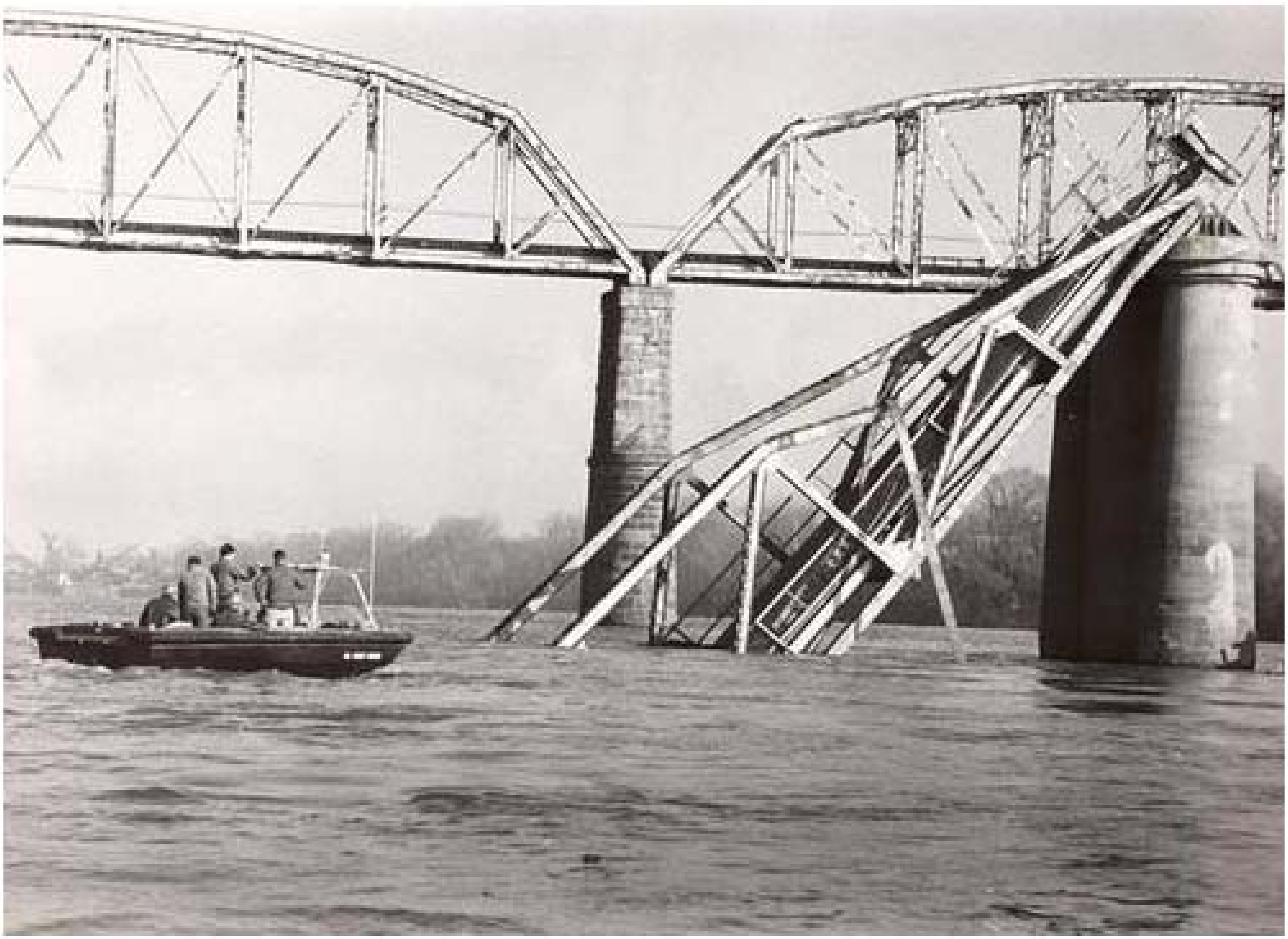
Wreckage



Wreckage



Wreckage



What’s Different About Silver Bridge?

- First “eyebar” suspension bridge in the U.S.
- First bridge that used high-strength, heat-treated carbon steel
- High Risk: new structure on a new scale, using new materials.

Silver Bridge Collapse

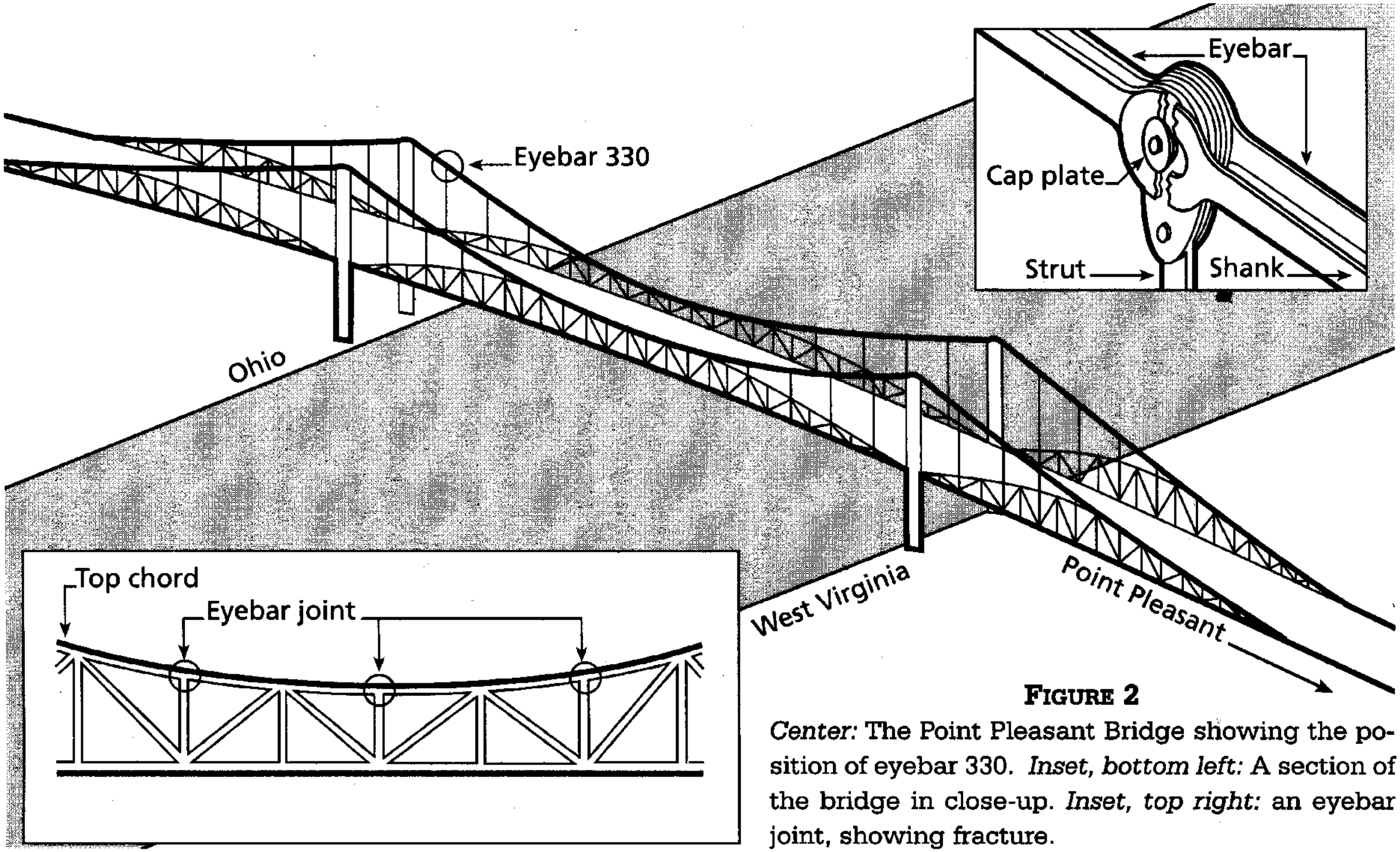
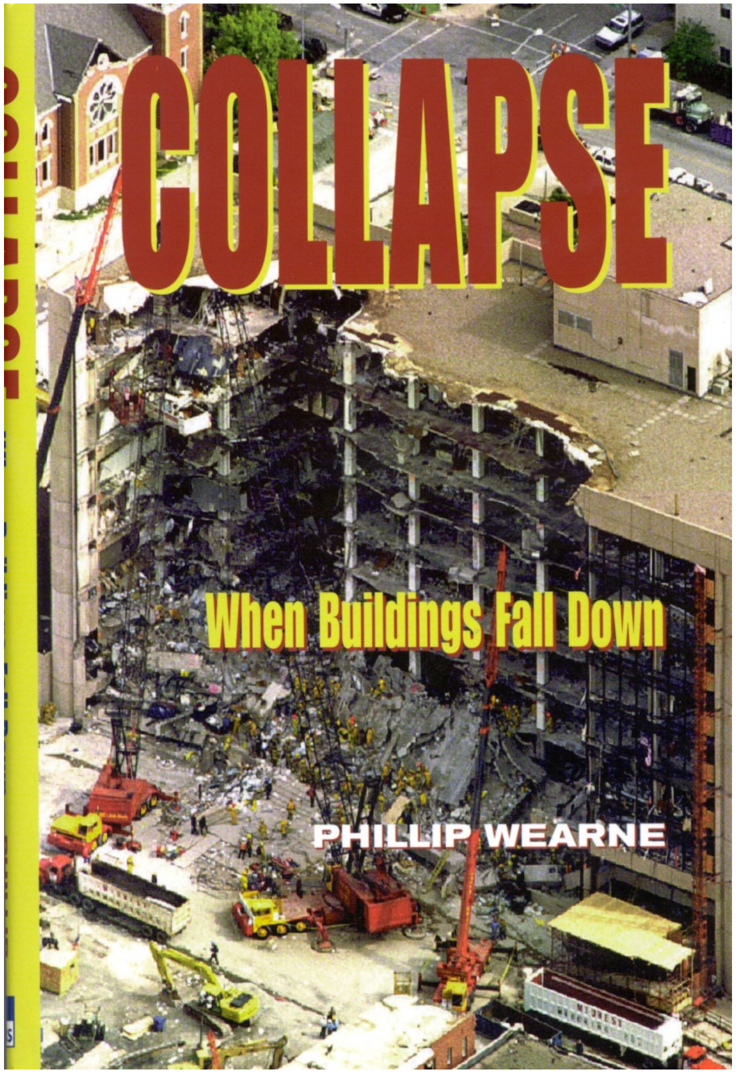


FIGURE 2

Center: The Point Pleasant Bridge showing the position of eyebar 330. *Inset, bottom left:* A section of the bridge in close-up. *Inset, top right:* an eyebar joint, showing fracture.

Collapse, Wearne, P. TV Books, NY 1999

Source



Cause of Failure

- Bridge Design?
- Eyebar Manufacturing Quality?
- Material Choice?

Bridge Design at Fault?

- Steel Eyebar Suspension
- Suspended “Bicycle Chain”
- Weakest Link, No Redundancy
- Cable Suspension has hundreds of links

Partially!

Failed Eyebar

Failure Evidence

John Bennet, US Bureau of Standards

- "The Ohio River there is very heavily traveled so the U.S. Corps of Engineers had taken all the debris and just piled it on the shore – it was a terrific mess."

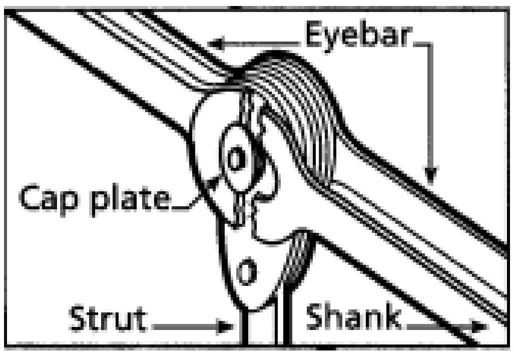
- "Fortunately, each piece had been photographed as they took it out."

Failure Evidence

Debris from the collapse of the Silver Bridge on Dec. 15, 1967.

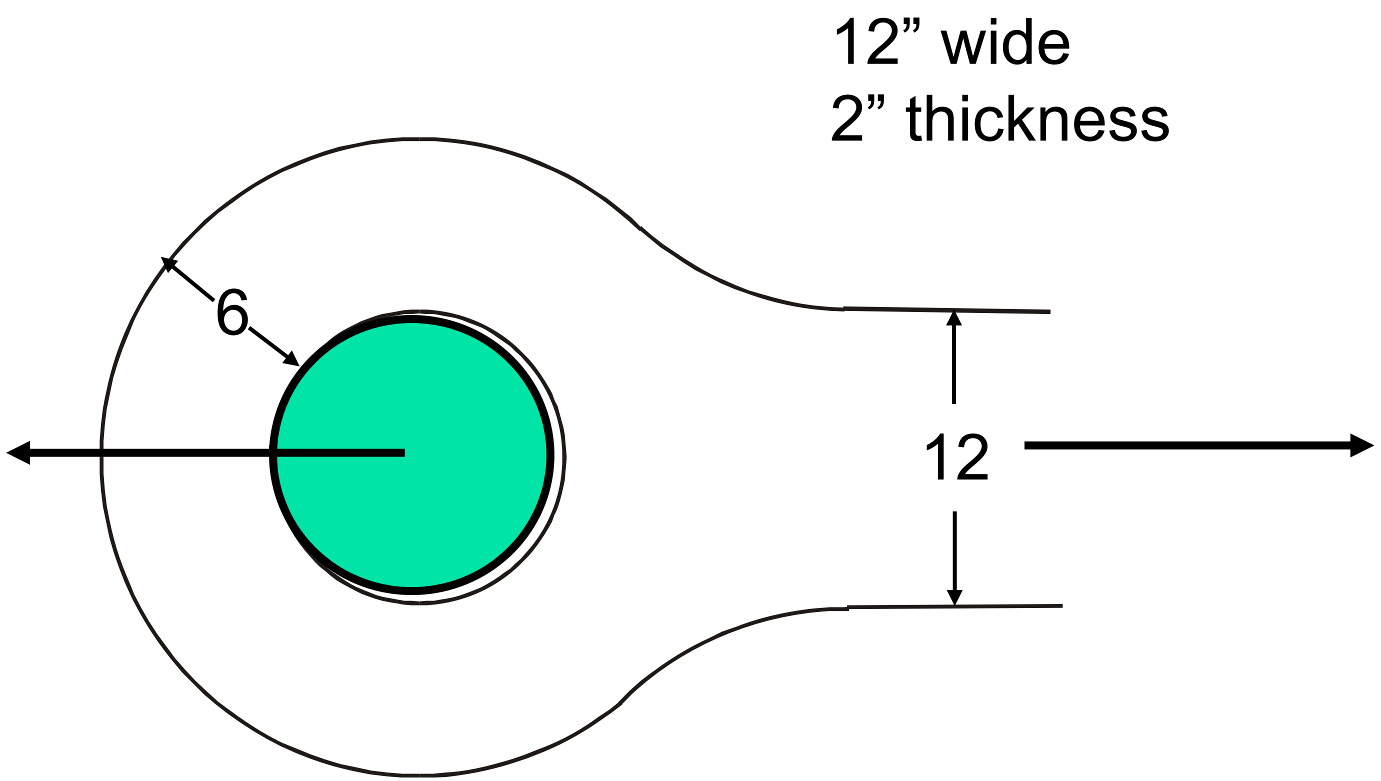
Photograph of Failed Eyebar 330

John Bennet, US Bureau of Standards

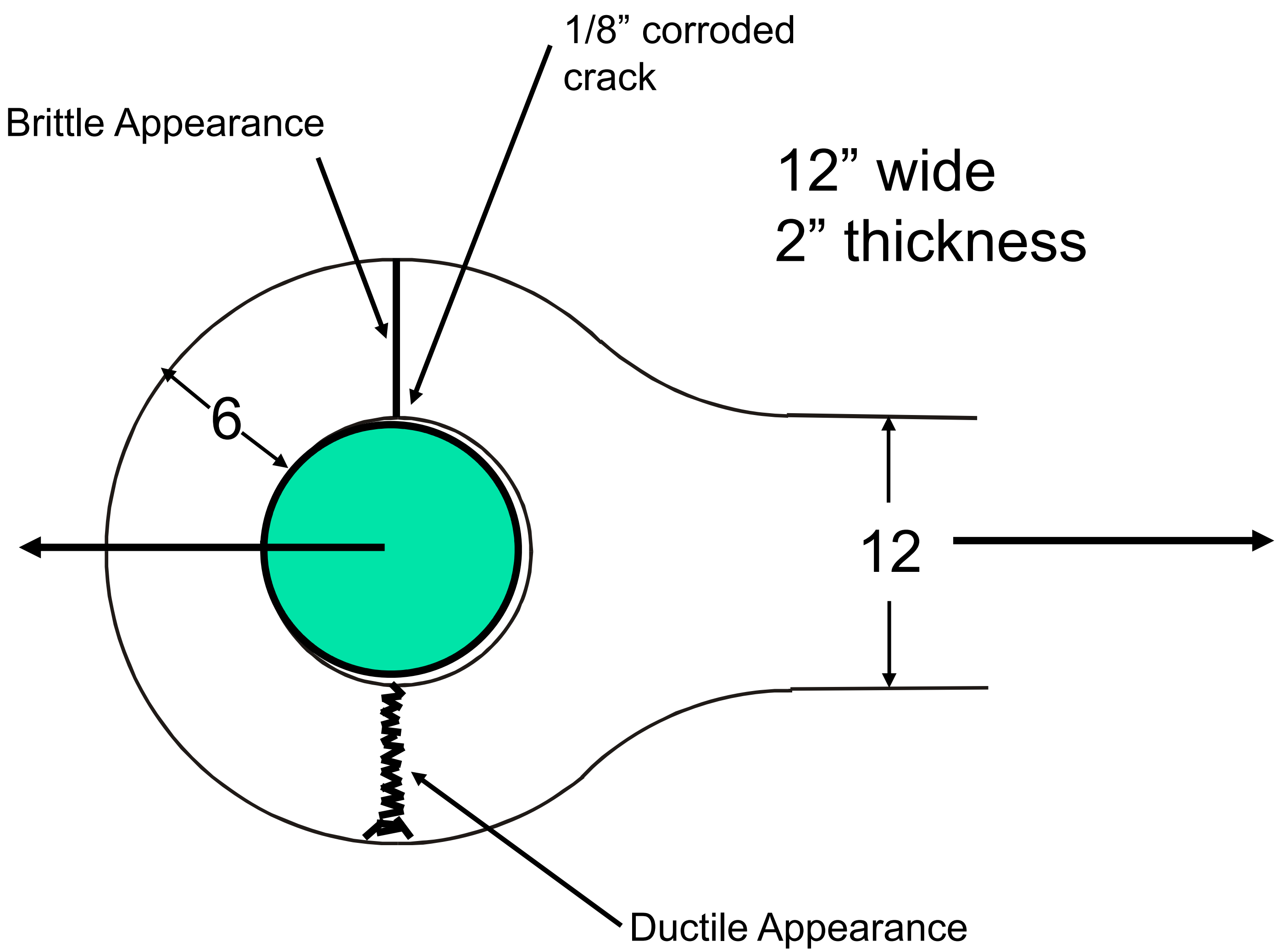


- “Looking at it, the fractures on the two sides were completely different.
- “One side was very straight, almost like a saw cut.
- “The other side was extensively deformed, the metal bent and the paint chipped off.

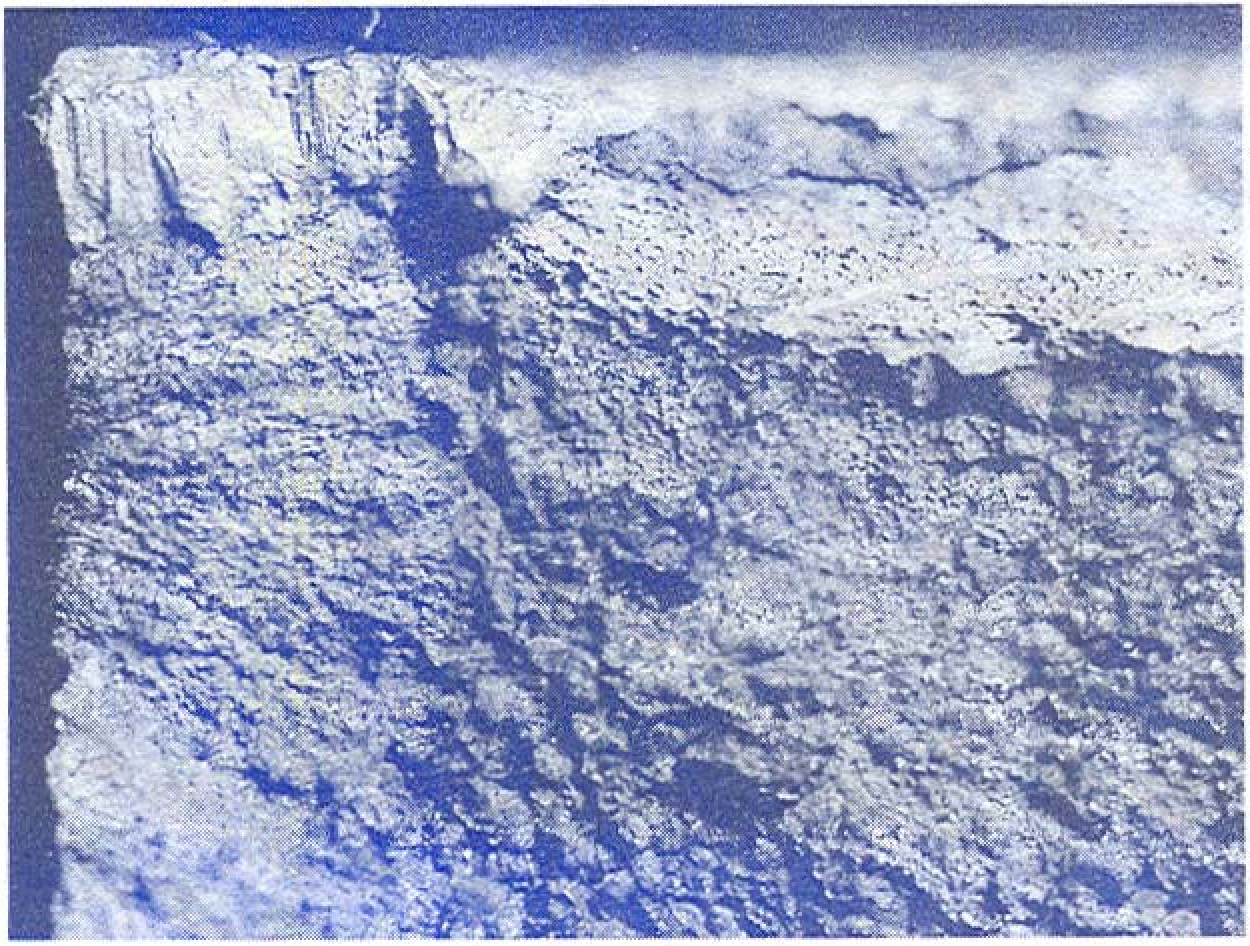
Eyebar Loading



Eyebar 330 Failure Sketch



Crack on Eyebar 330



The tiny area of deeply encrusted rust discovered inside the metal of eyebar 330. It indicated that a fatal crack had developed during the forging of the steel forty years before the bridge collapsed.

Conditions of Failure

- Crack formed by original forging operation
- Quenched and tempered steel
- Stress corrosion cracking
- 32^{o}F ambient temperature

Assignment

Make an estimate of the maximum allowable flaw size in the eyebar.

Barsom-Rolfe $\frac{K_{IC}^2}{E}(psi-in)=2(CVN)^{\frac{3}{2}}\ (ft-lb)$

Corten-Sailors $K_{IC}(ksi\sqrt{in})=15.5\sqrt{CVN}\ (ft-lb)$

Roberts-Newton $K_{IC}(ksi\sqrt{in})=9.35\,CVN^{1.65}\ (ft-lb)$

Material Properties

σ_u = 100 ksi
σ_y = 75 ksi
E = 29,000 ksi

Working stress 50 ksi

Charpy V-notch Tests

CVN = 2.6 ft-lb at 32° F

CVN = 8.6 ft-lb at 165° F

$$K_{IC} = \sigma\sqrt{\pi a}\, F\left(\frac{a}{b}\right)$$

Estimate K_{IC}

Barsom-Rolfe

$$K_{IC} = \sqrt{2E\,(CVN\ in\ \ ft-lb\,)^{\frac{3}{2}}} \approx 15.6\,ksi\sqrt{in}\ at\ 32^{o}\,F$$

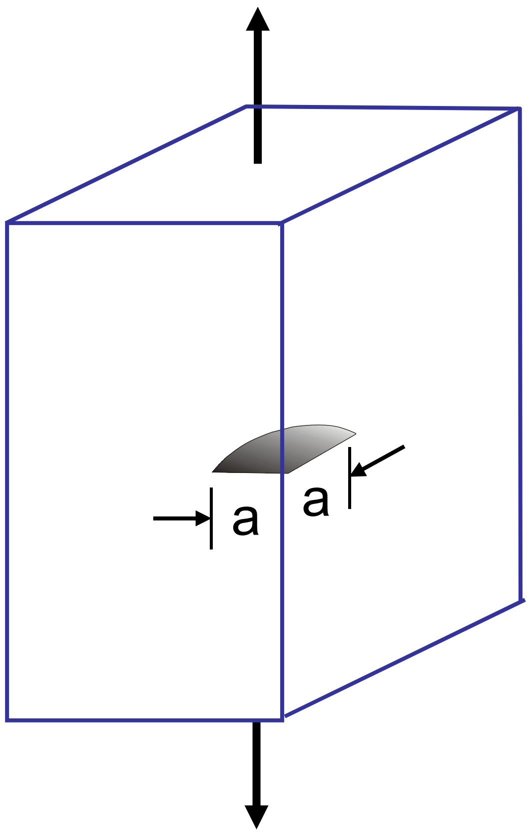
Corten-Sailors

$$K_{IC}\,(ksi\sqrt{in}\,) = 15.5\sqrt{CVN}\ \ (ft-lb) \approx 25.0\,ksi\sqrt{in}\ at\ 32^{o}\,F$$

Roberts-Newton

$$K_{IC}\,(ksi\sqrt{in}\,) = 9.35\,CVN^{1.65}\ \ (ft-lb) \approx 45.2\,ksi\sqrt{in}\ at\ 32^{o}\,F$$

Assume Flaw Geometry



Corner crack

Two free edges
Semicircular shape

$$K = \sigma (1.12)^2 \frac{2}{\pi} \sqrt{\pi a}$$

$$F\left(\frac{a}{b}\right) = (1.12)^2 \frac{2}{\pi} = 0.799$$

Critical Crack Size (Best Case)

$$a_{critical} = \frac{1}{\pi}\left(\frac{K_{IC}}{0.799\sigma_{applied}}\right)^2$$

= 0.045 in (using Barsom-Rolfe K_{IC} at 32^{o}F)

= 0.125 in (using Corten-Sailors K_{IC} at 32^{o}F)

= 0.407 in (using Roberts-Newton K_{IC} at 32^{o}F)

ME 431
Failure Analysis of Mechanical Components

Produced by the
College of Engineering
University of Illinois at Urbana-Champaign