SUBSECTION HB, SUBPART B

Robert Jetter

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Technical Seminar on Application of ASME Section III to New Materials for High Temperature Reactors

ROBERT JETTER BIOGRAPHICAL INFORMATION

Mr. Jetter has over 50 years' experience in the design and structural evaluation of nuclear components and systems for elevated temperature service. He was a contributor to the original ASME Code Cases eventually leading to Subsection NH and subsequent Section III, Division 5 for High Temperature Reactors. For over 25 years he chaired the Subgroup on Elevated Temperature Design (SG-ETD). He is currently a member of the Committee on Construction of Nuclear Facility Components (BPV-III), the Subcommittee on Design, Subgroup on High Temperature Reactors, Subgroup Elevated Temperature Design and Working Groups – High Temperature Gas Cooled Reactors, High Temperature Liquid Cooled Reactors, Analysis Methods, Creep-Fatigue and Negligible Creep, and Elevated Temperature Construction.

Mr. Jetter was a member of a Department of Energy (DOE) steering committee responsible for elevated temperature design criteria, and was a consultant and reviewer on various DOE projects. An employee of Rockwell /Atomics International, he participated in and directed design activities on the early sodium cooled reactors and space power plants through all the US LMFBR programs. He currently consults on the development and application of elevated temperature design criteria. He was an International Fellow for the Power Reactor and Nuclear Fuel Development Corporation at the Monju Fast Breeder Reactor site in Japan and co-authored the text "Design and Analysis of ASME Boiler and Pressure Vessel Components in the Creep Range". He is a Fellow of the ASME and received its Dedicated Service Award in 2011.

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Section III, Division 5

High Temperature Reactors – Subsection HB

SUBPART B
ELEVATED TEMPERATURE SERVICE

SUBSECTION HB, SUBPART B

- HBB-1000 Introduction
- HBB-2000 Material
- HBB-3000 Design
- HBB-4000 Fabrication and Installation
- HBB-5000 Examination
- HBB-6000 Testing
- Other Elevated Temperature Component Rules
- New Methods

HBB-1000 INTROUCION

- HBB picks up where NB allowable stresses stop
  - 700F for ferritic materials
  - 800F far austenitic materials
- HBB failure modes
  - Ductile rupture from short term loads
  - Creep-rupture from long term loads
  - Creep-fatigue
  - Gross distortion due to incremental collapse and ratcheting
  - Loss of function due to excessive deformation
  - Buckling due to short term loads
  - Buckling due to long term loads

HBB-1000 INTROUCION

- Additional procedures and material data not contained in HBB may be required
  - i.e. corrosion, mass transfer, irradiation
- Maximum service life and temperatures limited to values associated with S_{mt} data for the specified material

HBB-2000 MATERIALS

- Permitted Materials
  - Structural (pressure boundary): Types 304 & 316SS, Alloy 800H, 2¼Cr-1Mo and 9Cr-1Mo-V
  - Bolting: Types 304 & 316SS and Alloy 718
  - For long term stability and predictable properties, Types 304 & 316SS, Alloy 800H and 2¼Cr-1Mo are in the annealed condition
- Delta Ferrite
  - Limits in NB changed from 5-FN minimum to range of 3-FN to 10-FN.

HBB-2000 MATERIALS

- Deterioration of Materials in Service
  - Reduction in yield and ultimate strength due to ageing
- Hot Acceptance Test
  - Required for 304 & 316SS in the creep range
  - Based on heat of 304SS which met all acceptance criteria but had low creep ductility (0.5%) and low creep fatigue resistance
  - Creep-fatigue acceptance test
    - 1100F, 1% strain range, 1hr hold, > 200 cycles to failure

HBB-3000 DESIGN

- NB-Design (Review)
- Elevated Temperature Behavior
- Allowable Stresses
- Primary (Load Controlled) Stress Limits
- Secondary and Peak (Deformation Controlled) Stress Limits
  - Strain Limits
  - Ratcheting
  - Creep-Fatigue
  - Buckling and Instability

HBB-3000 DESIGN

- Other Issues
  - Welds
  - Bolts
  - Inelastic analysis methods
  - Restricted Material Specifications
  - Design Specifications and Load Histograms
- Component Design Rules

SUBSECTION NB

- Subsection NB – Design
  - Design, Service and Test Loadings
  - Stress classification
  - Allowable stress
  - Stress intensity limits
  - Stress calculation
  - Stress limits

GENERAL REQUIREMENTS
DESIGN, SERVICE & TEST LOADINGS

- Design Loads envelope Service Level A planned operation
  - Margins for instrument error etc.
- Service Level A are planned events
  - Typically without margins
- Service Level B are unscheduled events
  - Withstand without repair

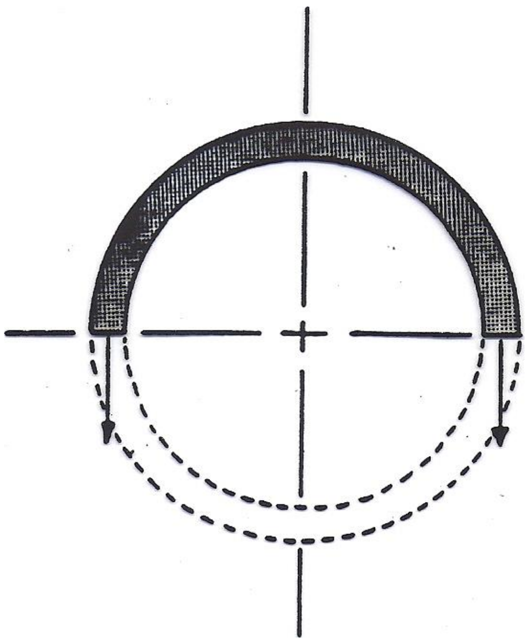
GENERAL REQUIREMENTS
DESIGN, SERVICE & TEST LOADINGS

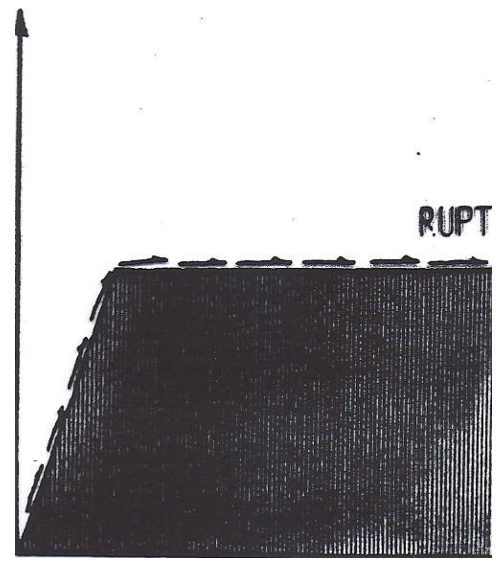
- Service Level C are limited number of low probability events
  - Large deformations - may require repair and replacement
- Service Level D is a single, terminal, remote probability event
  - Pressure boundary not breached - not reusable
- Test Limits
  - Prevent damage

Stress Classification

- Primary Sresses are :
  - Normal Sresses
    - Component normal to the plane of reference
  - Two types
    - Primary Membrane – average across thickness
    - Primary Bending – component of normal that varies from average with location across thickness
  - In equilibrium with external loads
    - Not relieved by yielding.

Primary Membrane Stress, P_m in Pressurized Cylinder





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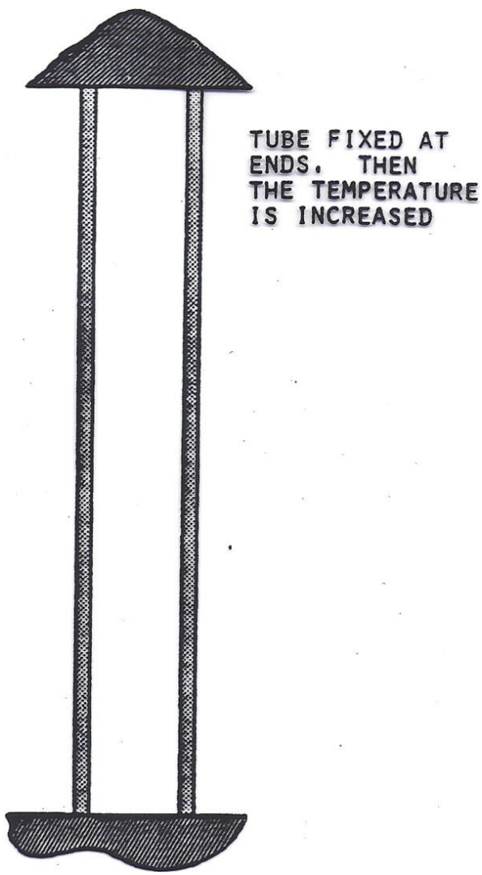
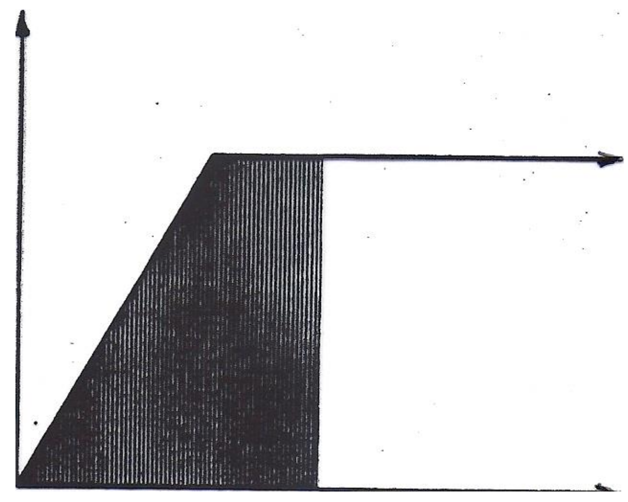
Stress Classification

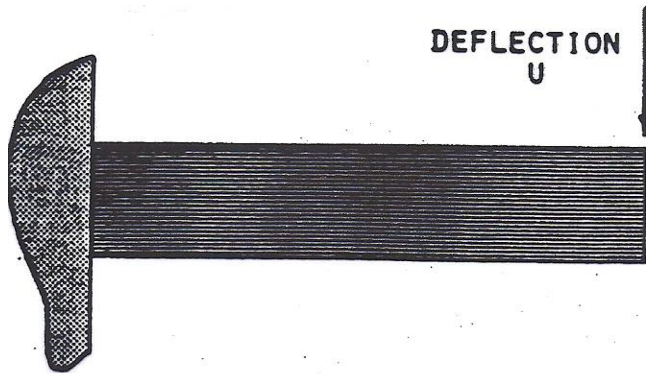
- Secondary Stresses are:
  - Required to maintain displacement compatibility – displacement controlled
  - Limited by yielding
  - Generated by restrained thermal expansion

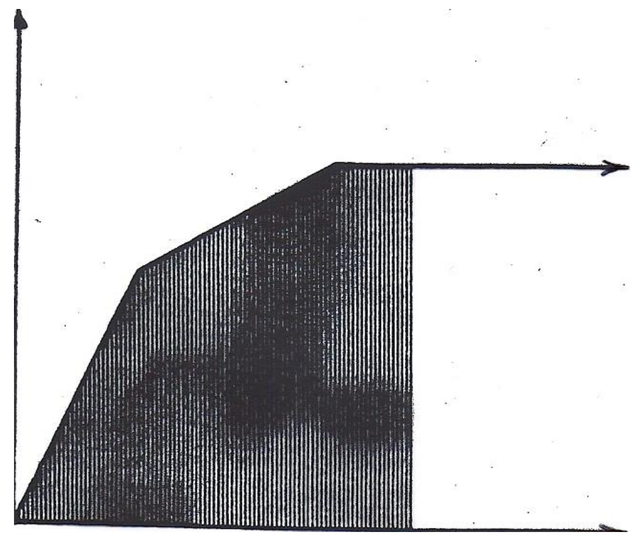
Secondary Stress, Q - Due to Restrained Thermal Expansion



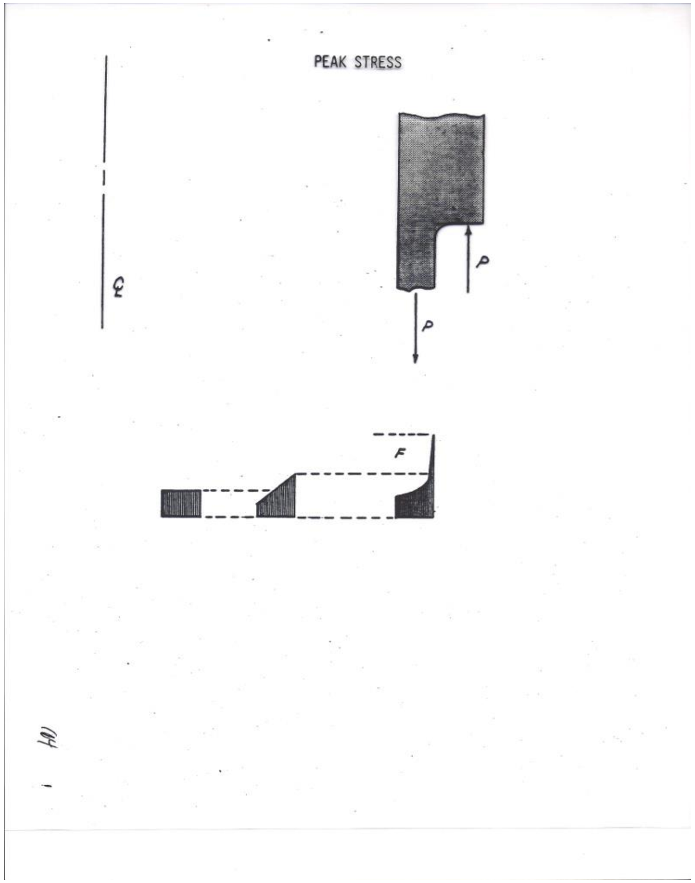


Secondary Stress, Q - Due to Applied Displacement





Peak Stress, F, is incremental stress due to stress concentrations and non linear portion of thermal gradient



STRESS CLASSIFICATION
PRIMARY AND SECONDARY STRESSES

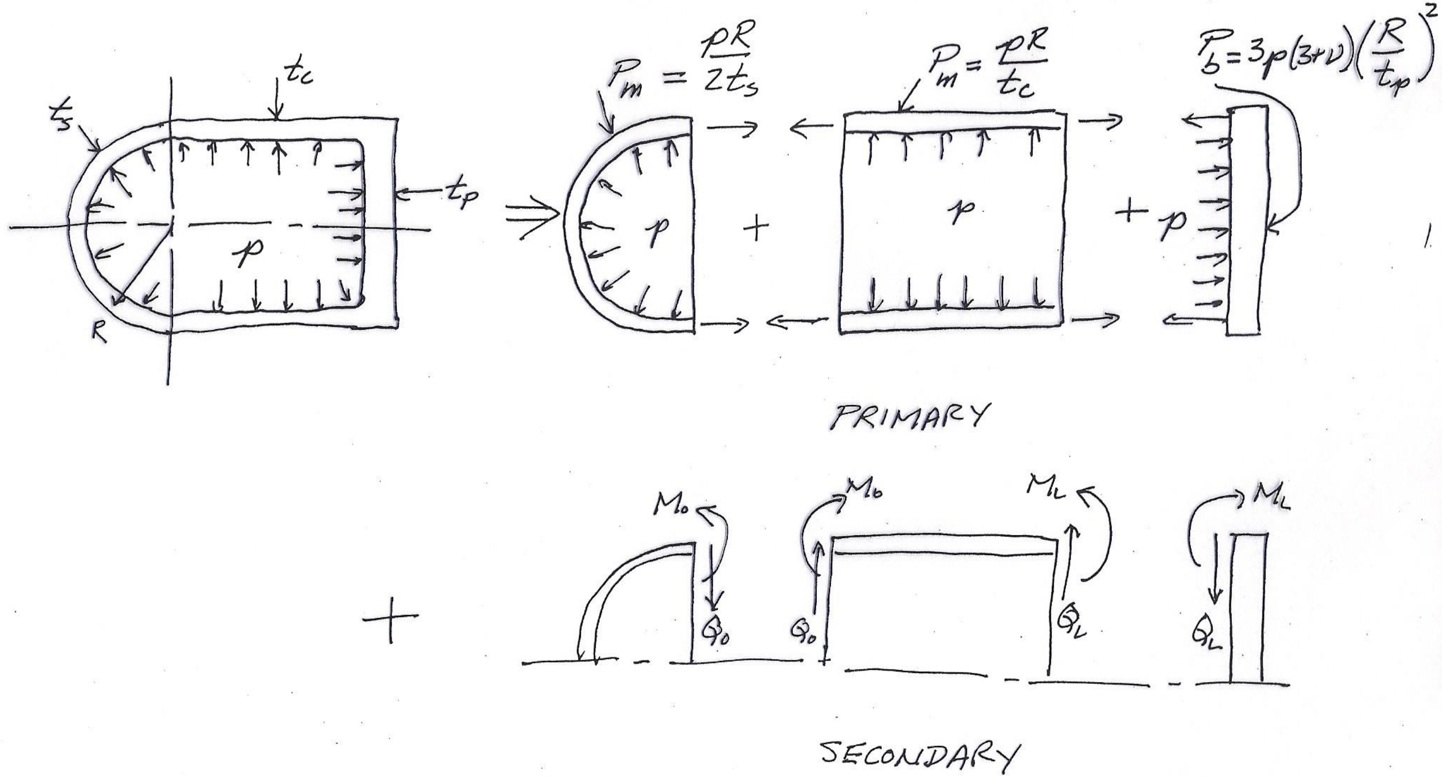
- Definitions of primary and secondary stress are based on analytical methods used prior to FEM
  - Separate vessel into shells of simple geometry (free body diagrams) with external loads applied
    - Determine redundant (self limiting) system of forces at the edges required to restore structural continuity – these "discontinuity forces are secondary
    - Determine forces for static equilibrium
      - Compute primary stresses

STRESS CLASSIFICATION
PRIMARY AND SECONDARY STRESSES

- Determine deflections at the edges of the free bodies
  - Compute secondary stresses
- Secondary stresses are limited to ensure shakedown to the elastic stress range so that strain controlled fatigue data can be used to evaluate cyclic damage.

- It can be difficult to distinguish between primary and secondary stresses without free body definition

PRIMARY AND SECONDARY STRESS EXAMPLE – PRESSURIZED VESSEL



- NOTE: IF M_L IS USED TO RESTRAIN THE FLAT HEAD AND REDUCE P_b , THEN M_L IS ALSO CONSIDERED PRIMARY BENDING
  - CONSISTENT WITH FEM

ALLOWABLE STRESS
S_m CRITERIA

2010 SECTION II, PART D (CUSTOMARY)

TABLE 2-100(a)
CRITERIA FOR ESTABLISHING DESIGN STRESS INTENSITY VALUES FOR TABLES 2A AND 2B

Product/Material	Room Temperature and Below		Above Room Temperature			
	Tensile Strength	Yield Strength	Tensile Strength		Yield Strength	
Wrought or cast, ferrous and nonferrous	$\frac{S_T}{3}$	$\frac{2}{3}S_Y$	$\frac{S_T}{3}$	$\frac{1.1}{3}S_T R_T$	$\frac{2}{3}S_Y$	$\frac{2}{3}S_Y R_Y$ or $0.9 S_Y R_Y$ [Note (1)]
Welded pipe or tube, ferrous and nonferrous	$\frac{0.85}{3}S_T$	$\frac{2}{3} \times 0.85 S_Y$	$\frac{0.85}{3}S_T$	$\frac{1.1 \times 0.85}{3}S_T R_T$	$\frac{2}{3} \times 0.85 S_Y$	$\frac{2}{3} \times 0.85 S_Y R_Y$ or $0.9 \times 0.85 S_Y R_Y$ [Note (1)]

NOTE:

(1) For austenitic materials in Table 2A and for specific nonferrous alloys in Table 2B, the design stress intensity values may exceed two-thirds and may be as high as 90% of the yield strength at temperature.

STRESS INTENSITY LIMIT

Stresses are limited to guard against ductile rupture, gross distortion (buckling and incremental collapse), and fatigue

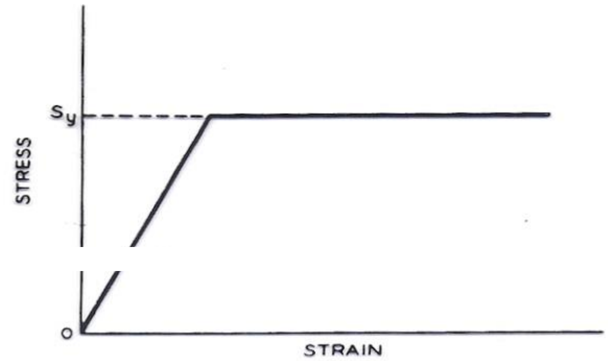


FIGURE 1. IDEALIZED STRESS – STRAIN RELATIONSHIP

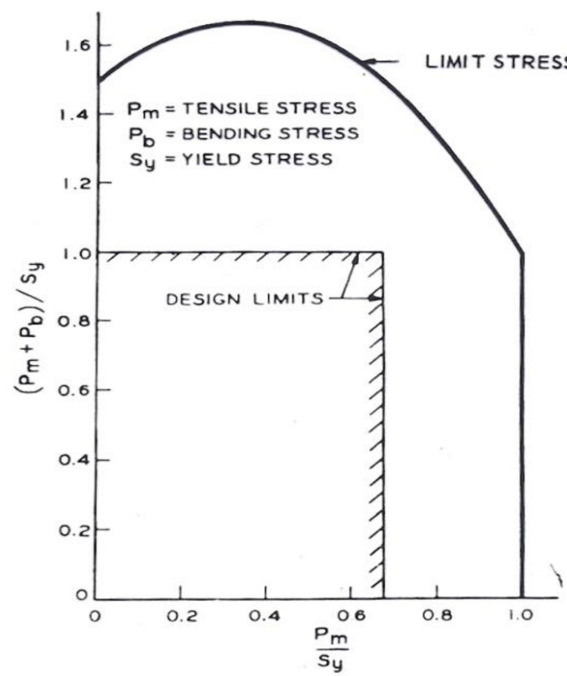
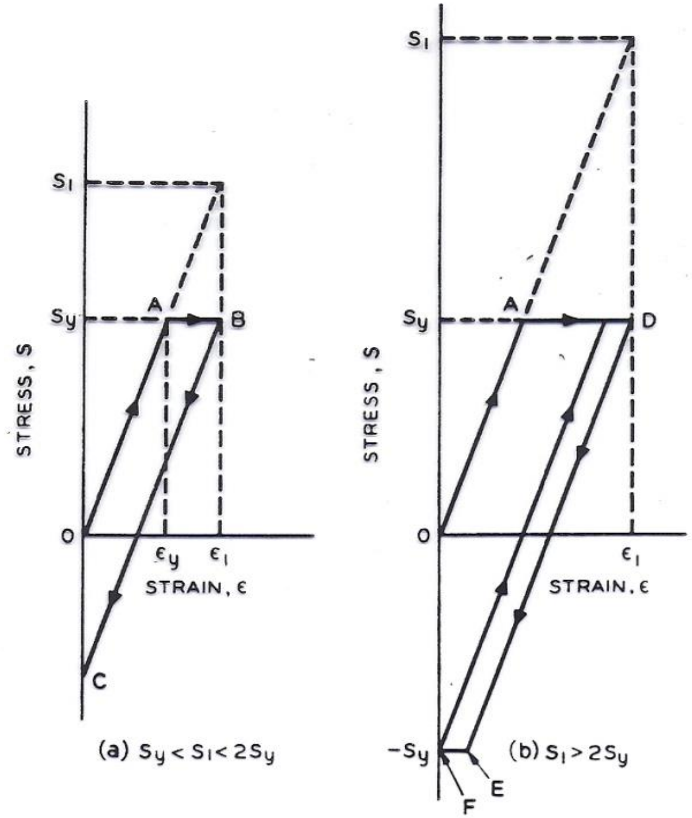


FIGURE 2. LIMIT STRESS FOR COMBINED TENSION AND BENDING (RECTANGULAR SECTION)

was used to choose allowable values, in terms of the yield stress, for general



STRAIN HISTORY BEYOND YIELD

TABLE I. BASIC STRESS INTENSITY LIMITS

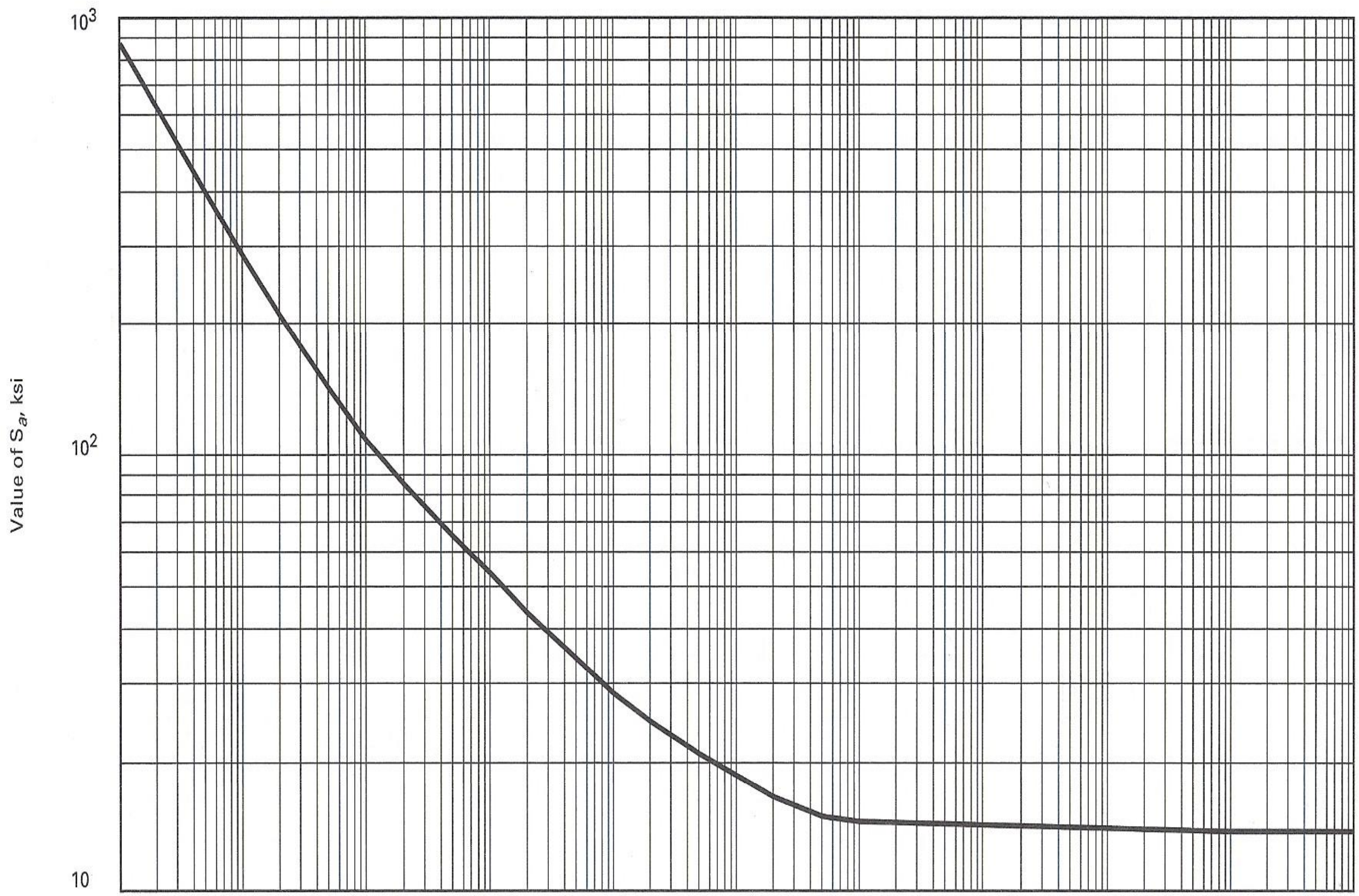
Stress Intensity	Tabulated Value	Yield Strength	Ultimate Tensile Strength
General primary membrane (P_m)	S_m	$\leqslant \frac{2}{3} S_y$	$\leqslant \frac{1}{3} S_u$
Local primary membrane (P_l)	$1.5\ S_m$	$\leqslant S_y$	$\leqslant \frac{1}{2} S_u$
Primary membrane plus bending ($(P_l + P_b)$)	$1.5\ S_m$	$\leqslant S_y$	$\leqslant \frac{1}{2} S_u$
Primary plus secondary ($P_l + P_b + Q$)	$3\ S_m$	$\leqslant 2\ S_y$	$\leqslant S_u$

FATIGUE

ALTERNATING STRESS LIMIT

Fatigue design curve is the lower of a factor of two on alternating stress or twenty on cycles applied to strain controlled, average cycles to failure data

FIG. I-9.2 DESIGN FATIGUE CURVES FOR AUSTENITIC STEELS, NICKEL–CHROMIUM–IRON ALLOY, NICKEL–IRON–CHROMIUM ALLOY, AND NICKEL–COPPER ALLOY FOR TEMPERATURES NOT EXCEEDING 800°F

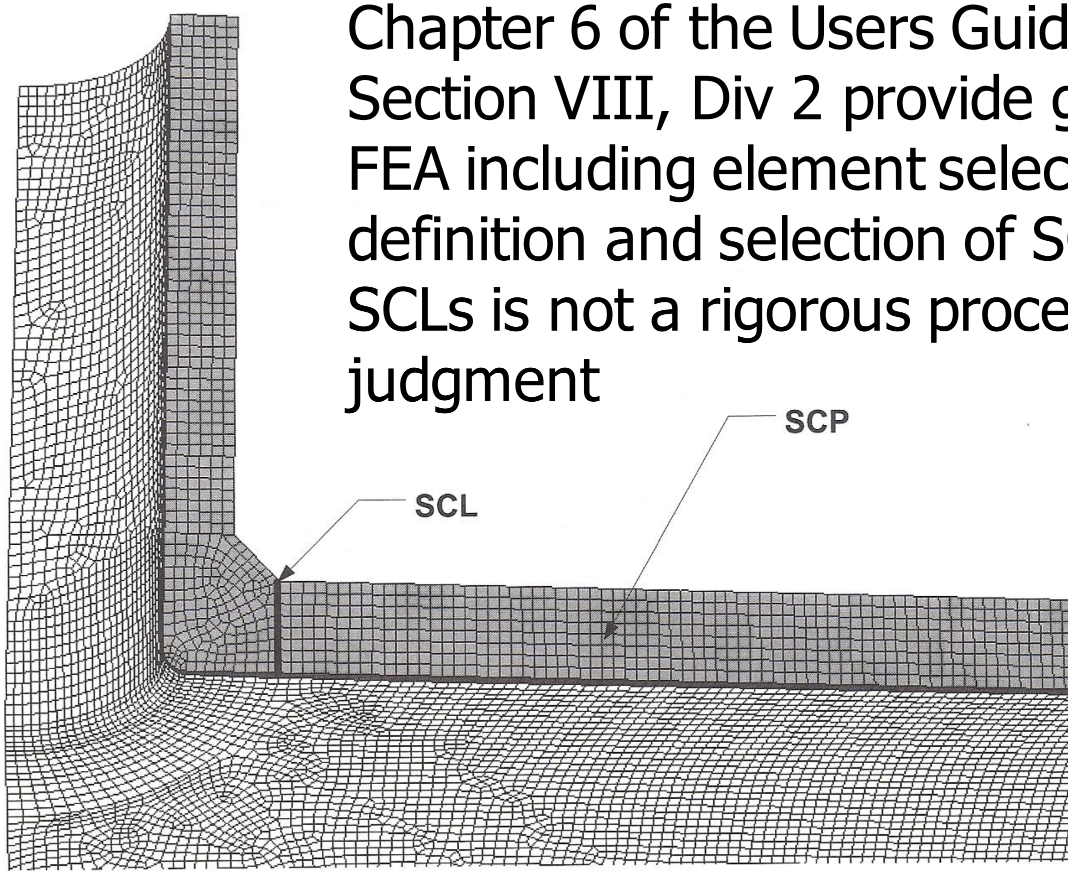


STRESS CALCULATION

- Subsection NB is based on maximum shear stress theory
  - Maximum shear stress is ½ the difference between maximum and minimum principal stresses
- Allowable stress levels are based on stress intensity
  - Stress intensity = twice maximum shear stress
- Stress intensities in each stress category (i.e. $P_l + P_b + Q$) are based on the summation of stresses at the stress component level followed by stress linearization, determination of principal stresses and, then, calculation of applicable stress intensity

STRESS CLASSIFICATION LINE (SCL) AND PLANE (SCP)

Chapter 6 of the Users Guide and Annex 5A in Section VIII, Div 2 provide guidance on use of FEA including element selection , mesh definition and selection of SCLs. Selection of SCLs is not a rigorous process and requires judgment



ELEVATED TEMPERATURE MATERIAL BEHAVIOR

- Creep
- Creep-Fatigue
- Elastic Follow-up
- Ratcheting
- Pressure Induced Discontinuity Stresses
- Shakedown

CREEP – LOAD HISTORY

Creep has a significant effect on load history

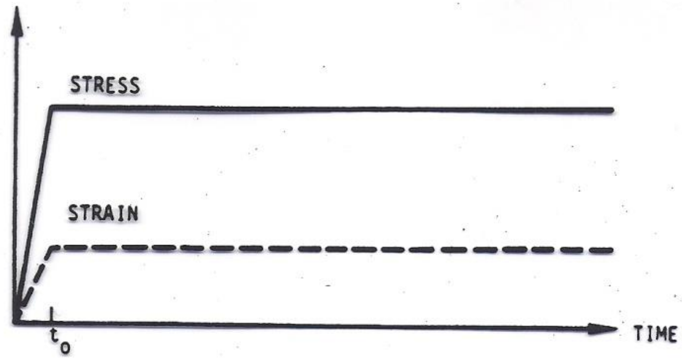


Fig. 1(a) HISTORIES FROM A LOADING AT LOW TEMPERATURE

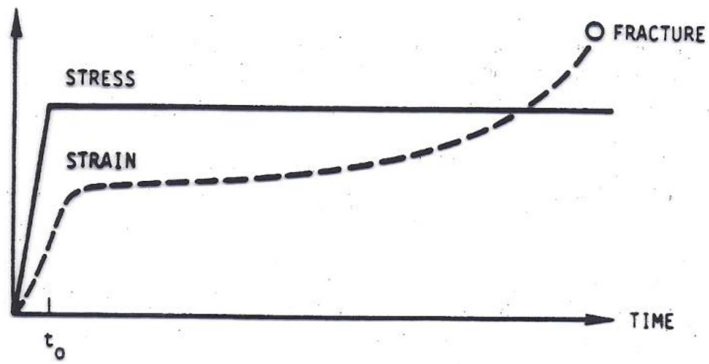


Fig. 1(b) HISTORIES FROM A LOAD-CONTROLLED LOADING AT ELEVATED TEMPERATURE

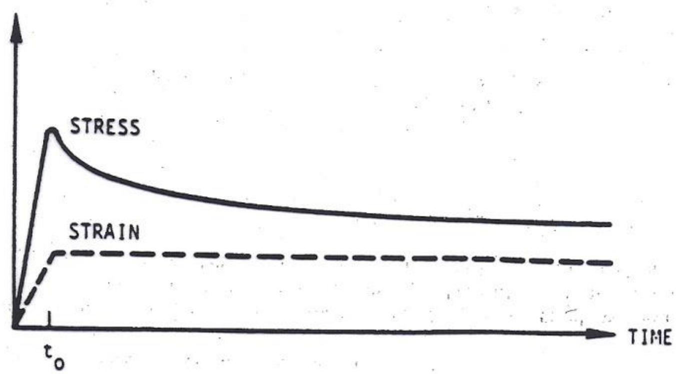
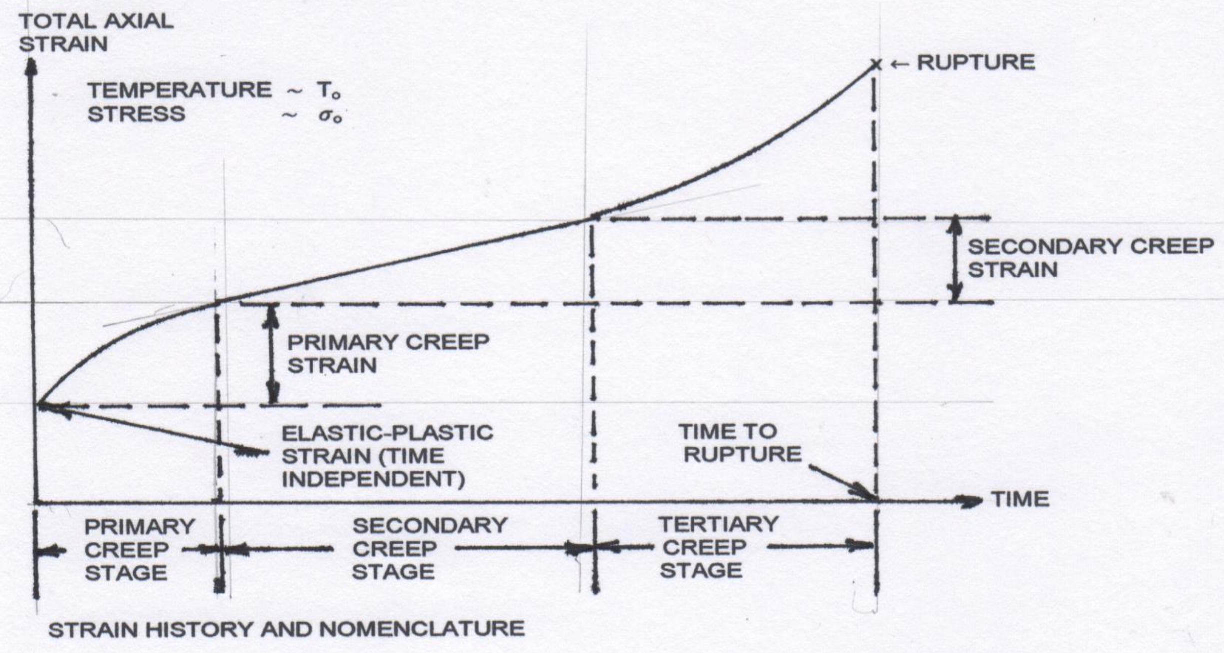
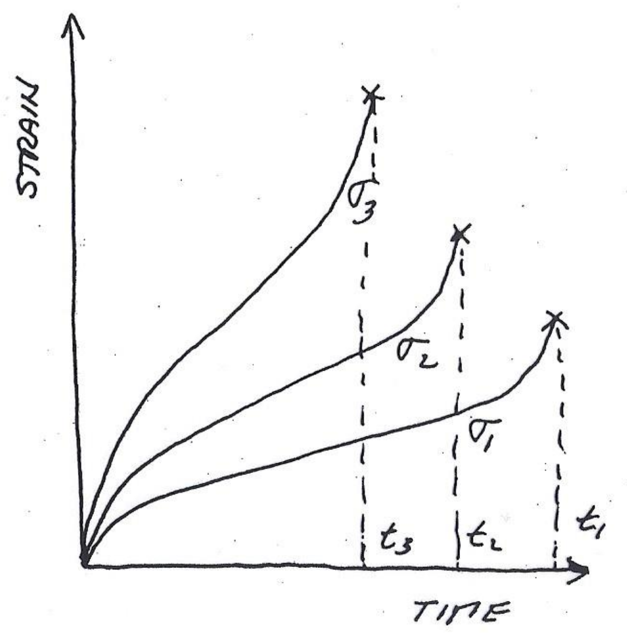


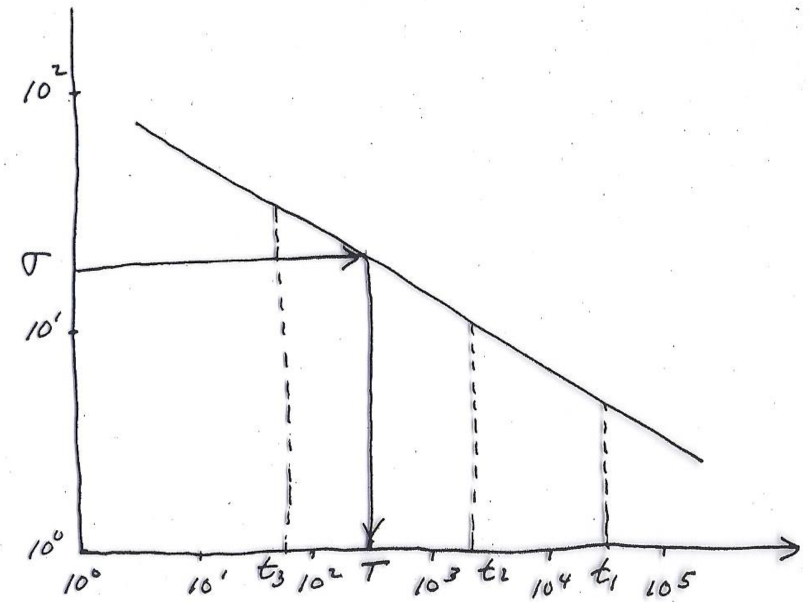
Fig. 1(c) HISTORIES FROM A STRAIN-CONTROLLED LOADING AT ELEVATED TEMPERATURE

CREEP – Standard Model



CREEP – STRESS RUPTURE AT CONSTANT TEMPERATURE

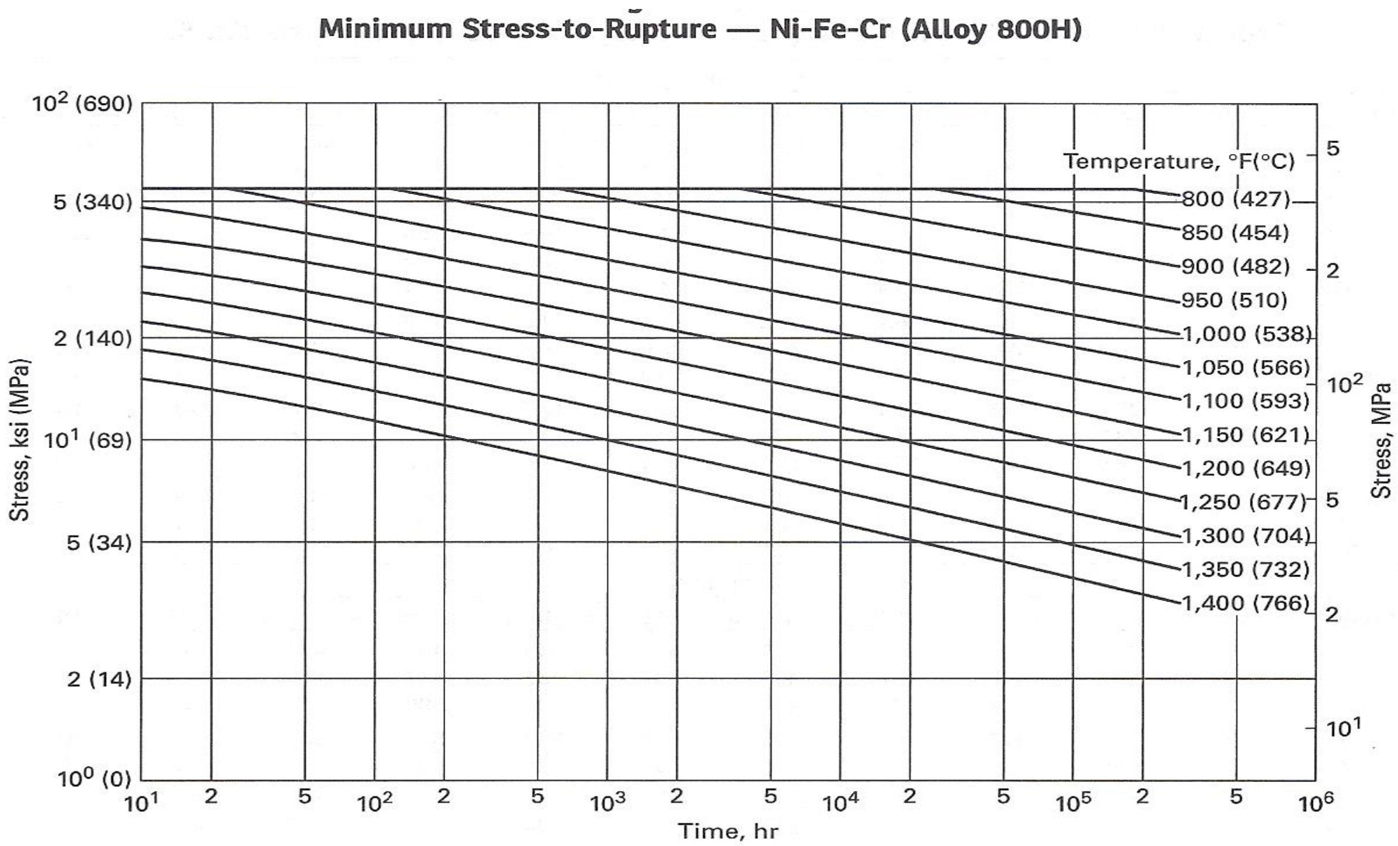




- CREEP CURVE
- CREEP RUPTURE

MINIMUM STRESS RUPTURE CURVES FOR 800H FROM

SUBSECTION NH



ISOCHRONOUS STRESS – STRAIN CURVES

Isochronous stress strain curves represent the strain that would be accumulated at a given stress at various values of constant time

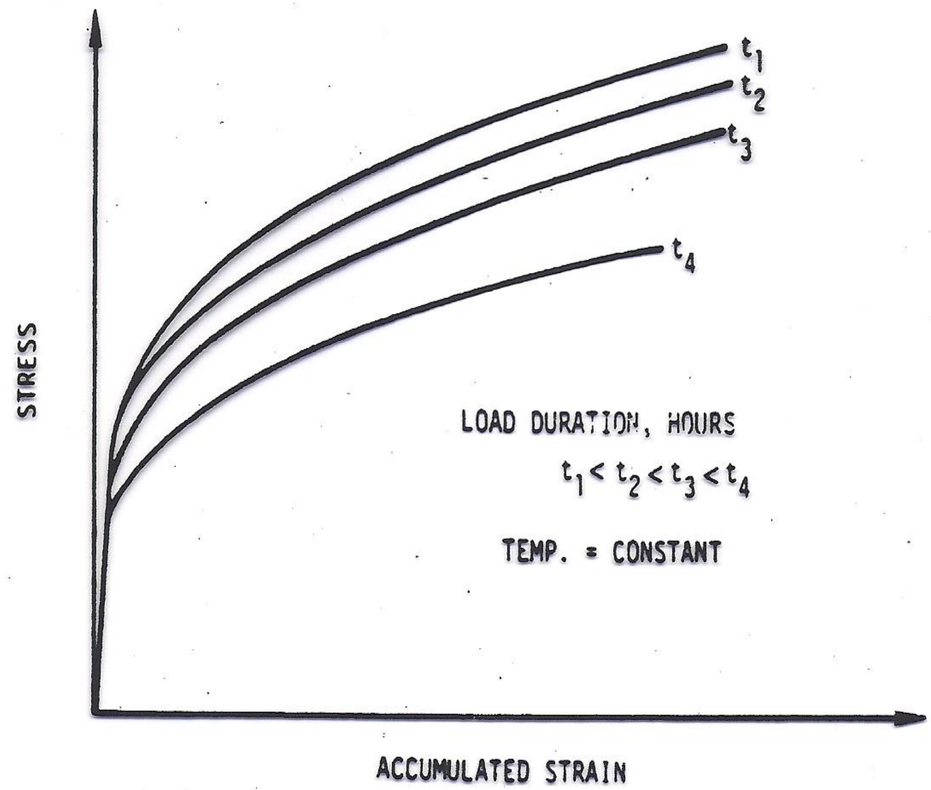


Fig. 5 ISOCHRONOUS STRESS-STRAIN CURVES FROM CREEP TESTS AT CONSTANT TEMPERATURE

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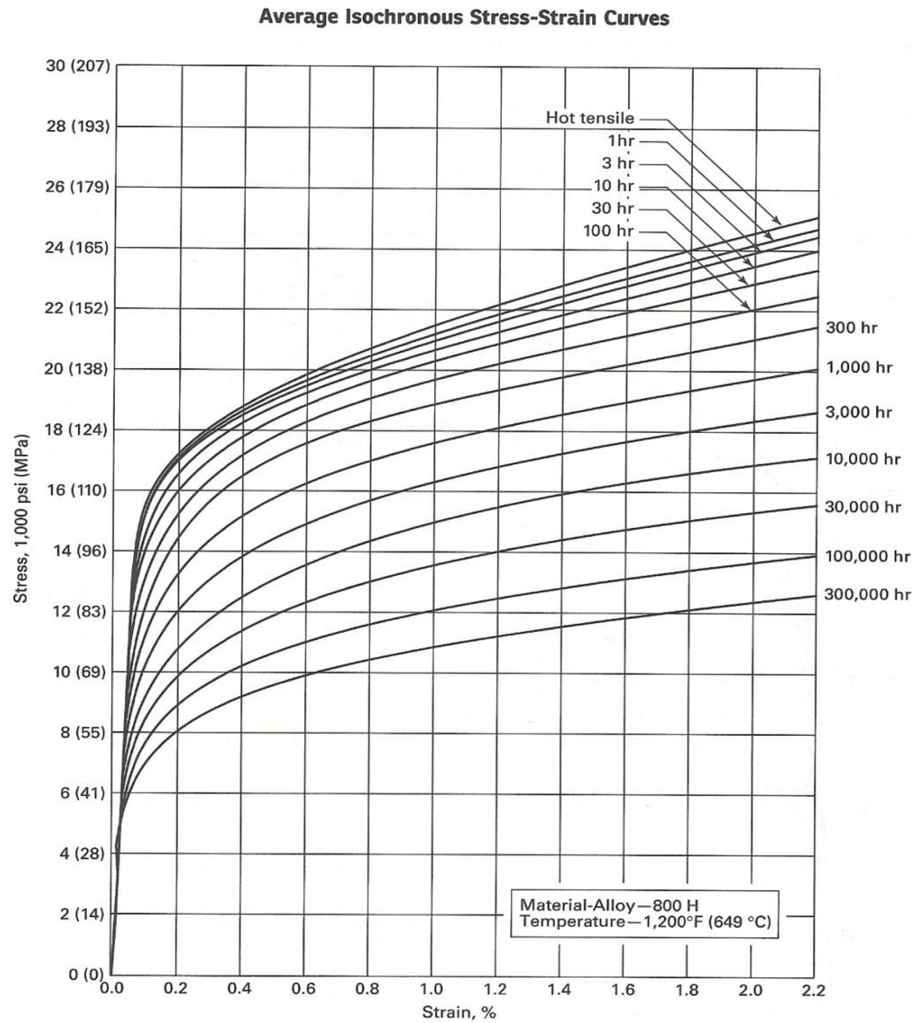
ISOCHRONOUS CURVE FROM SUBSECTION NH

Isochronous curves are used to calculate accumulated strain and stress relaxation.

Note that they represent average behavior.



CREEP-FATIGUE EFFECT OF HOLD TIME ON CYCLIC LIFE

Test data demonstrating that a hold time at constrain in a strain controlled fatigue life can consume most of the design margin of twenty on cyclic life

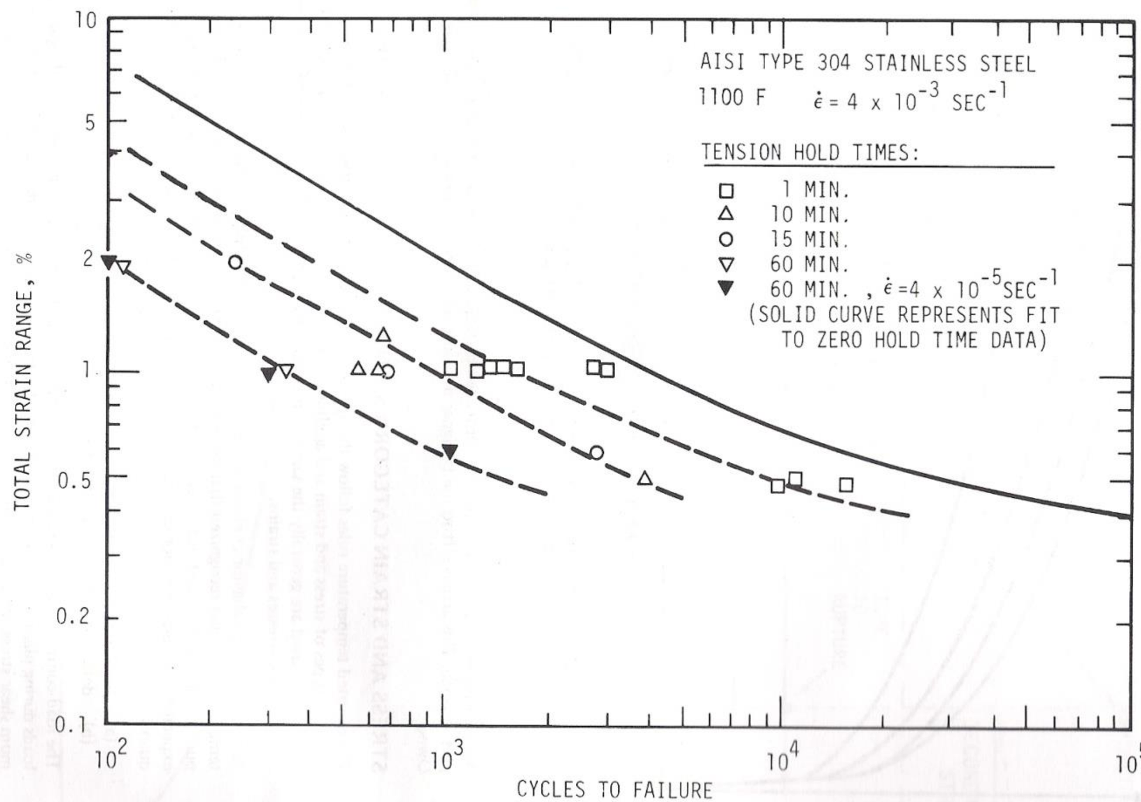
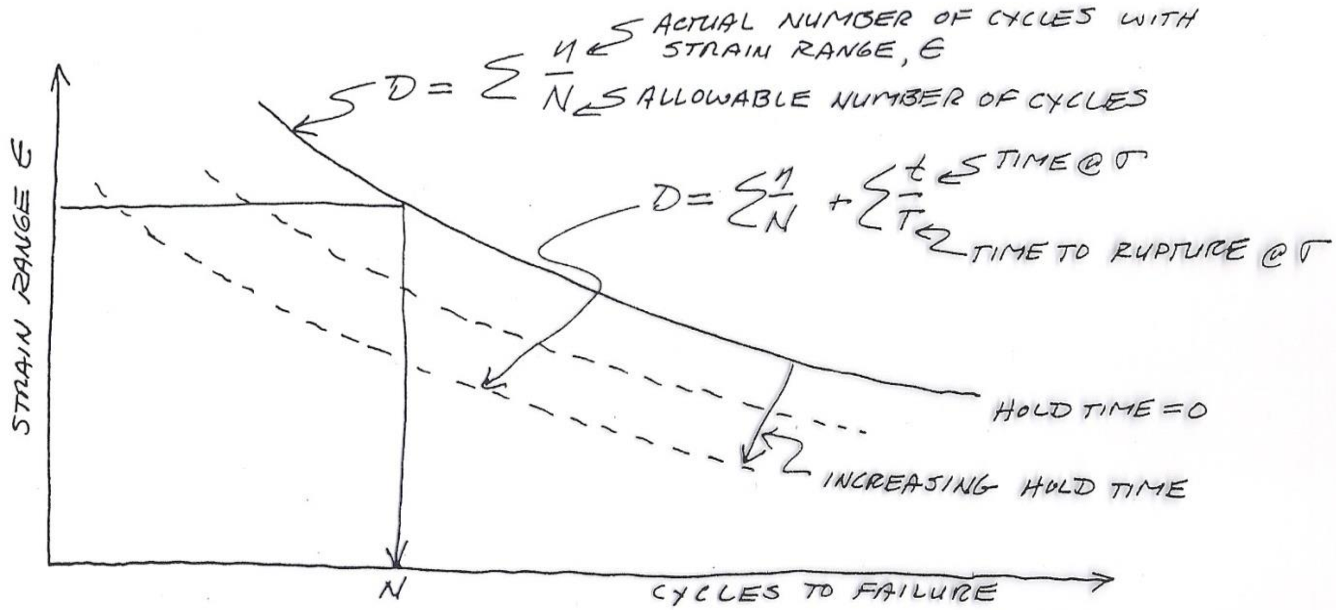
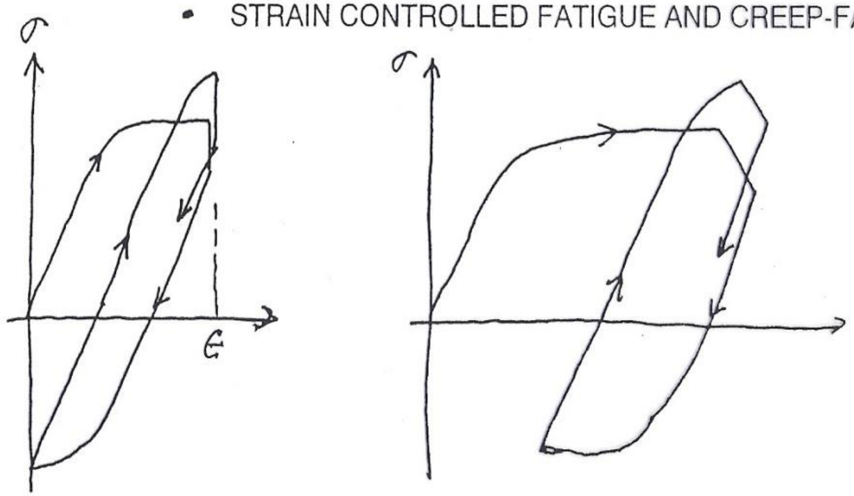


Fig. 6 EFFECT OF TENSION HOLD TIME ON THE FATIGUE LIFE OF AISI TYPE 304 STAINLESS STEEL AT 1000 F IN AIR

FATIGUE AND CREEP FATIGUE DAMAGE



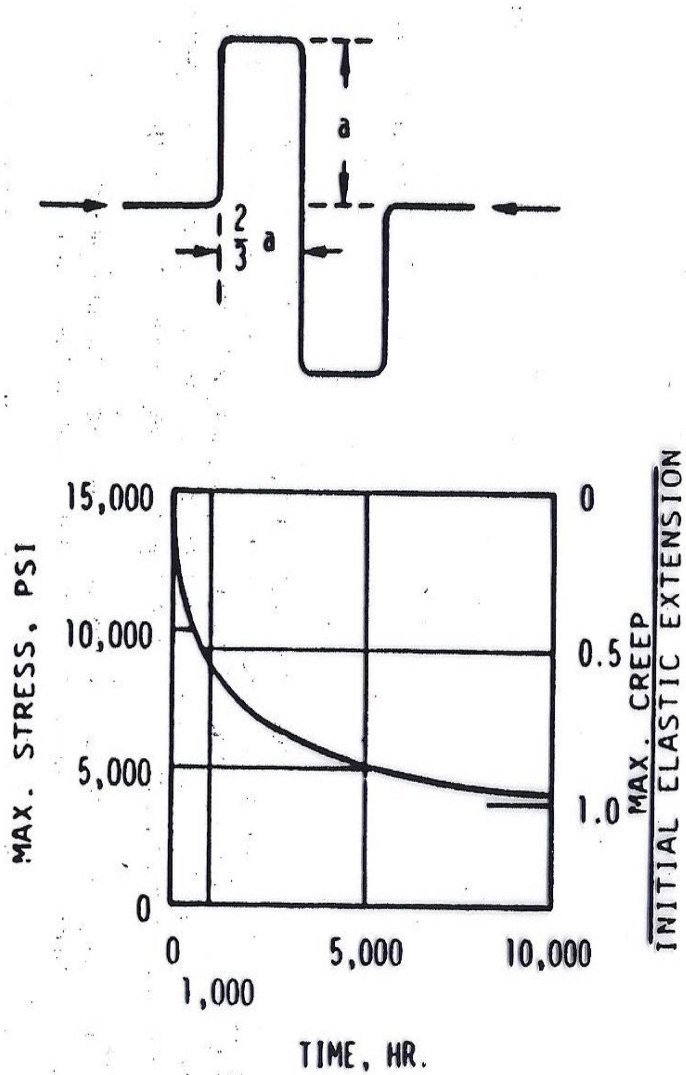
- STRAIN CONTROLLED FATIGUE AND CREEP-FATIGUE TEST WITH HOLD TIME

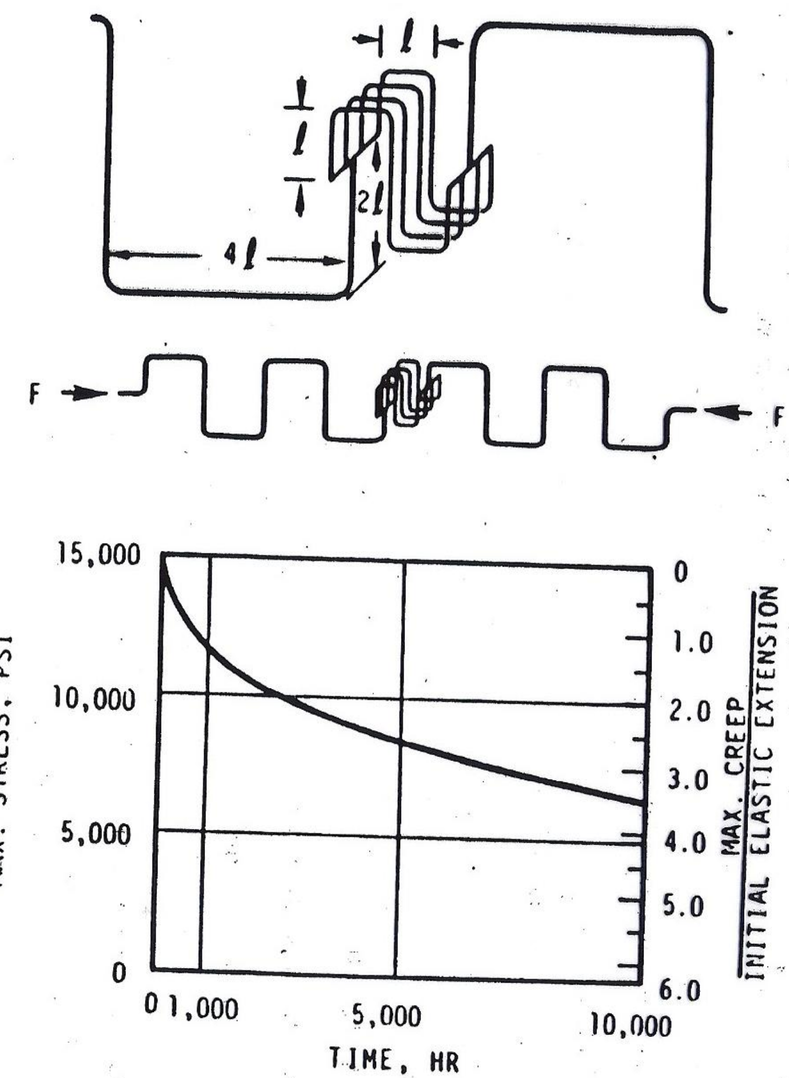


- STRAIN CONTROLLED VS. ELASTIC FOLLOW-UP

- FOR REAL STRUCTURES WITH ELASTIC FOLLOW-UP, STRESS AND STRAIN ARE DIFFICULT TO DETERMINE
  - INELASTIC ANALYSIS
    - REQUIRES COMPLEX MATERIAL MODEL
  - ELASTIC ANALYSIS
    - REQUIRES ADDITIONAL APPROXIMATIONS TO ACCOUNT FOR PLASTICITY AND CREEP

PIPING EXAMPLE OF ELASTIC FOLLOW-UP





ELASTIC FOLLOW-UP TWO BAR MODEL

Example is discontinuity stress due to temperature difference

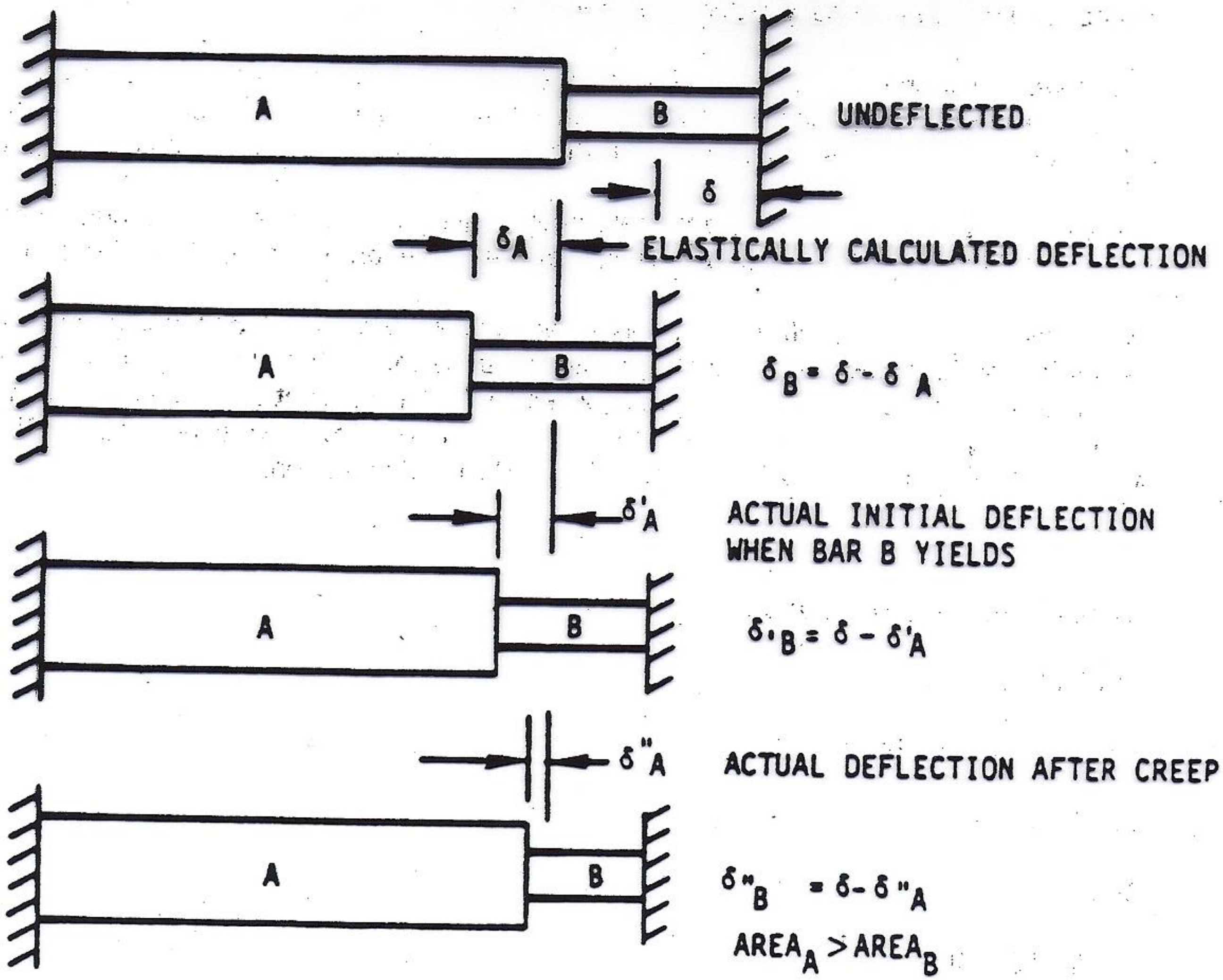
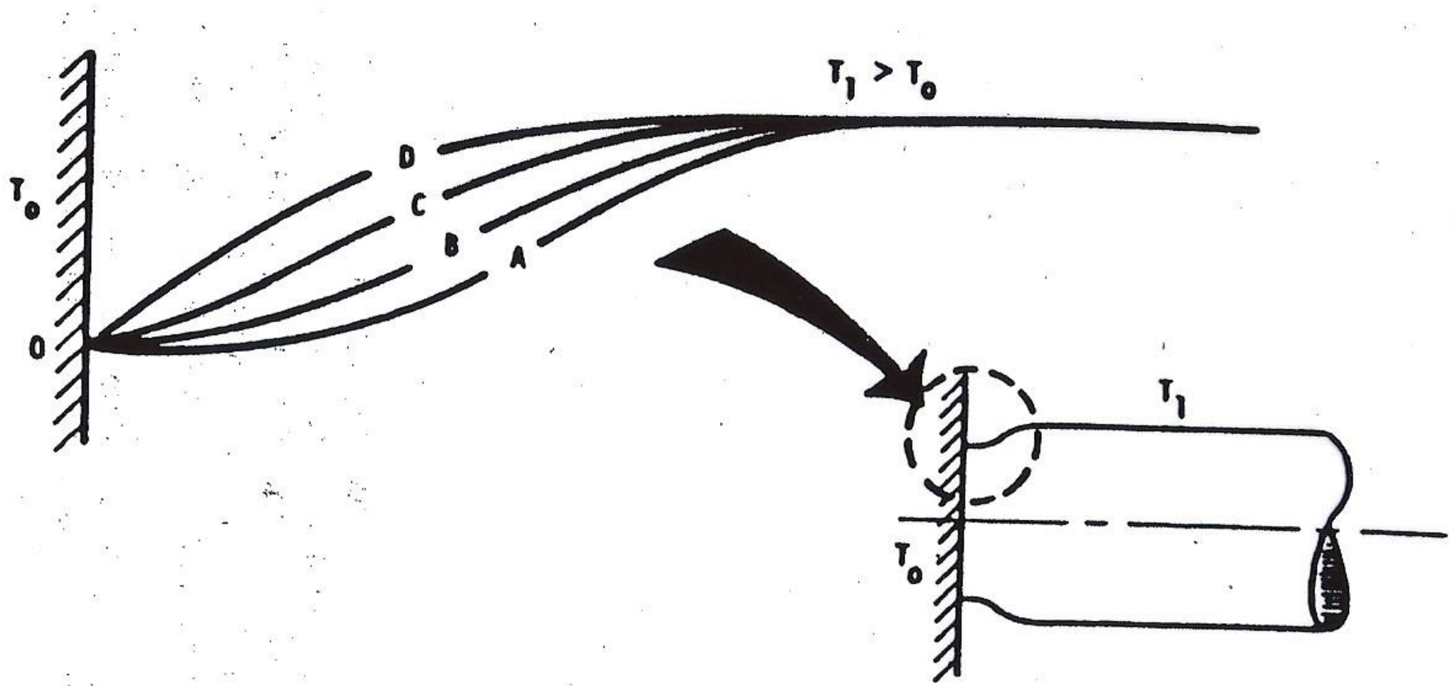


Fig. 40 TWO-BAR MODEL WITH ELASTIC FOLLOW-UP AND STRAIN CONCENTRATION

BUILT IN CYLINDER WITH ELASTIC FOLLOW-UP



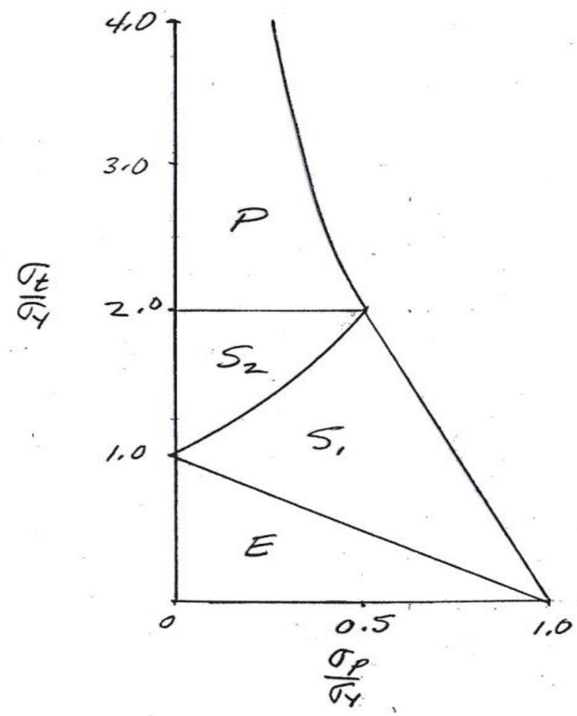
Thermal expansion of cylinder is restrained by fixed wall. As creep progresses the deflection of the cylinder becomes more concentrated next to the wall.

RATCHETING BREE DIAGRAM

BREE DIAGRAM

- Based on pressurized cylinder with cyclic through the wall thermal gradient
- Creep during operation relaxes the residual stress pattern
- "After some cycling, a so-called steady stress cycle is developed" O'Donnell & Porowski
  - Fredrick and Armstrong theorem provides rigorous basis

- No progressive circumferential deformation in S_1, S_2, & P
- No "creep ratcheting" in E
- Shakedown in S_1 & S_2
- Plastic cycling in P



RATCHETING O'DONNELL & POROWSKI

O'Donnell and Porowski recognized that the accumulated strain due to ratcheting of a pressurized cylinder with a cyclic radial thermal gradient could be bounded by the creep strain of the elastic core.

The maximum elastic core stress can be quantified as a function of σ_p and σ_t in regions E, S_1, S_2 and P.

The ratchet strain per cycle was also quantified for regions R_1 and R_2

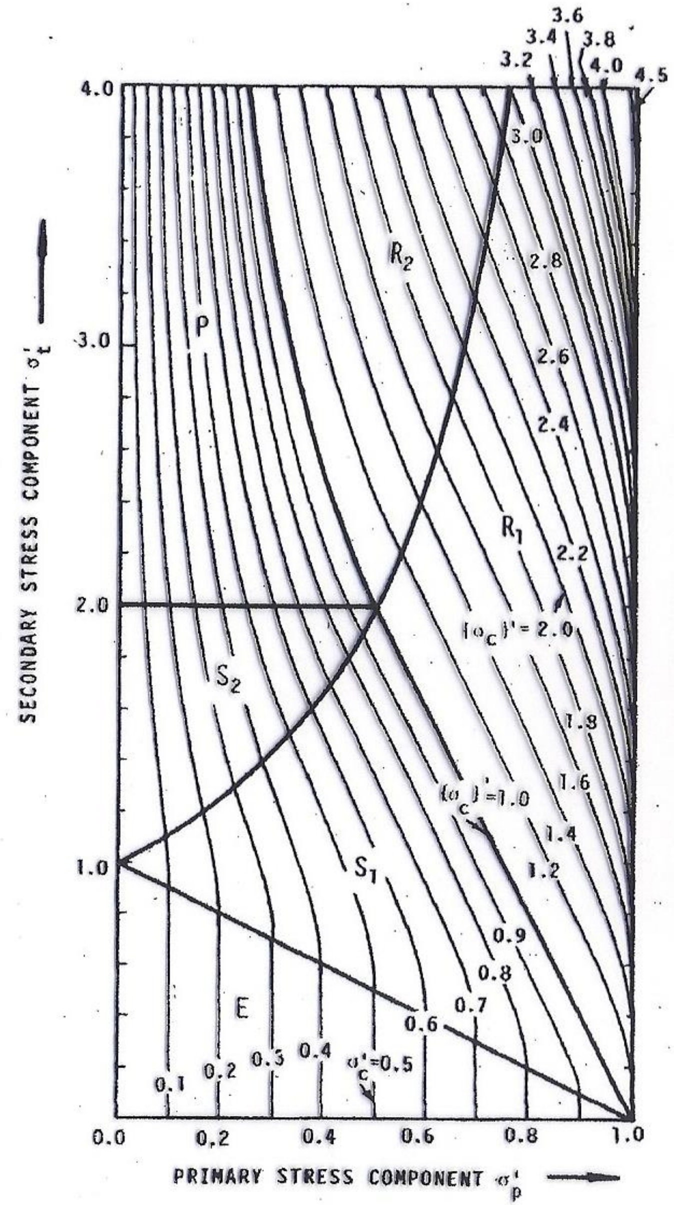


FIGURE 9 GENERALIZED CORE STRESS GRAPH

$\{\sigma_c\}' = 1 + \sigma_t' - 2\sqrt{\sigma_t'(1 - \sigma_p')}$ in Regime R_1

$\{\sigma_c\}' = \sigma_p + \sigma_t$ in Regime R_2

RATCHETING - SARTORY

- Bilinear, thru wall thermal gradients
- Concluded non-conservatism of O'Donnell Porowski was explained by difference in response between linear and non-linear temperature profiles
- Concluded charts were applicable without geometric limitations
  - Checked numerous 2D axisymetric models and a 3D model

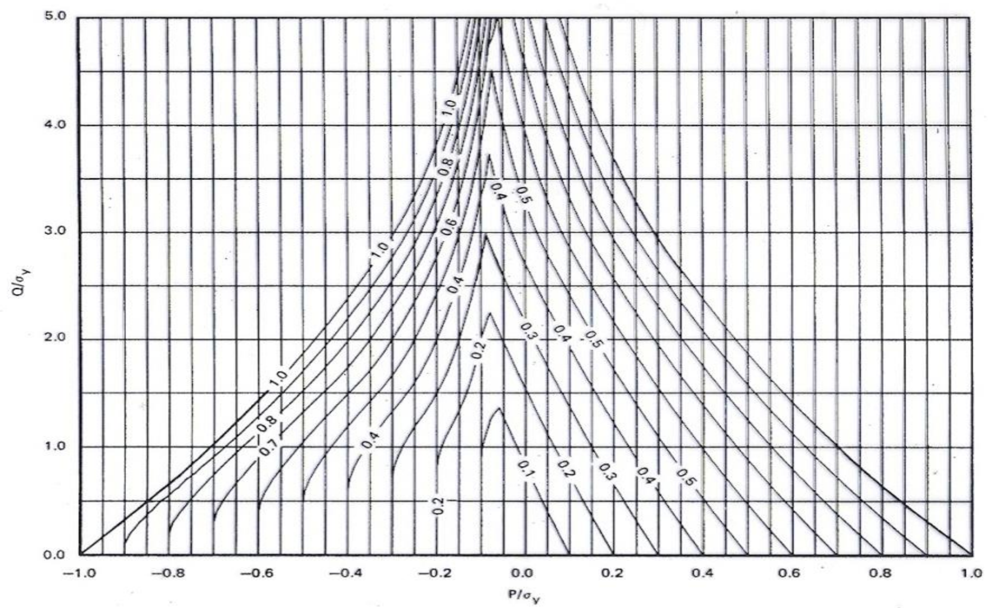


Fig. 4. Design chart of elastic core stress contours obtained from equation $|\sigma_{c_{conservative}}(P,Q)| = f(Q)\,|\sigma_{c_{closed\ form}}(P,Q)|$ and correlated in terms of dimensionless secondary or Q stress and primary stress.

PRESSURE INDUCED DISCONTINUITY STRESSES

- Becht "Behavior of Pressure-Induced Discontinuity Stresses at Elevated Temperature" Journal of Pressure Vessel Technology, August 1889

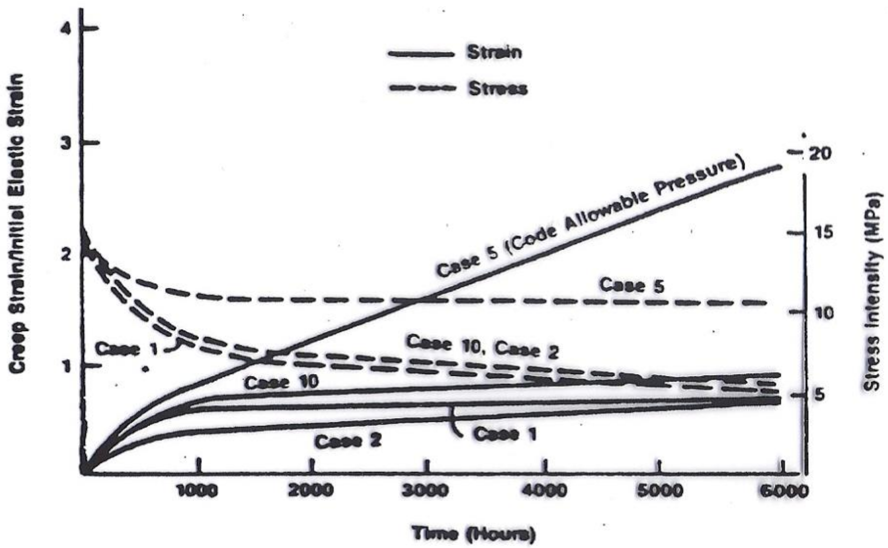


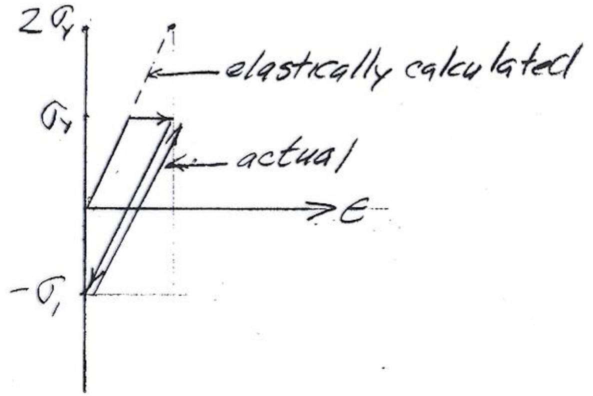
FIG. 12.36 STRESS RELAXATION AND STRAIN ACCUMULATION FOR PRESSURE DISCONTINUITY (CASE 5), THERMAL DISCONTINUITY (CASE 10), AND SECONDARY STRESS (CASES 1, 2)

- Corum & Battiste "Predictability of Long Term Creep and Rupture in Nozzle-to-Sphere Vessel Model" Journal of Pressure Vessel Technology, May 1993
  - 304SS at 1105F (595C)
  - Failure in 21,707hr due to pinhole leaks attributed to inter-granular cracking
  - Pressure-induced discontinuity stresses in the junction region did not relax appreciably

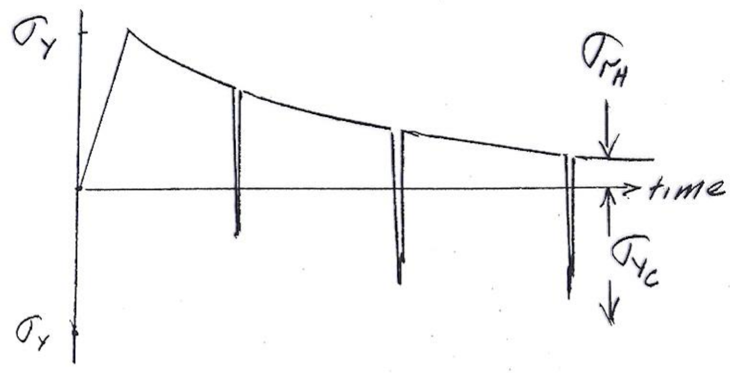
SHAKEDOWN

If the stress range $\Delta\sigma \leq (\sigma_{rH} + \sigma_{yC})$ then shakedown occurs and there is no plastic straining. If both ends of the cycle are in the creep regime then $\Delta\sigma \leq (\sigma_{rH} + \sigma_{rC})$

- Below creep range



- Creep range



ALLOWABLE STRESS CRITERIA FOR TIME DEPENDENT, S_t

- Temperature and time dependent stress intensity limit based on data from long term, constant load, uniaxial tests
- For each specific time, S_t is the lesser of:
  - 100% of the average stress required to obtain a total (elastic, plastic and creep) strain of 1%
    - Analogous to Section VIII, Div 1 limit on minimum creep rate except time dependent and includes more factors

ALLOWABLE STRESS CRITERIA
FOR TIME DEPENDENT, S_t

- 80% of the minimum stress to cause initiation of tertiary creep
  - Based on 0.2% offset from secondary creep
  - Avoids instability and intergranular cracking
  - Can be quite critical for nickel based alloysNo analogous limit for Sections I or VIII
- 67% of minimum stress to cause rupture
  - Compares to 67% of average and 80% of minimum for Sections I and VIII
  - However, applies to Service Loadings not Design Loadings
  - Initial proposals ranged from 25% of minimum to 80%

ALLOWABLE STRESS CRITERIA
FOR TIME DEPENDENT, S_t

- Allowable stress at welds reduced by weld strength reduction factor, *R*, applied to the base metal creep rupture strength

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STRESS CLASIFICATION

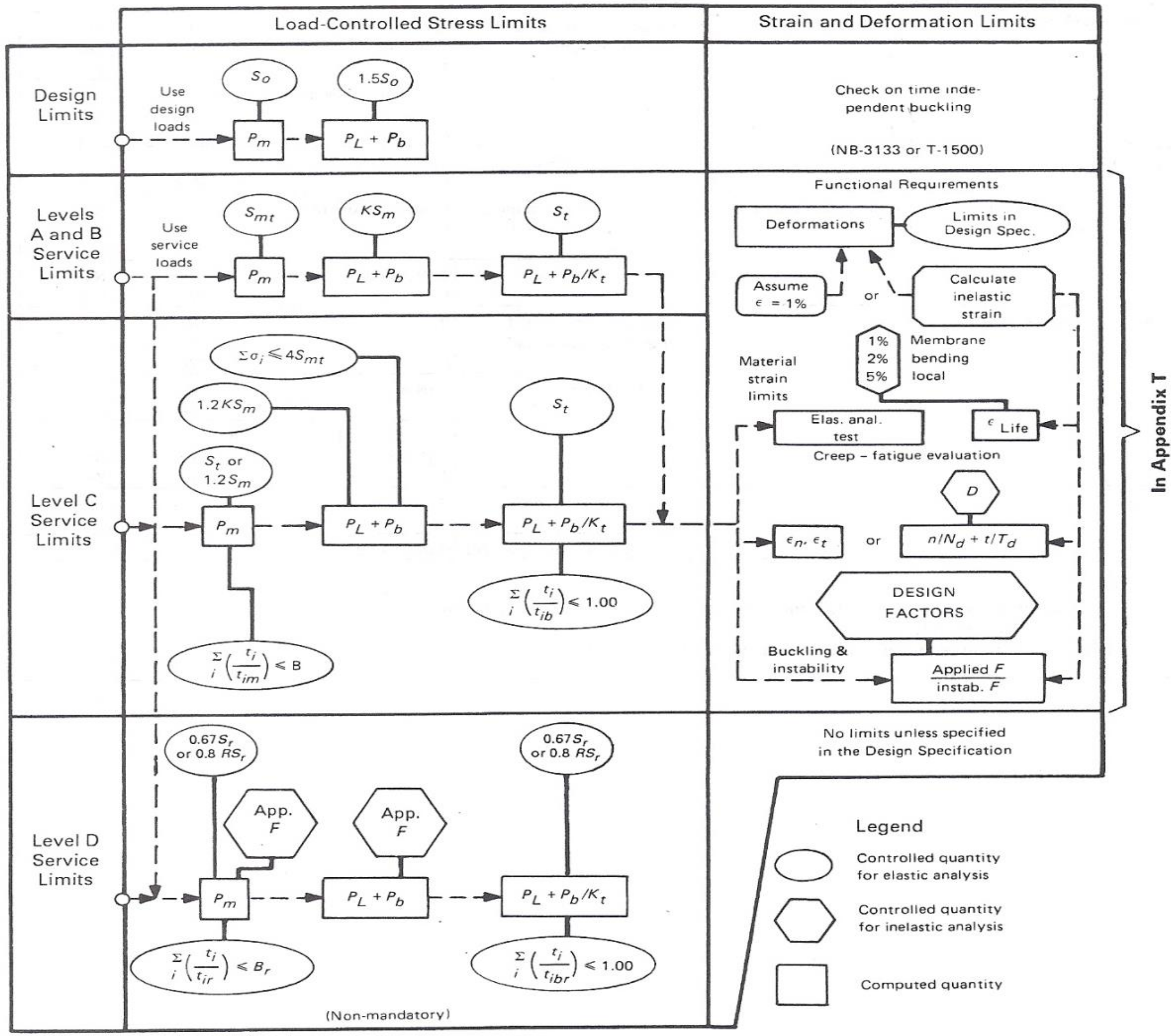
- Primary Stress (Pm & Pb)
  - Developed by imposed loading necessary to satisfy equilibrium of external and internal forces and moments
  - Basic characteristic - not self limiting
    - General primary membrane stress not changed by yielding
    - Membrane stress in a shell due to internal pressure
- Secondary Stress (Q)
  - Developed by constraint of adjacent material or self constraint
  - Basic characteristic - self limiting
    - Local yielding and minor distortions can satisfy constraints
    - Discontinuity stress due to the temperature difference between a cylinder and attached head

STRESS CLASIFICATION

- Local Primary Membrane Stress (PL)
  - Produced by pressure or mechanical load that can result in excessive distortion in transfer of load to other portions of the structure
  - Has some characteristics of secondary stress
    - Can result in excessive distortion
    - Membrane stress in a shell due to nozzle load
- Peak Stress (F)
  - Additive to primary plus secondary stress due to stress concentration or local thermal stress
  - Basic characteristic - localized effect with no noticeable distortion
    - Concern is cyclic failure or brittle fracture
    - Stress at a local structural discontinuity, stress at a small hot spot in a vessel wall

FLOW DIAGRAM FOR HIGH TEMPERATURE ANALYSIS

Analogous to hopper diagrams in Subsection NB etc.


Load-Controlled Stress Limits
Strain and Deformation Limits
Design Limits
Use design loads
S_o
$1.5S_o$
P_m
$P_L + P_b$
Check on time independent buckling
(NB-3133 or T-1500)
Levels A and B Service Limits
Use service loads
S_{mt}
KS_m
S_t
P_m
$P_L + P_b$
$P_L + P_b/K_t$
Functional Requirements
Deformations
Limits in Design Spec.
Assume ϵ = 1%
or
Calculate inelastic strain
1% 2% 5%
Membrane bending local
Material strain limits
Elas. anal. test
ϵ Life
Creep – fatigue evaluation
Level C Service Limits
$\Sigma\sigma_i \leqslant 4S_{mt}$
$1.2KS_m$
S_t or $1.2S_m$
S_t
P_m
$P_L + P_b$
$P_L + P_b/K_t$
$\sum_i \left(\frac{t_i}{t_{ib}}\right) \leqslant 1.00$
$\sum_i \left(\frac{t_i}{t_{im}}\right) \leqslant B$
D
ϵ_n, ϵ_t
or
$n/N_d + t/T_d$
DESIGN FACTORS
Buckling & instability
Applied F / instab. F
In Appendix T
Level D Service Limits
0.67S_r or 0.8 RS_r
App. F
App. F
0.67S_r or 0.8 RS_r
P_m
$P_L + P_b$
$P_L + P_b/K_t$
$\sum_i \left(\frac{t_i}{t_{ir}}\right) \leqslant B_r$
$\sum_i \left(\frac{t_i}{t_{ibr}}\right) \leqslant 1.00$
(Non-mandatory)
No limits unless specified in the Design Specification
Legend
Controlled quantity for elastic analysis
Controlled quantity for inelastic analysis
Computed quantity

PRIMARY (LOAD CONTROLLED) STRESS LIMITS

- Stress redistribution
- Design Limits
- Level A and B Service Limits
- Level C Service Limits
- Level D Service Limits

BENDING STRESS REDISTRIBUTION

Bending stress redistribution in a rectangular cross section approaches ideally plastic distribution as the power law creep exponent, n, approaches infinity. Primary bending stress factor needs to be adjusted for lower, more representative, values of n.

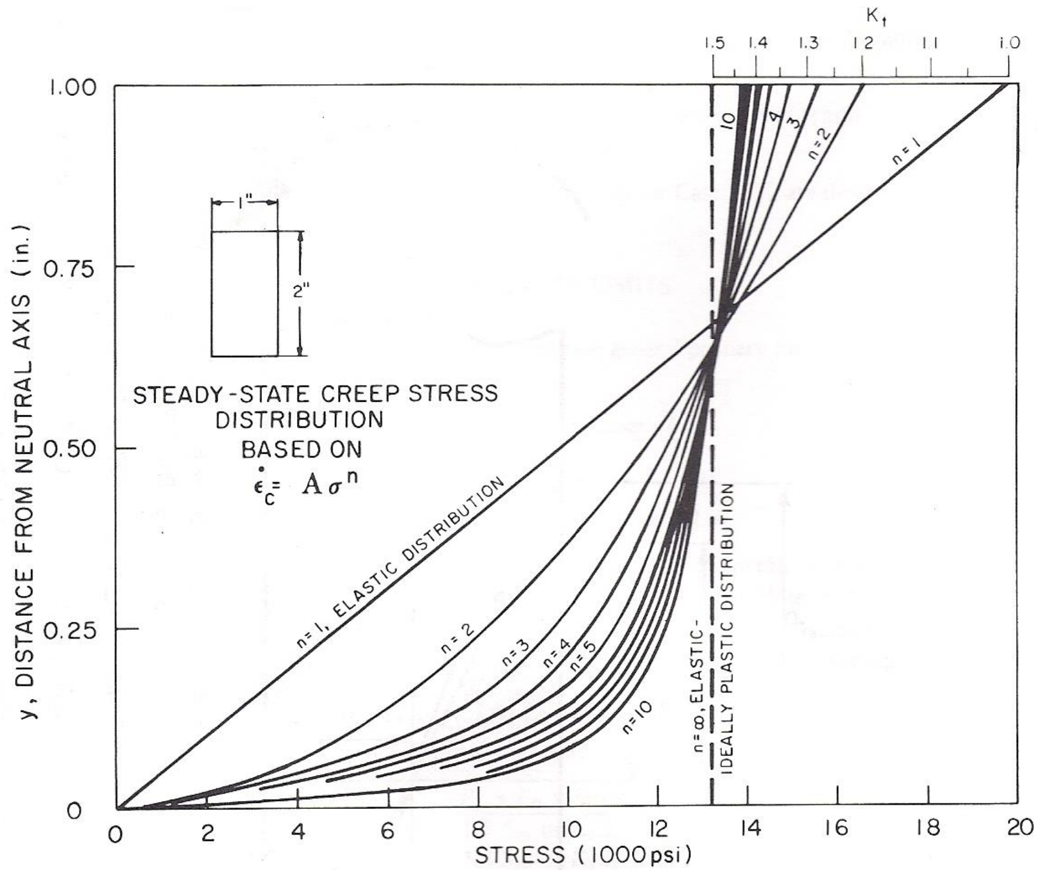


Fig. 10 STEADY-STATE CREEP STRESS DISTRIBUTION ACROSS A RECTANGULAR BEAM IN PURE BENDING AND HAVING A STEADY-STATE CREEP LAW OF THE FORM, $\dot{\epsilon}_c = A\sigma^n$

PRIMARY BENDING STRESS REDISTRIBUTION FACTORS

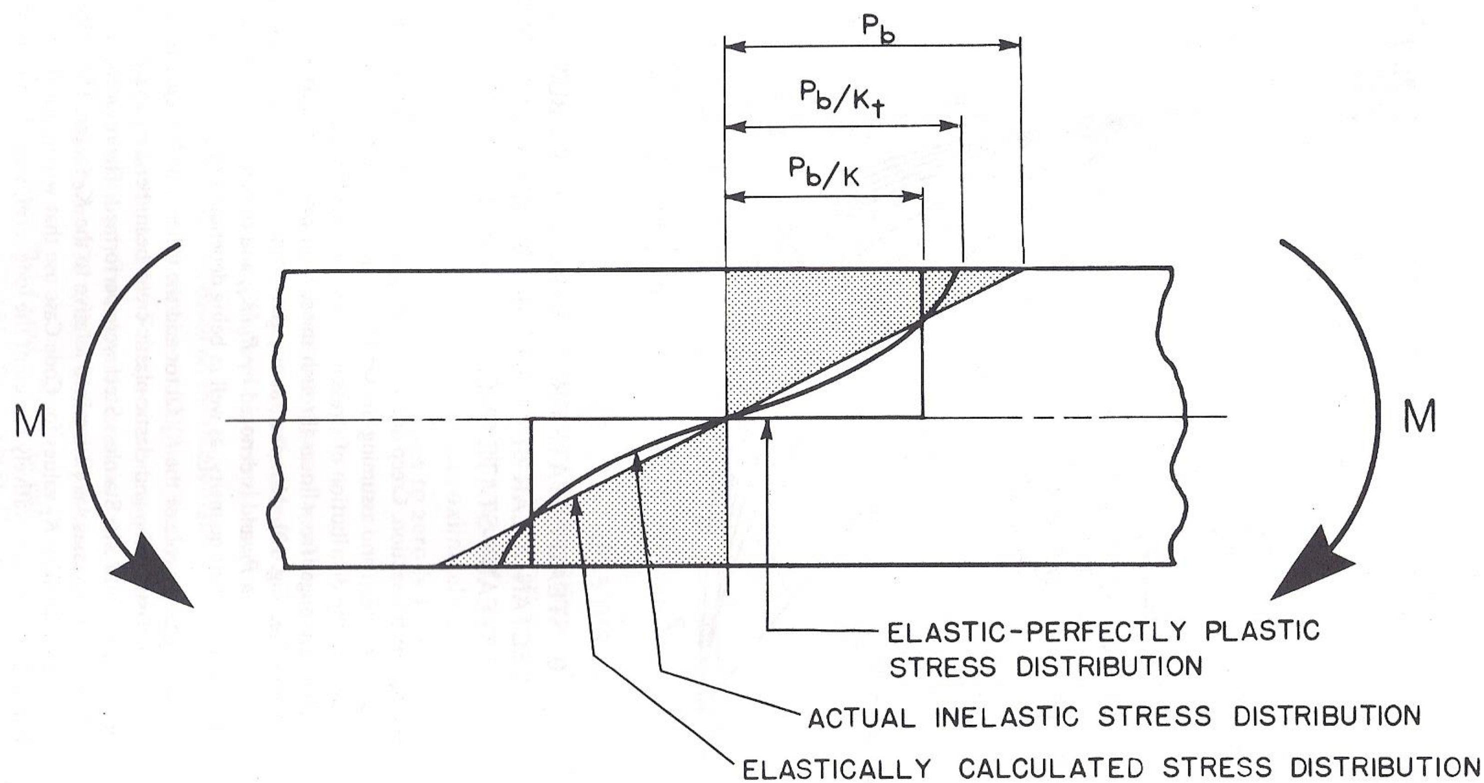


Fig. 9 ELASTICALLY CALCULATED PRIMARY BENDING STRESS DISTRIBUTION COMPARED TO ACTUAL TIME-DEPENDENT INELASTIC STRESS DISTRIBUTION

DESIGN LIMITS

- Conceptually, "design by analysis" stress determination with "design by rule" allowable stresses
  - Based on linear elastic material model

- $P_m \leq S_o$

- $(P_L + P_b) \leq 1.5S_o$

- Where S_o is allowable stress for Section I and VIII, Div 1
  - Lesser of:
    - 2/3 (90%)S_y, (1.1/3.5)S_u
    - 67% avg. S_r, 80% min. S_r, 100% of avg. stress for min. creep rate 0.01%/1000hr
    - <u>and</u> above 1500, F_{avg} S_r
      - where F_{avg} is, conceptually, determined from equivalent time factor of safety on creep rupture
      - S_r is stress to cause rupture (creep rupture) in 100,000hr

LEVEL A & B SERVICE LIMITS

- "Design by analysis" stress determination with time independent, S_m (same criteria as Subsection NB), and time dependent, S_t , allowable stresses
  - Based on linear elastic material model

- $P_m \leq S_{mt}$ where S_{mt} is the lesser of S_m or S_t

- $(P_L + P_b) \leq KS_m$, $(P_L + P_b/K_t) \leq S_t$

  - K_t is factor to account for reduction in extreme fiber stress due to creep
  - $K_t = (K + 1)/2$ and K is section factor given by load to produce fully plastic section to load to initiate yielding at the extreme fiber.
  - For a rectangular section $K = 1.5$ and $K_t = 1.25$

- If the load duration, t, for a given load set is less than the total service life at elevated temperature then cumulative effect of all loads is evaluated using the use-fraction sum in the Level C Service limits.

- The allowable stress is based on the "maximum wall averaged" temperature

LEVEL C SERVICE LIMITS

- Similar to Subsection NB for time independent allowable stress; the time dependent allowable stress limits are the same as those for Level A & B Service Limits
- $P_m \leq 1.2\ S_m$, $(P_L + P_b) \leq 1.2KS_m$
- $P_m \leq S_t$, $(P_L + P_b/K_t) \leq S_t$
- The use-fraction is given by $\sum(t_i/t_{im}) \leq 1.0$ and $\sum(t_i/t_{ib}) \leq 1.0$ where t_{im} and t_{ib} are show below:

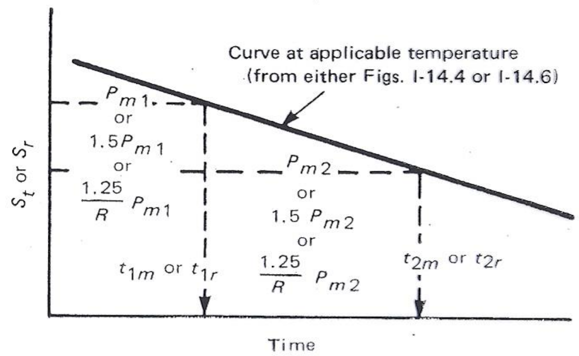


FIG. NH-3224-1 USE-FRACTIONS FOR MEMBRANE STRESS

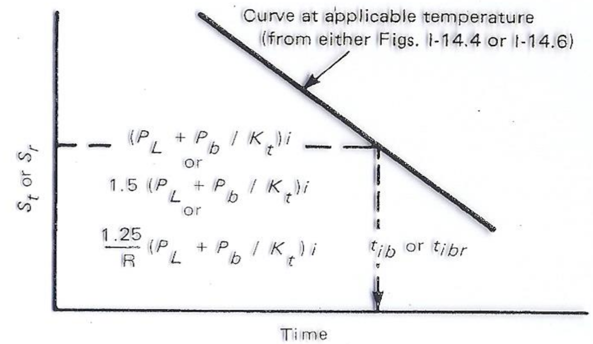


FIG. NH-3224-2 USE-FRACTIONS FOR MEMBRANE PLUS BENDING STRESS

LEVEL D SERVICE LIMITS

- Must be used unless other criteria are in the Design Specification
- Time independent limits follow Appendix F of Section III, time independent limits are based on creep-rupture strength
- $P_m \leq$ Limit in Appendix F, $0.67S_r$, $0.8RS_r$
- $(P_L + P_b)$ Limit in Appendix F, $(P_L + P_b/K_t) \leq 0.67S_r$, $0.8RS_r$
  - R is weld strength reduction factor used in evaluation of creep-fatigue
    - Tables as a function of time and temperature are provided for combinations of base metal, weld metal and welding process
- Plus use-fraction including all Service Loadings
- Allowable stress is based on "maximum local wall averaged temperature"

DEFORMATION CONTROLLED LIMITS

Acceptable Deformation Controlled Limits in Appendix T

- Alternative criteria may be used subject to the Owner's approval and incorporation in the Design Specification
- Covers strain limits/ratching (analogous to P+Q), creep-fatigue damage (analogous to P+Q+F), buckling and welds

Strain Limits and Creep Fatigue Damage rules can be satisfied using either elastic or inelastic analysis methods

- Elastic analysis rules originally seen as simpler, more conservative and less costly screening method to satisfy strain limits and creep-fatigue
  - Actually, considerably more complex than analogous "low" temperature rules in NB

DEFORMATION CONTROLLED LIMITS

- Inelastic rules envisioned as a more costly and time consuming "gold standard"
  - Conceptually simple but requires sophisticated modeling of material behaviour in the creep regime
  - Requirements for material modeling only addressed in general terms/performance criteria
  - Did not want to stifle the development of improved methods

STRAIN LIMIT FOR INELASTIC ANALYSIS

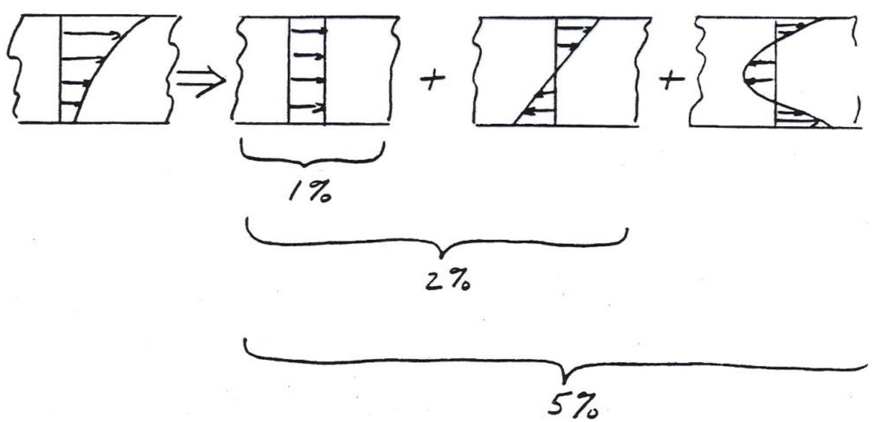
Purpose is to provide control of gross and local deformations beyond that provided by strain criteria in primary stress limit and by creep-fatigue summation

Applies to accumulated strain given by total strain less elastic strain

1% AVERAGED THROUGH THICKNESS (ANALOGOUS TO MEMBRANE STRESS)

2% LINEARIZED THROUGH THICKNESS (ANALOGOUS TO MEMBRANE + BENDING STRESS)

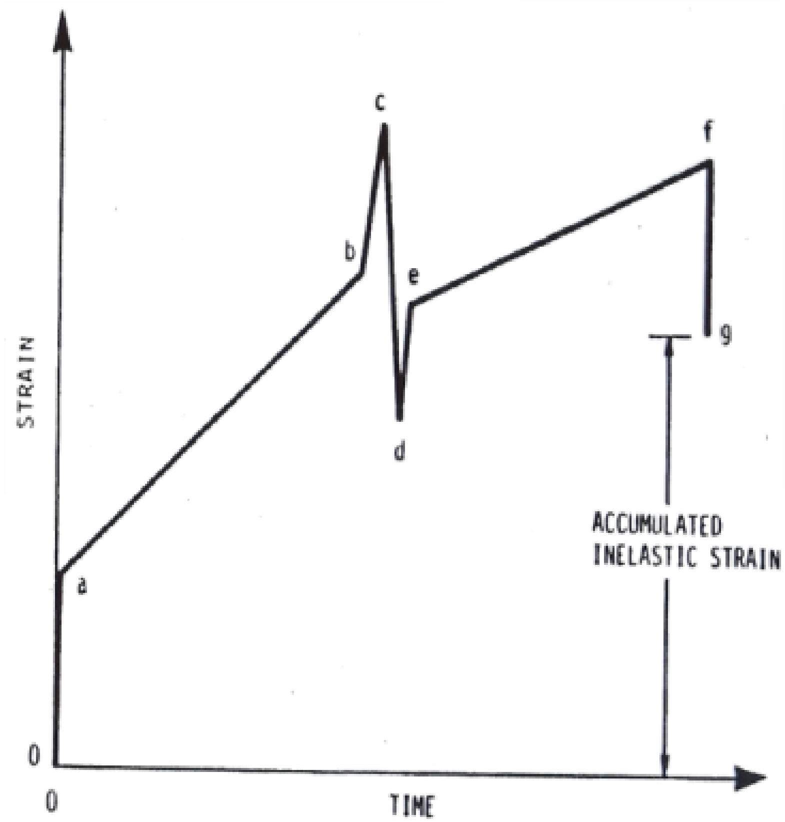
5% MAXIMUM AT ANY LOCATION (ANALOGOUS TO PEAK STRESS)



MAXIMUM POSITIVE PRINCIPAL STRAIN

ACCUMULATED INELASTIC STRAIN AT STEADY STATE

ALLOWABLE FOR WELDS IS ½ OF ABOVE



ELASTIC ANALYSIS STRAIN LIMITS

2004 SECTION III, DIVISION 1 — NH

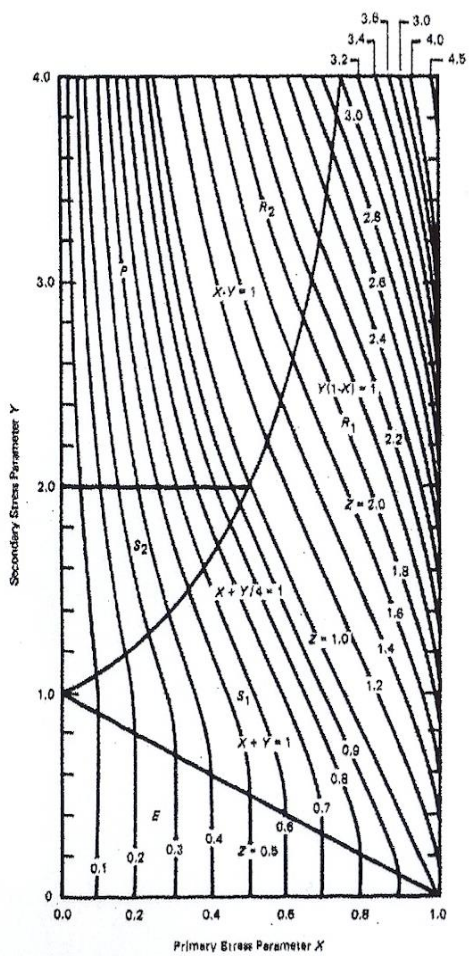


FIG. T-1332-1 EFFECTIVE CREEP STRESS PARAMETER *Z* FOR SIMPLIFIED INELASTIC ANALYSIS USING TEST NOS. B-1 AND B-3
[For Use Only When the Restrictions of T-1331(a) for Test No. B-1 Are Met]

Strain Limits

- Accumulated averaged membrane strain, 1%; membrane plus linearized bending strain, 2%; total strain, 5%
- Based on collective judgment and numerous rationale; no rigorous, failure related basis

Strain Limits Using Elastic Analysis

- Based on elastic section of Bree Diagram
  - Simplest to use but most conservative
- T-1324, Test No. A-3 provides criteria for negligible creep
  - Time fraction summation of creep damage less than 0.1 based on sustained stress 1.5 times min. yield
  - Accumulated strain less than 0.2% based on sustained stress 1.25 times min. yield
- Requires max. primary stress over lifetime considered with max. secondary stress range over whole life

Strain Limits Using Simplified Inelastic Analysis

- Based on extension of Bree analysis by O'Donnell & Porowski and, later, Sartory
- Key is elastic core stress limit and subsequent deformation
- Requires pressure induced membrane and bending and thermal induced membrane stresses to be classified as primary
- Requires max. primary stress over lifetime be considered with max. secondary stress range over whole life
- More complex than analogous NB primary plus secondary stress limits

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ELASTIC ANALYSIS STRAIN LIMITS

- Strain limits are considered satisfied if the limits of T-1320 are met
- Based on extension of applicability of Bree charts - stay in elastic regime, E
  - $X = (P_L + P_b/K_t)_{max} \div S_y$
  - $Y = (Q_R)_{max} \div S_y$
  - where: $(P_L + P_b/K_t)_{max}$ is maximum primary stress during cycle being evaluated
    $(Q_R)_{max}$ is maximum range of secondary stress during cycle evaluated
    S_y is average of values at max and min wall averaged temp. during cycle
  - At least one cycle must include maximum values of $(P_L + P_b/K_t)$ and (Q_R) which occur during all Level A, B and C Service Loadings
- Test A-1

  $X + Y \leq S_a/S_y$ where S_a is lesser of S_t at 10^4 hr or S_y
- Test A-2

  $X + Y \leq 1$ if the cold end of the temperature range is below the temperature where $S_m = S_t$ at 10^5 hr

NEGLIGIBLE CREEP

- The Subsection NB rules may be used to evaluate ($P_L + P_b + Q$) subject to the following conditions:

  $\sum(ti/tid) \leq 0.1$ at $1.5S_y$

  $\sum\epsilon_i \leq 0.2\%$ at $1.25\ S_y$

- And the following criteria modifications

  $3S_m$ lesser of $3S_m$ and ($1.5\ S_m + S_{rH}$) if only one end of the cycle is above NB
  or ($1.5\ S_{rH} + S_{rL}$) if both temperature extremes are above NB

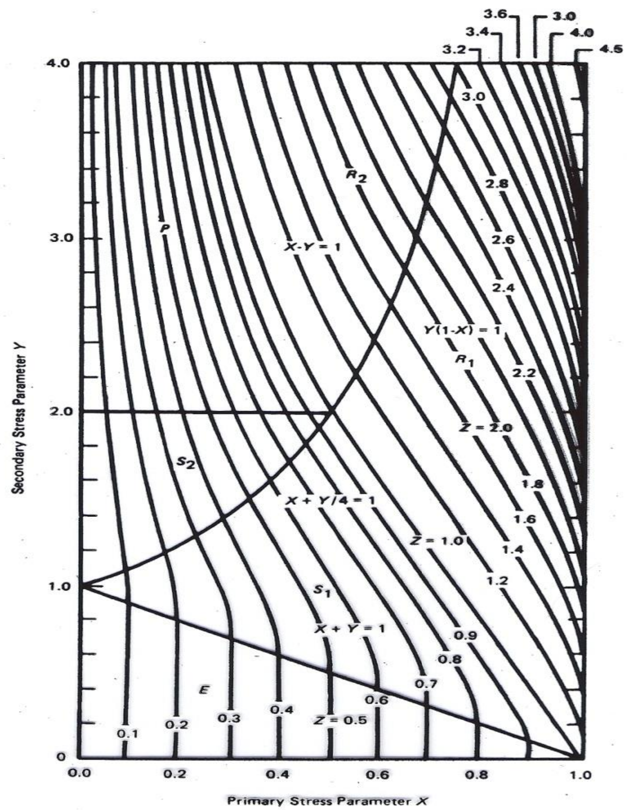
  S_{rH} and S_{rL} are the hot and cold relaxation strengths at the respective hot and cold ends of the cycle. It is the stress level an initial stress of $1.5\ S_m$ relaxes to at the end of the total Service Level A, B and C time above the temperature limits of NB. (Note that this is a creep modified shakedown criteria.)

SIMPLIFIED INELASTIC ANALYSIS - STRAIN LIMIT

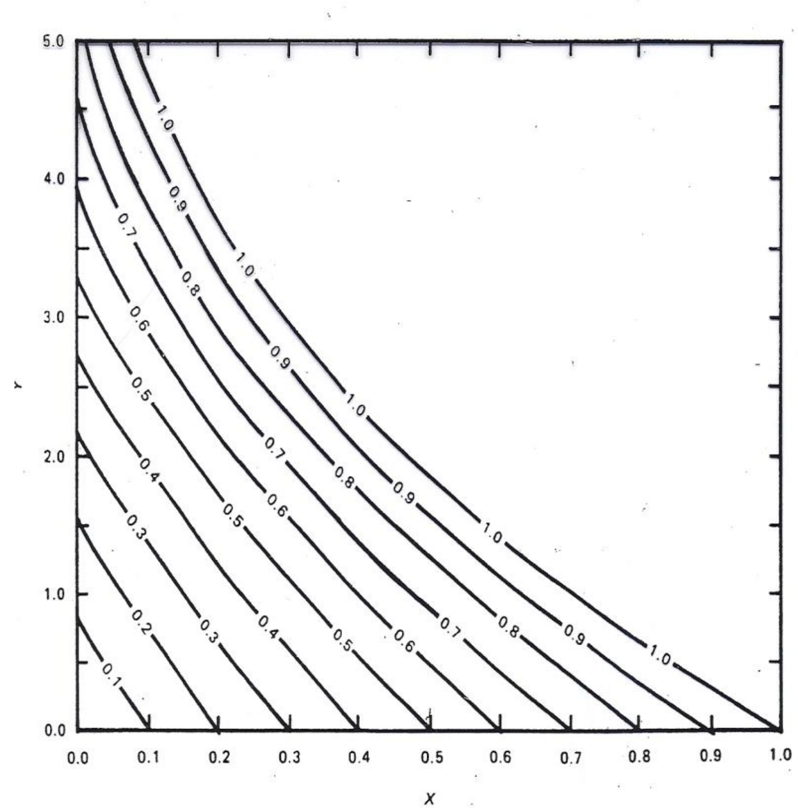
- Based on O'Donnel-Porowski (Test B-1 and B-3) and Satory (B-2) elastic core stress, σ_c, concepts where $\sigma_c = Z(S_{yL})$ and Z is determined from the applicable chart or equation
- Permits operation in regimes E, S_1, S_2 and P and limited operation in R_1 and R_2
- Methodology determines membrane strain required to meet 1% strain limit
  - B-1 and B-2 provide elastic core upper bound strain (no cycle limit)
  - B-3 provides strain per cycle - may also be used in regions covered by B-1
- Test B-1 and B-3 should not be used where there are significant peak stresses
- Test B-2 is more conservative but applicable to any geometry and loading
- Test B-1 and B-2 require one end of the cycle to be below temperature where $S_m = S_t$ at 10^5 hr
- For all Tests, pressure induced membrane and bending stresses and thermally induced membrane stresses are considered primary
- For all Tests, X and Y are same as in T-1320 except S_y is evaluated at the cold end

SIMPLIFIED INELASTIC ANALYSIS CHARTS

Effective creep stress parameter, Z, for simplified inelastic analysis using Tests No. B-1 and B-3



Effective creep stress parameter, Z, for simplified inelastic analysis using Test B-2



CHARACTERISTICS OF SIMPLIFIED METHODS FOR STRAIN LIMITS

Test No.	Geometry/Loading Restrictions?	Cycle Temperature Restrictions?	Strain Calculation?	Cycle Definition
A-3	None	Entirely below creep range (1)	None	Same as Subsection NB
A-1	None	None	None	Whole life
A-2	None	Cold end below creep range (2)	None	Whole life
B-2	None	Cold end below creep range (2)	Core stress	Block
B-1	Either discontinuity or nonlinear temp.	Cold end below creep range (2)	Core stress	Block
B-3	Either discontinuity or nonlinear temp.	None	Incremental summation	Individual

Notes: (1) Per strain and stress criteria of T-1324

(2) Per T-1323, temp. at $S_m = S_t$ at 10^5hr

CREEP FATIGUE

- General Requirements
  - $\sum(n/N_d)_j + \sum(\Delta t/T_d)_k \leq D$

    where: D = Total creep-fatigue damage ≤ allowable damage from Creep-Fatigue Damage Envelope
    n = number of cycles of type j
    N_d = number of cycles of type j from design fatigue curve
    Δt = duration of time interval k
    T_d = allowable time from stress-to-rupture curves at stress level during time interval k obtained by dividing the calculated stress by a factor, K' which is 0.67 for current materials using inelastic analysis and .9 using elastic analysis
  - For elastic analysis the appropriate stress quantities are defined in the procedure. For inelastic analysis the following equivalent stress quantity should be used:

$$\sigma_c = (\sigma_{eff})\exp[C(J_1/S_s - 1)]$$

where: $J_1 = \sigma_1 + \sigma_2 + \sigma_3$
$S_s = (\sigma_1^2 + \sigma_2^2 + \sigma_3^2)^{1/2}$
$\sigma_{eff} = [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}/2^{1/2}$

and the values for the material constant, C, are provided in T-1411

CREEP-FATIGUE DAMAGE ENVELOPE

- The sum of the creep damage and the fatigue damage must be less than or equal to the allowable damage shown in FIG. T-1420-2

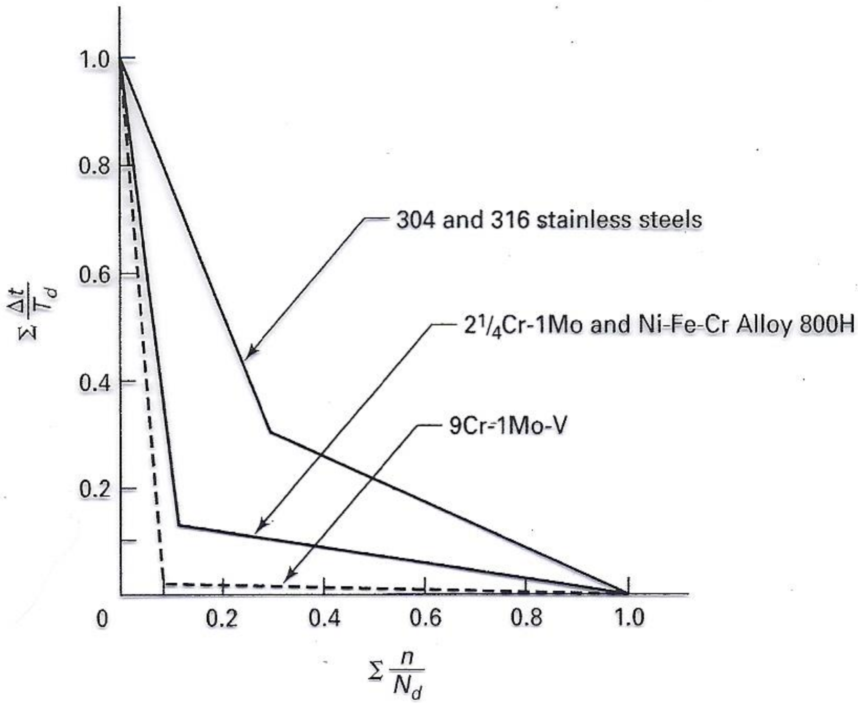


FIG. T-1420-2 CREEP-FATIGUE DAMAGE ENVELOPE

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CREEP-FATIGUE USING ELASTIC ANALYSIS

- General Requirements
  - Must meet ($P_L + P_b + Q$) with 3Sm replaced by $3\hat{S}_m$, the creep shakedown limit
  - Pressure induced discontinuity stresses and thermal induced membrane stresses included as primary
- Strain Range Determination
  - Calculate $\Delta\epsilon_{max}$ without local stress concentration effects
  - Three procedures for modified max equivalent strain range, $\Delta\epsilon_{MOD}$
    - More accurate/less conservative - requires iterative solution:
      $$\Delta\epsilon_{MOD} = (K^2 S^* \Delta\epsilon_{max})/(\Delta\sigma_{MOD})$$
    - Reference:
      $$\Delta\epsilon_{MOD} = (S^*/\hat{S})K^2 \Delta\epsilon_{max}$$
    - Simplest, most conservative:
      $$\Delta\epsilon MOD = K_e K \Delta\epsilon_{max}$$
      where: $K_e = 1$ if $K\Delta\epsilon_{max} \le 3\hat{S}_m/E$
      $K_e = K\Delta\epsilon_{max}/(3\hat{S}_m/E)$ if $K\Delta\epsilon_{max} > 3\hat{S}_m/E$

EQUIVALENT STRAIN RANGE

- Calculate all strain components for each point in time for complete cycle
  - For inelastic analysis local strain concentrations and peak thermal strain are included
  - For elastic analysis don't included local strain concentrations as these are effects are added in the procedure
- Select a point at one of the extremes of the cycle and compute the strain component differences with respect to the components at this point
- Calculate $\Delta\epsilon_{equiv.\, i}$ from the formula provided in T-1413, Step 4, using the differential strain components at each point in time during the cycle
- $\Delta\epsilon_{max}$ is the maximum value of the above calculated equivalent strain ranges
- The above procedure applies to both inelastic and elastic analysis and to rotating principal strains. If the principal strains do not change direction a simpler procedure is provided

STRAIN RANGE FOR ELASTIC CREEP-FATIGUE EVALUATION

1. Determine $\Delta\epsilon_{mod} = (S^*/\hat{S})K^2\Delta\epsilon_{max}$

   a. $\Delta\epsilon_{max}$ from outlined methodology but not including geometric stress concentration factors

   b. Construct modified isochronous stress-strain curve by adding elastic stress-strain curve for stress range S_{rh}

   c. Determine S^* and $\hat{S}$ on the curve from $\Delta\epsilon_{max}$ and $K\Delta\epsilon_{max}$ respectively and calculate $\Delta\epsilon_{mod}$

2. Calculate creep strain increment per cycle, $\Delta\epsilon_c$

   a. Given by core stress $\sigma_c = Z \cdot S_y$ and determine the incremental $\Delta\epsilon_c$ for the hold time between transients from the isochronous stress-strain curve at a stress level of $1.25\sigma_c$

3. Compute the total strain range from:

   $\epsilon_t = k_v\,\Delta\epsilon_{mod} + K\,\Delta\epsilon_c$

   where k_v is mutiaxial plasticity factor and poisons ratio adjustment factor

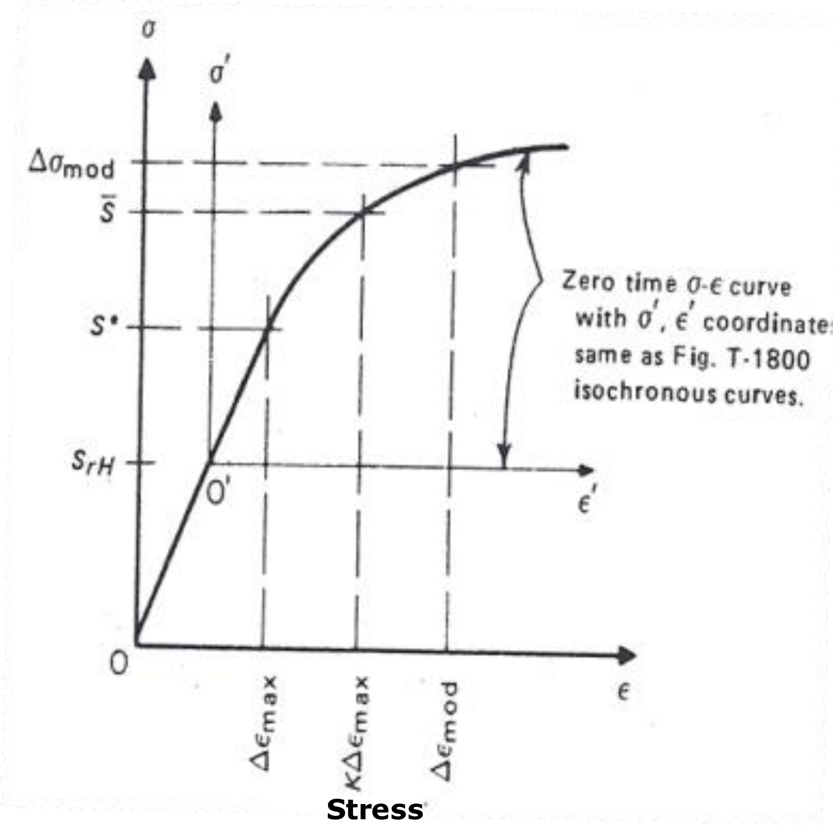

Fig. T-1432-1 Stress-Strain Relationship

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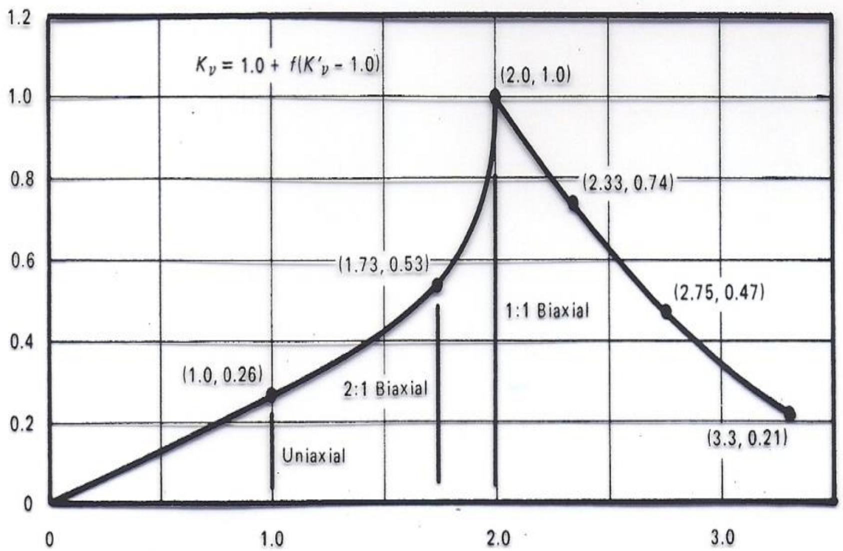
MULTIAXIALITY AND POISSON'S RATIO ADJUSTMENT FACTORS



$$T.F. = \frac{|\sigma_1 + \sigma_2 + \sigma_3|}{\frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2}}$$

σ's are principal stresses at extreme of stress cycle.

FIG. T-1432-2 INELASTIC MULTIAXIAL ADJUSTMENTS

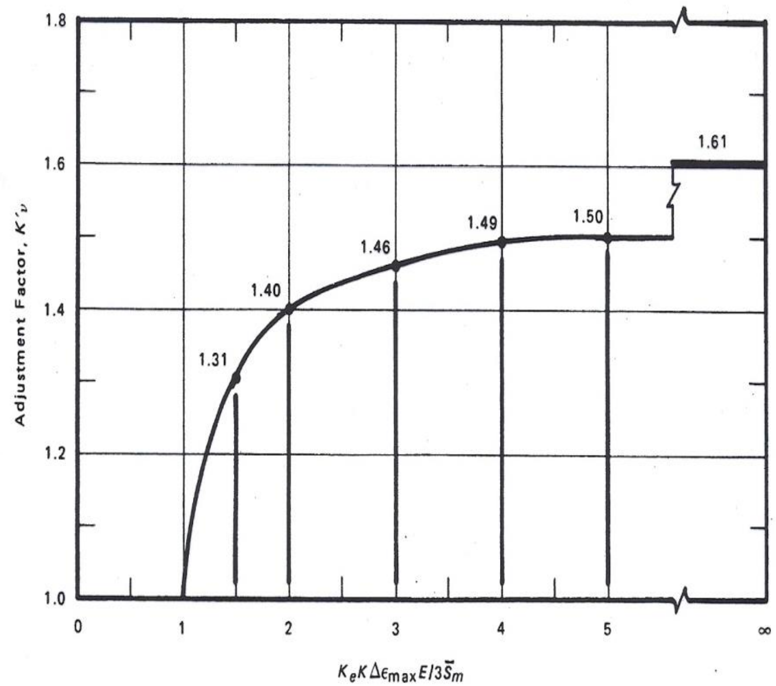


FIG. T-1432-3 ADJUSTMENT FOR INELASTIC BIAXIAL POISSON'S RATIO

CREEP DAMAGE EVALUATION FOR ELASTIC CREEP-FATIGUE

- Two procedures
  (a) General procedure
  (b) Alternate procedure if $\epsilon_t \leq 3\hat{S}_m/E$

- General procedure (10 steps)
  - Define average cycle time, $\bar{t}_j$, for cycle type, j
    1. Define total number of hours, t_H
    2. Define local metal hold temperature, T_{HT}, sustained normal operation
    3. $\bar{t}_j = t_H/n_j$

- Step 4 Select time independent isochronous stress-strain curve corresponding to T_{HT}

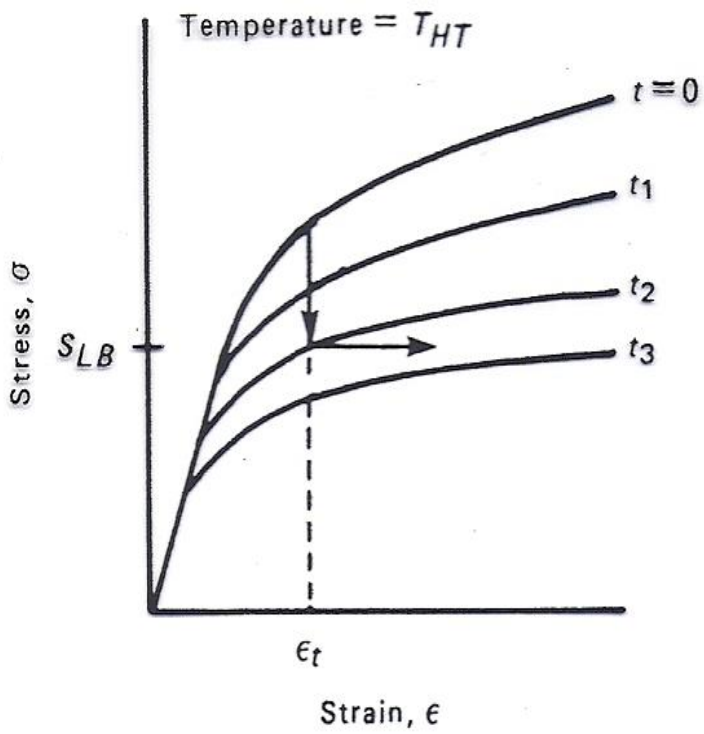
- Step 5 Account for stress relaxation during $\bar{t}_j$
  - Adjust uniaxial relaxation with multiaxial correction factor
  - $S_r = S_j - 0.8G(S_j - \hat{S}_r)$ see FIG T-1433-(b)
  - $G = [\sigma_1 - 0.5(\sigma_2 + \sigma_3)]/ [\sigma_1 - 0.3 (\sigma_2 + \sigma_3)]$

- Step 6
  - Define transient load controlled stresses, S_{TRAN}, and transient time, t_{TRAN}, FIG T-1433a
  - Modify stress-strain history if indicated

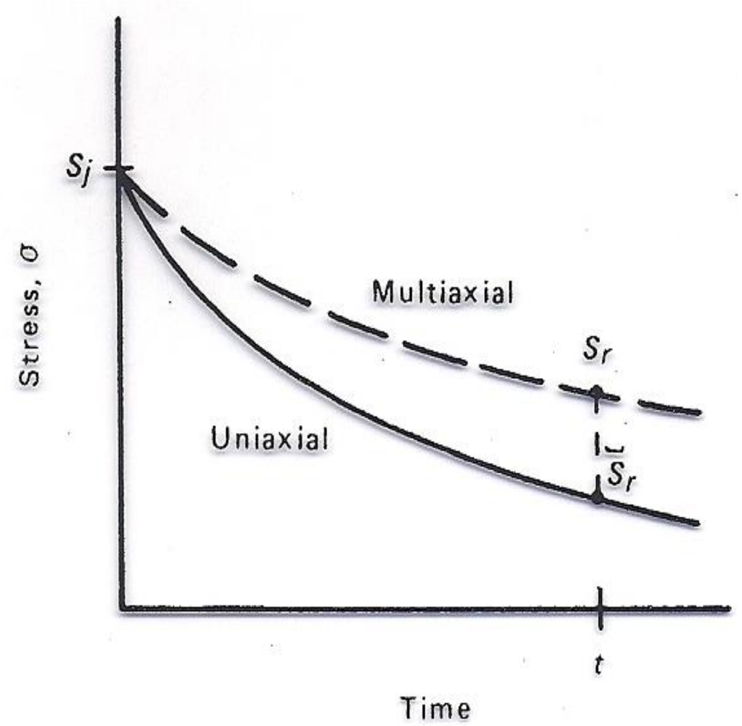
CREEP DAMAGE EVALUATION FOR ELASTIC CREEP-FATIGUE

- Step 7
  - Define cycle transient temperature, T_{TRAN}
    - considered in creep damage but not in stress relaxation
- Step 8
  - Repeat steps 3 - 7 for all cycles and superimpose, FIG T-1433-4
- Step 9
  - Divide composite stress/time history into q time intervals of constant stress $(S)_k$ and temperature $(T)_k$
- Step 10
  - For each time interval $(\Delta t)_k$ obtain allowable time duration from stress-to-rupture curve per Eq. (10)

METHODS OF STRESS RELAXATION CALCULATION



(a)
Stress Relaxation from Isochronous Stress-Strain Curves



(b)
Multiaxial Relaxation, S_r, Calculated from Uniaxial Relaxation, $\bar{S}_r$

STRESS RELAXATION LIMITS FOR CREEP DAMAGE

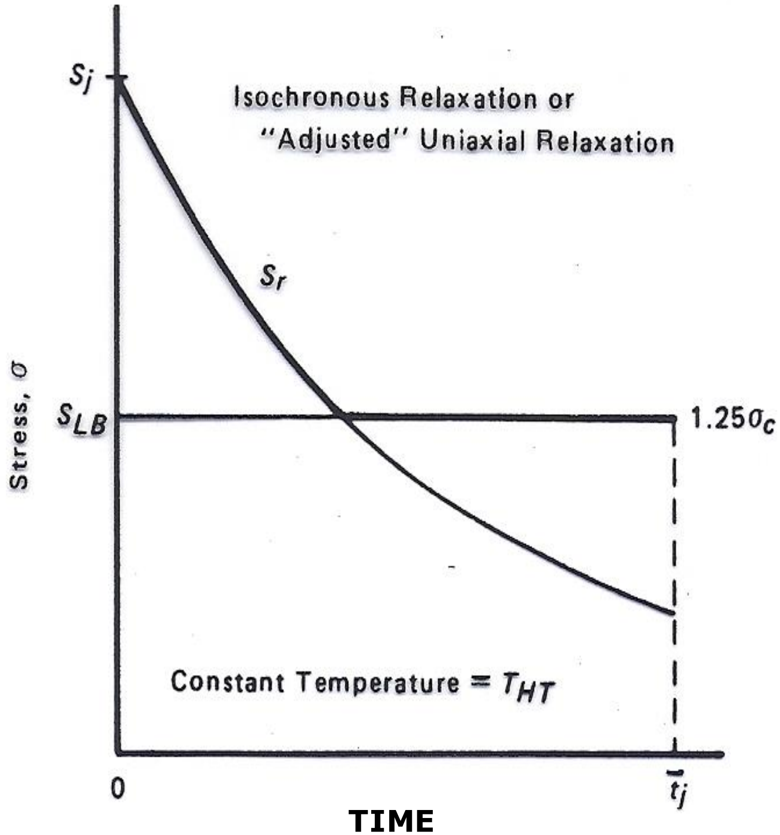
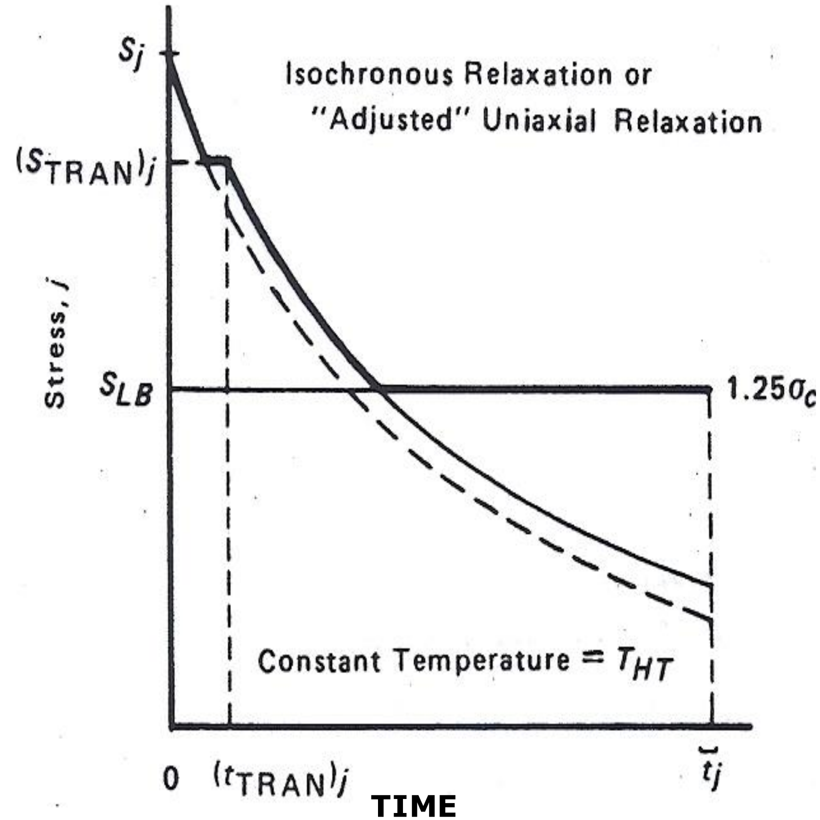
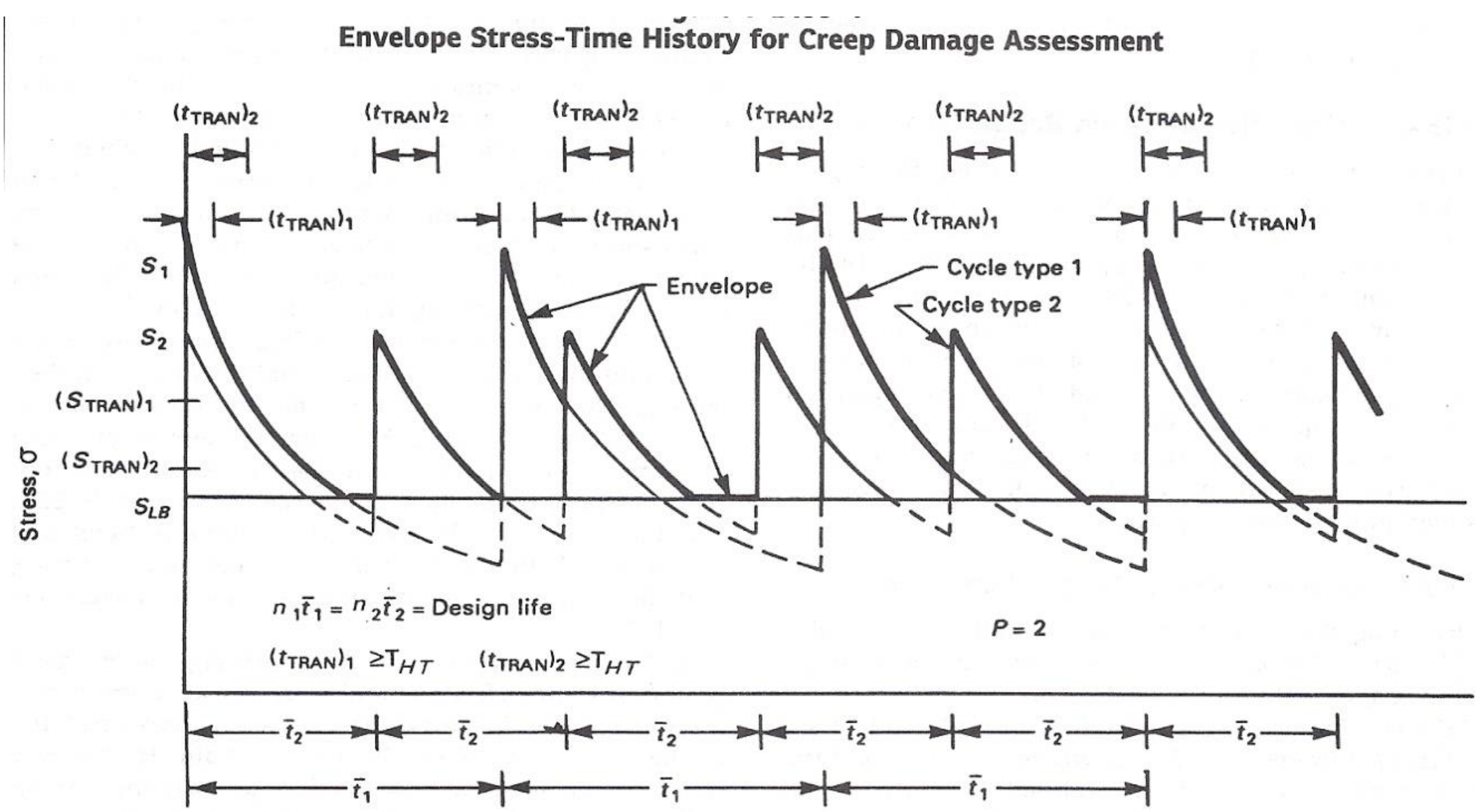


Fig. T-1433-2 Stress-Relaxation Limits for Creep Damage



Load Controlled Transient Effects

CREEP DAMAGE EVALUATION FOR ELASTIC CREEP-FATIGUE



BUCKLING AND INSTABILITY

- The buckling rules in Subsection NB and Sections I and VIII do not address the effects of creep and address limited geometries

- General Requirements

  - The T-1500 are applicable to general geometries, address time-independent and time-dependent behavior and consider both load controlled and strain controlled buckling and instability

  - If strain controlled and load controlled interact or if there is significant elastic follow-up, the load controlled buckling factors apply

  - For load controlled buckling, the initial imperfections and tolerances shall be considered but need not be considered for pure strain controlled buckling

  - Calculations are based on expected minimum stress-strain curves
    - Yield values for re-solution annealed SS are reduced 17% unless demonstrated by test that material meets specified minimum yield

  - The limits apply to both Design and Service Loadings

BUCKLING LIMITS

- Load factors supplied for time independent and time dependent load and strain controlled buckling
  - Time-Independent Load and Strain Factors are 3.0 and 1.67 respectively for Design and Service Level A & B Loadings, less for Level C & D
  - Time-Dependent Load Factors for Design and Service Levels A, B & C are 1.5 and D is 1.25
  - Alternatively, the limits of NB may be applied if time/temperature limits are satisfied

WELD EVALUATION

- Evaluation based on assumption that characteristics (yield, hardening, creep) are the same as base material

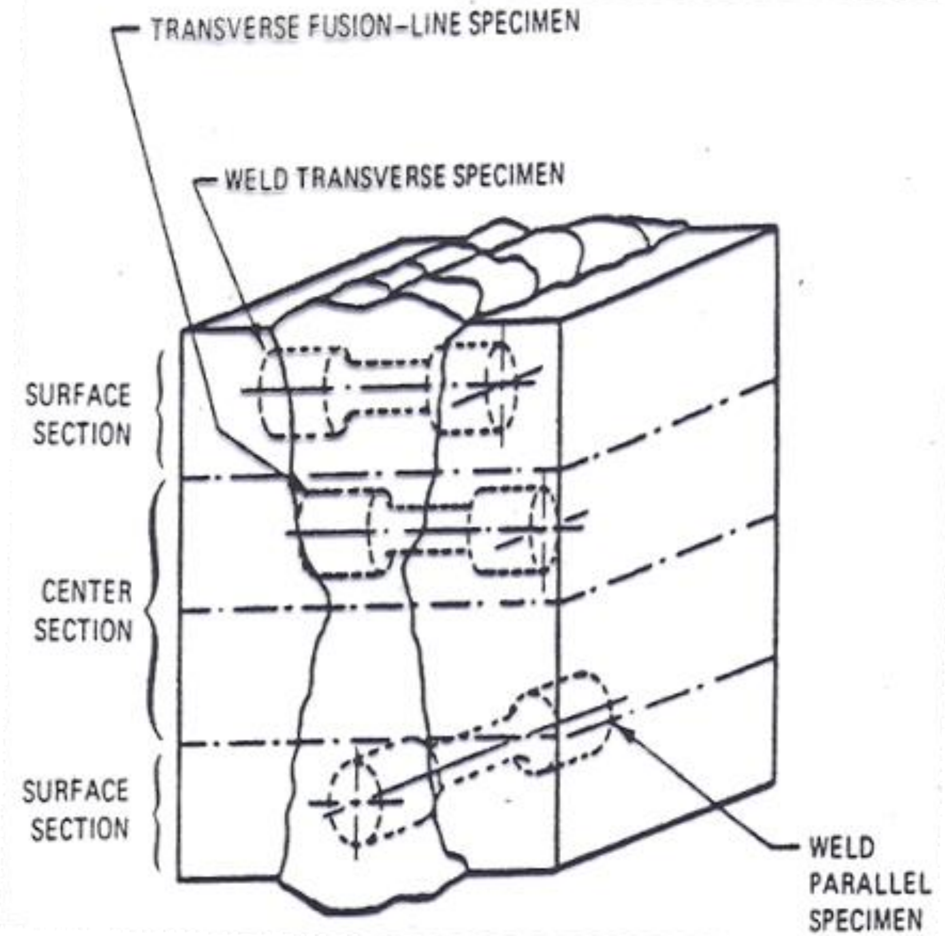
- Limits are adjusted to account for strength degradation due to weld
    - Weld strength reduction factors applied to base metal creep-rupture strength
    - Strain limits half that of base metal
    - Creep-fatigue limits
        - Allowable number of cycles reduced by factor of two
        - Minimum base metal creep-rupture strength reduced by weld strength reduction factor

- Weld geometry
    - Worst case geometry used in analysis
        - Confirmed by inspection

WELD STRENGTH REDUCTION FACTORS

- Time- and temperature-dependent tables of the ratio of weld metal creep rupture strength to base metal strength
  - Usually small, consistent with some 40 tests in which the weld metal creep rupture strength was never below the Code expected minimum base metal creep-rupture strength
  - The tables, which are for specific filler metals and processes, effectively limit construction to those materials and processes
  - The allowable primary stress, Smt, for welds is 80% of the minimum factored weld metal creep rupture strength vs. 67% for base metal
    - Weld metal only governs at higher temperatures and times
- The fatigue strength reduction factor of two is based on observed reductions in fatigue strength of 1.5 to 1.8
- Multi-zone analytical studies helped confirm understanding of creep-rupture failure mechanisms in weldments

WELD STRENGTH REDUCTION FACTORS



Location/orientation of three types of uniaxial Fatigue and creep-fatigue specimen taken from weldments

BOLTS

- **Only three materials: 304 & 316 SS and Alloy 718**
- **Bolting allowable stress is about ½ that of base metal**
  - Allowable stress for 718 at 550C about 5 times that of 304 & 316 SS Alloy 718 limited to 550C
- **Design condition limits**
  - Rules same as NB but with high temperature allowable stress
    - Gasket seating
- **Level A & B Service limits**
  - Average stress due to pressure limited to S_{mt}
  - Average stress due to combined loading limited to $2S_{mt}$
    - Use fraction limited to 0.5 for multiple loading conditions
  - Maximum linearized stress at periphery limited to $3S_{mt}$
    - Use fraction limited to 0.67 for multiple loading conditions

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INELASTIC ANALYSIS METHODS

- General guidance provided in NH-3214.2
    - Modeling elevated material behavior is on going - didn't want to stifle development
    - Features of constitutive equations
        - effects of plastic strain hardening including cyclic loading effects and hardening or softening which can occur with high temperature exposure
        - primary creep and the effects of creep strain hardening as well as softening (due to reverse loadings)
        - effects of prior creep on subsequent plasticity and vice versa
    - Generally appropriate to use average stress-strain and creep data - except for buckling and instability which should be based on minimum stress-strain curve
    - Unified constitutive equations which don't distinguish between rate dependent plasticity and time dependent creep more appropriate for 9Cr-1Mo-V, particularly at higher temperatures

- More comprehensive discussion including comparisons to data in VOl. III of WRC Bulletin on Recommended Practices....
    - Abridged discussion in recent ASME Guidelines Document

- Full technical detail in RDT Standard F9-5T
    - Based on decoupling plastic and creep strains
    - Frequent references to use of eng. judgment for particular design situations
    - No longer maintained by DOE

INELASTIC ANALYSIS CREEP HARDENING RULES

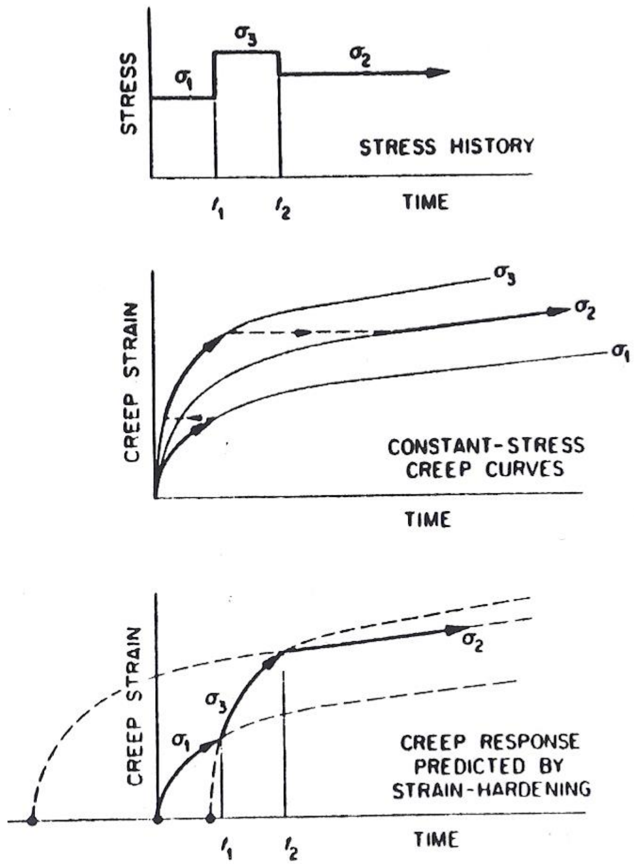


Fig. 1 Axial creep strains predicted by strain-hardening analysis (based on total creep strains) for variable uniaxial loads in the absence of stress reversals.

3

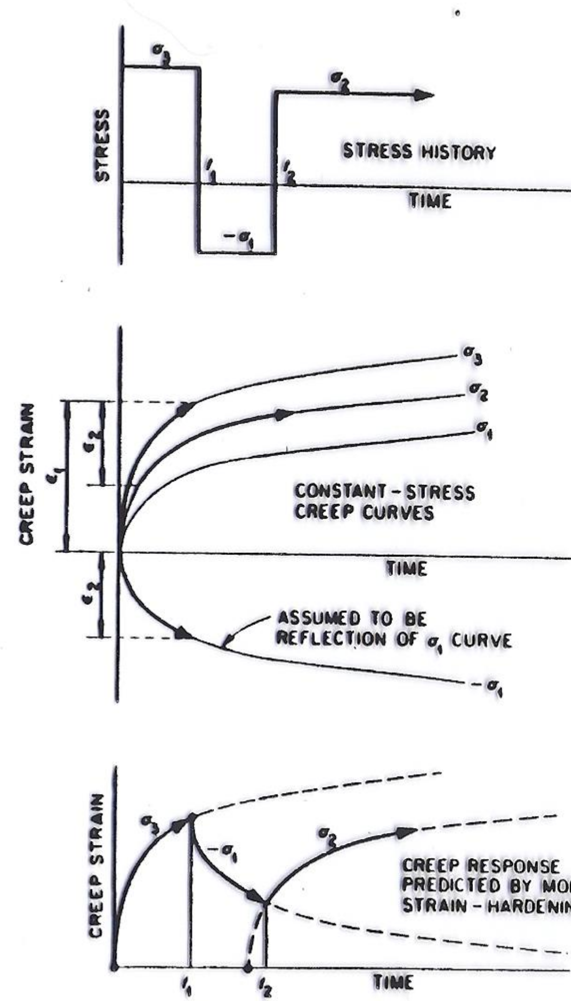
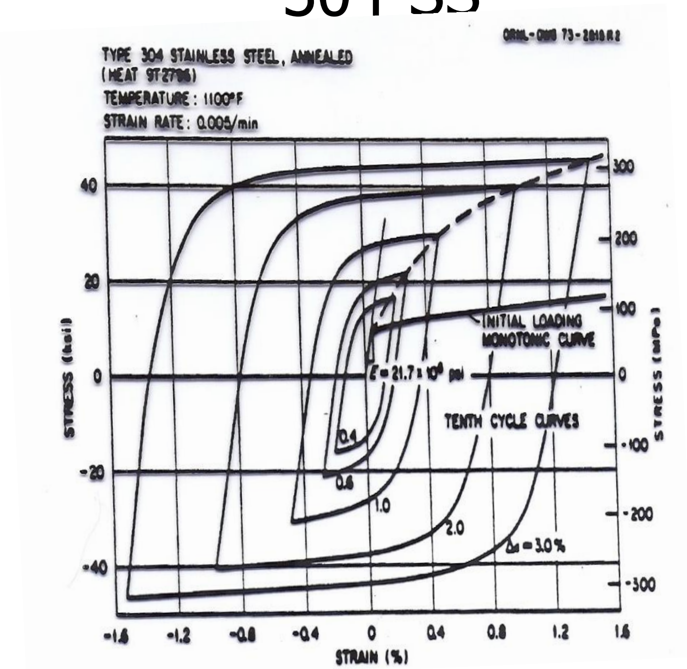


Fig. 2 Axial creep strain response predicted by auxiliary procedures for reversed uniaxial creep loads.

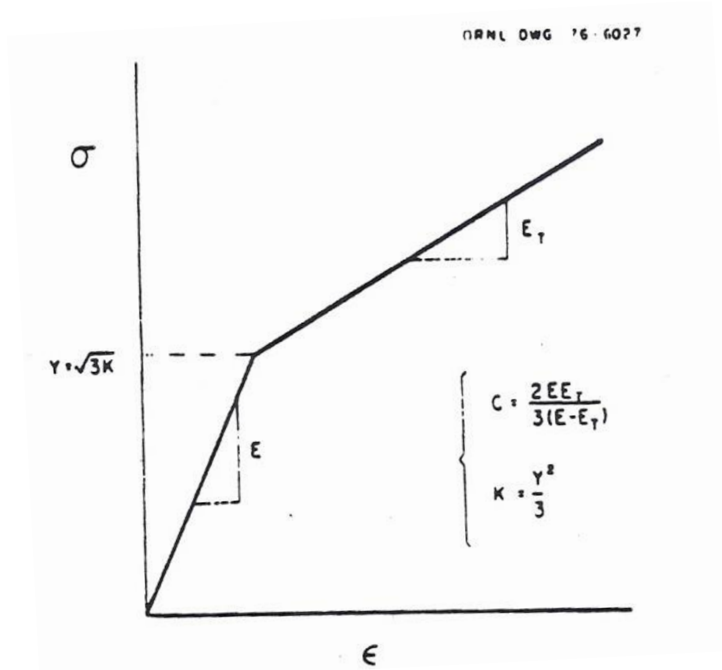
REPRESENTATION OF TENSILE PROPERTIES

- Cyclic hardening in 304 SS



Monotonic Loading Stress-Strain Curve and Tenth-Cycle Stress-Strain Curves for Different Total-Stress Ranges. Annealed Type 304 Stainless Steel at 593^{0}C (1100^{0}F)

- Bilinear stress-strain curve



Bilinear idealization of material stress-strain curve giving definition of X and C

RESTRICTED MATERIAL SPECIFICATIONS

- Incentive: To minimize heat-to-heat mechanical property variations
  - Wide variations in 304 & 316SS
  - Arose in discussions of proper choice of flow and strength properties when evaluating strain limits and creep-fatigue damage
    - What is "conservative" depends on load magnitude and limit under consideration
    - Average properties were selected
- Recommendations include
  - Composition limits
  - Melt practice
  - Fabrication processes
  - Grain size limitations
  - Control of cold/hot work

DESIGN SPECIFICATIONS AND LOAD HISTOGRAMS

- Load Histograms
  - The rules of HBB require that the time duration of the loading events be specified
  - The transients need to be specified in sufficient detail to compute realistic temperature distributions
  - WRC Bulletin on Recommended Practices…. Provides examples of transient definition and development of histograms for thermal and stress analyses

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HBB-3300 Vessels, -3400 Pumps, -3500 Valves, -3600 Piping

COMPONENT DESIGN RULES

COMPONENT DESIGN RULES

- Covers
  - HBB-3300 Vessels, -3400 Pumps, -3500 Valves, -3600 Piping
- HBB rules for design by analysis generally take precedent over component rules
  - Reverse of NB rules
- Generally OK for load controlled stresses
  - i.e. reinforcement of opening
- Numerous restrictions in HBB on the use of NB rules for deformation controlled stresses
  - Generally require that creep effects are not significant
    - Exception is piping where the use of stress indices is specifically permitted for meeting strain limits and detailed stress indices for creep-fatigue limits

HBB-4000 FABRICATION AND INSTALLATION

- Supplements NB
  - Cold work effects
    - Loss of ductility, particularly 304 &316SS
    - Loss of creep-rupture strength, particularly at low strain and long times
    - Two processes involved, recovery and recrystallization
    - Re-annealing required if CW exceeds 5% unless justified in Design Report
    - %5 < CW < 20% permitted for limited time at temperature combinations
- References NB which invokes Section IX Welding and Brazing Qualifications

HBB-5000 EXAMINATION

- Supplements NB
- Concern that single radiography of NB might miss a crack-like defect more likely to propagate at elevated temperature
  - Additional volumetric examination required
    - radiography plus ultrasonic
    - radiography plus eddy current
    - radiography from two angles

HBB-6000 TESTING

- Replaces NB
- Pneumatic test made equal alternative to hydrostatic
- Helium leak test only on certain closure welds
- Use of internal pressure test to account for external pressure

OTHER COMPONENT RULES AT ELEVATED TEMPERATURES

- Subsection HC, Subpart B, Class B Metallic Pressure Boundary Component
  - Basically reverts to Design by Rule analogous to Section VIII Div. 1
    - Much larger material selection than Class A
    - Option to use Class A rules in their entirety – limited to Class A materials
    - Piping has creep based design rules for thermal expansion
  - Was CC N-253 for Design & Materials, CC N-254 for Fabrication and Installation, CC N-257 for Overpressure protection

OTHER COMPONENT RULES AT ELEVATED TEMPERATURES

- Subsection HG, Class A Metallic Core Support Structures
  - Subpart A, Negligible creep effects
  - Subpart B, Creep effects non-negligible
    - Closely follows HBB
  - Was CC N-201
- Appendix HBB-II Use of SA-533 & 508 in Class A Construction
  - Limited time, temperature and cycles at elevated temperature
  - Was CC N-499
- CC N-290 Expansion Joints in Class A Liquid Metal Systems
  - Requires extensive design demonstration testing

NEW RULES ADDRESS CONCERNS WITH CURRENT RULES

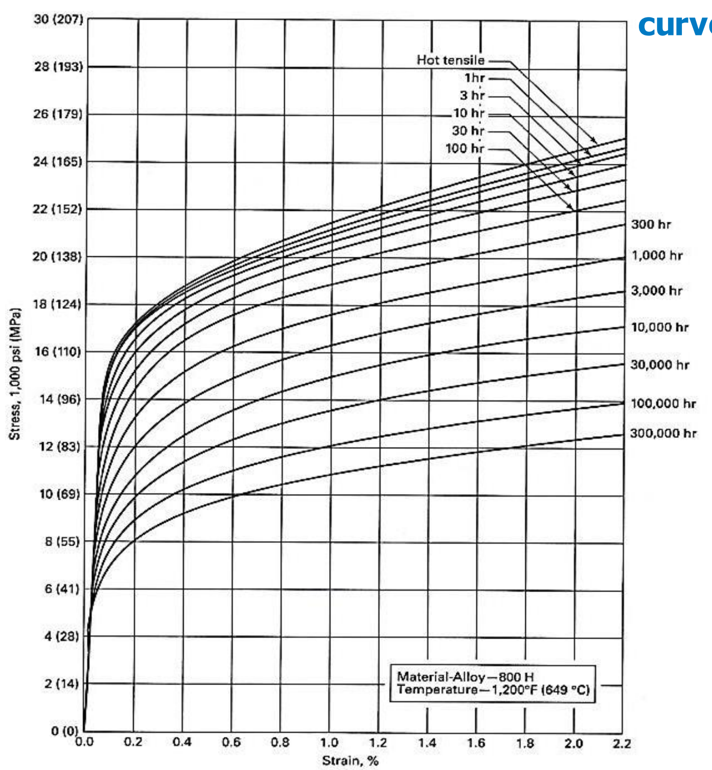
RECENT DEVELOPMENTS

NEW RULES ADDRESS CONCERNS WITH CURRENT RULES

- Based on Elastic-Perfectly Plastic (E-PP) analysis
  - Ratcheting analysis to assess strain limits
  - Shakedown analysis to assess creep-fatigue damage
- Avoids stress classification
  - Stress and strain redistribution approximated with E-PP material model
- Addresses current restriction on applicability of simplified methods to Alloy 617 at very high temperature
  - Current simplified methods deemed inappropriate for Alloy 617 above 1200°F
  - Cannot decouple plasticity and creep – the basis for current simplified methods
- Two separate code cases
  - Strain Limits and Creep-fatigue
  - Initial rules for 304 and 316
  - E-PP rules planned part of Alloy 617 Code Case

STRAIN LIMITS RULES USE ISOCHRONOUS STRESS-STRAIN CURVE

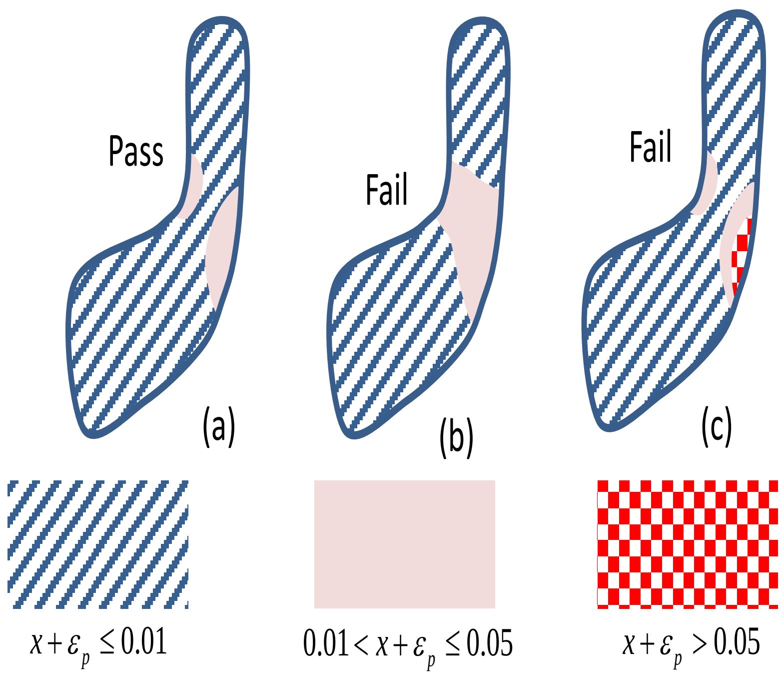
Figure T-1800-C-8
Average Isochronous Stress-Strain Curves



Isochronous stress-strain curves

- Creep strain limit is the sum of the target steady creep strain, *x*, and the accumulated inelastic strain, ε_p
- Pseudo yield strength for E-PP analysis is the lesser of S_y and S_x *where* S_x is from isochronous stress-strain curve (ISSC)
- Iterate ratcheting analysis for values of *x* until there is no ratcheting

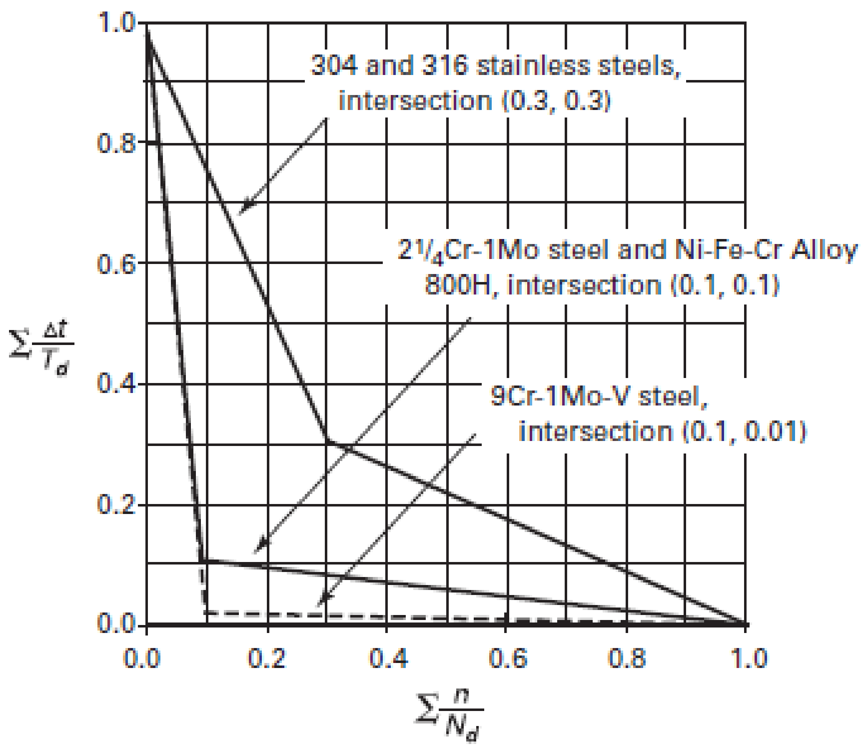
STRAIN LIMITS RULES USE ISOCHRONOUS STRESS-STRAIN CURVE



- Determine plastic strain, ε_p, from E-PP analysis
- If $(x + \varepsilon_p) \le 0.01$ at least one point at each through thickness location and $(x + \varepsilon_p) \le 0.05$ at all locations, then strain limits are satisfied
- Limits for welds are one-half of above

CREEP-FATIGUE RULES USE ALLOWABLE DAMAGE ENVELOPE

Creep-fatigue Damage Envelope



- Pseudo yield stress is lower of S_y and stress to cause rupture in trial time T_d
- Iterate E-PP analysis with T_d until shakedown (no yielding) occurs
- Determine strain at a point and compute fatigue damage, D_f, using NH
- Compute creep damage, D_c, from
  - $D_c = (t_{design} / T_d)$
  - where t_{design} = design life
- Design is acceptable if D_f and D_c satisfy the allowable damage envelope

EXAMPLE PROBLEMS, COMPARISONS TO TEST RESULTS & INELASTIC ANALYSIS USED TO VERIFY APPLICABILITY

- Representative geometry and loading to illustrate applicability of E-PP to strain limit and creep – fatigue
  - Reinforced nozzle in spherical shell
  - Steady and cyclic, pressure, thermal and nozzle loads,
  - Level A, B and C Service Loadings
  - Weld joint

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EXAMPLE PROBLEMS, COMPARISONS TO TEST RESULTS (cont'd)

- **Simpler models and loading to compare E-PP to HBB and inelastic analysis**
  - **Pressurized 316 cylinder with cyclic through wall thermal gradient**
    - **Strain limits showed equivalent margins between E-PP and HBB**
    - **Creep-fatigue estimated allowable life from HBB procedure is 1430 hr compared to approximately 10,000 hr from E-PP**
  - **Inelastic design envelope for pressurized 617 cylinder with thermal gradients showed close agreement with E-PP**
  - **Analytic comparison of rapid cycle (RC) E-PP solution with real steady cyclic (SC) solution demonstrated conservatism of RC solution for creep-fatigue**
- **SMT and Two-bar key feature test results used for experimental verification**
  - **Strain limits and creep-fatigue damage**

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CURRENT RULES IN HBB USE TWO APPROACHES

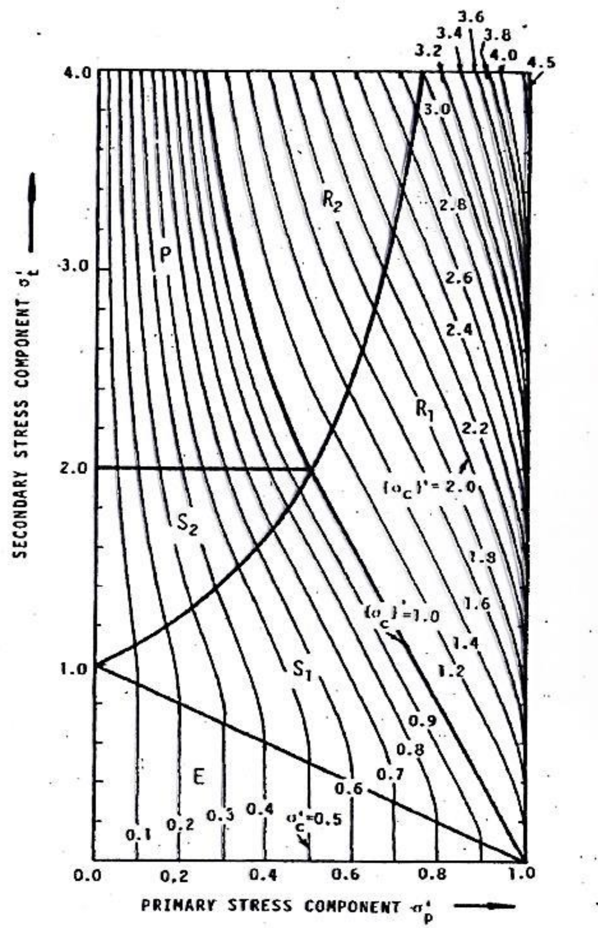


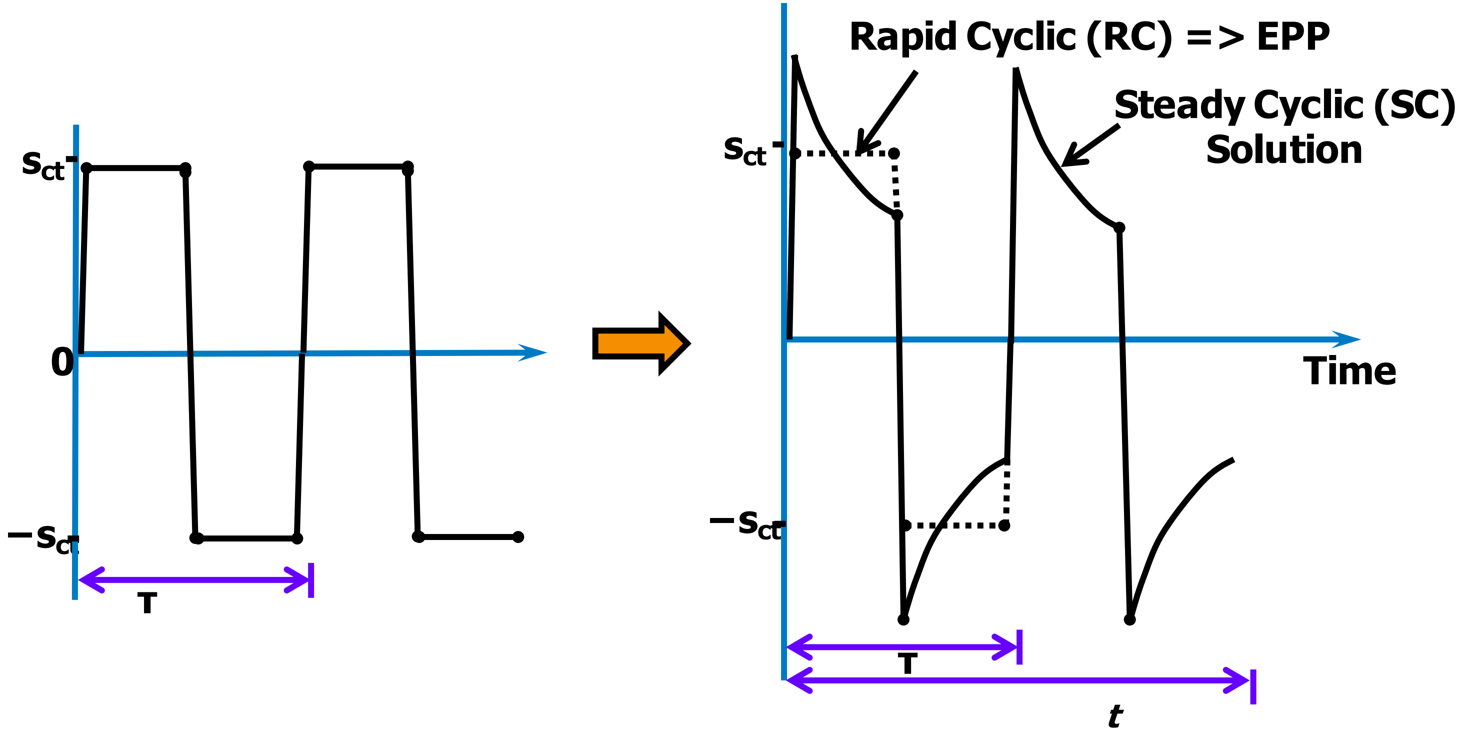
FIGURE 9 GENERALIZED CORE STRESS GRAPH

$\{\sigma_c\}' = 1 + \sigma_t' - 2\sqrt{\sigma_t'(1 - \sigma_p')}$ in Regime R

$\{\sigma_c\}' = \sigma_p - \sigma_t$ in Regime R

- Elastic analysis results
  - Load controlled (primary stress) limits
  - Displacement controlled limits
    - Strain limits (P + Q)
    - Creep-fatigue damage (P + Q + F)
  - Require stress classification
  - Referred to as "Simplified Methods" but more complex than NB equivalent
- Inelastic analysis results
  - Strain Limits and Creep-fatigue
    - Considered "Gold Standard"
  - Full inelastic analysis per HBB-3214.2
    - Stress-strain history
    - Creep, plasticity and interaction

NEW RULES BASED ON ELASTIC-PERFECTLY PLASTIC ANALYSIS & “PSEUDO” YIELD STRENGTH



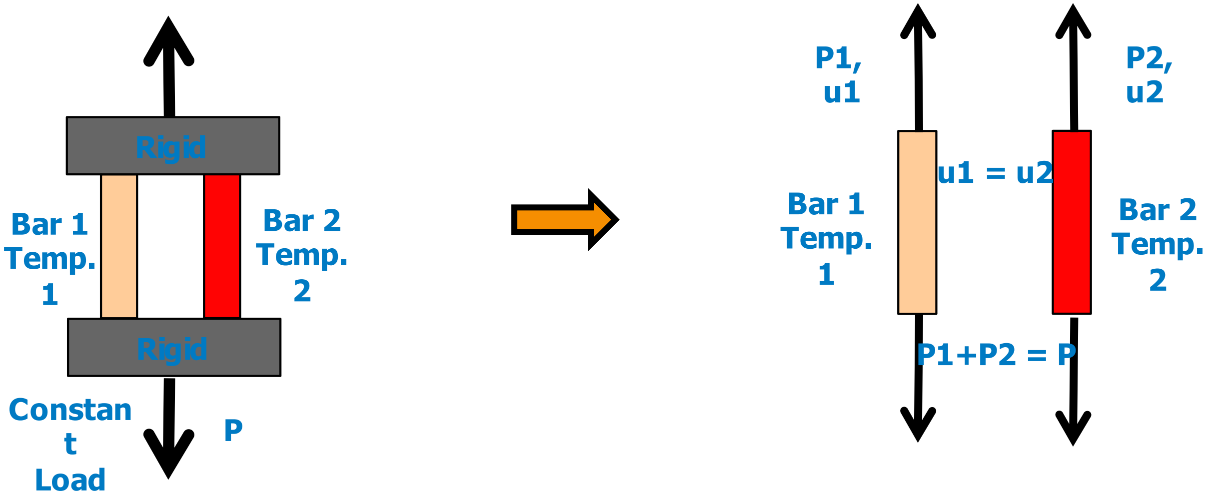
NEW RULES BASED ON ELASTIC-PERFECTLY PLASTIC ANALYSIS & “PSEUDO” YIELD STRENGTH

- **Bounding solutions by Goodall et.al extended by Carter to cover cyclic loading**
- **Consideration of work and energy dissipation permits rank ordering of cyclic solutions**

  $D_{CP} > D_{RC} > D_{SC}$
- **The Rapid Cycle (RC) solution is the limiting case of the Cyclic Plasticity (CP) solution that doesn’t ratchet as the yield strength is decreased. This implies that the RC solution will bound the real Steady Cyclic (SC) solution.**
- **The yield strength is a “pseudo” yield strength given by the limiting design parameter, e.g. stress for 1% strain and stress to cause creep rupture at time greater than design life.**

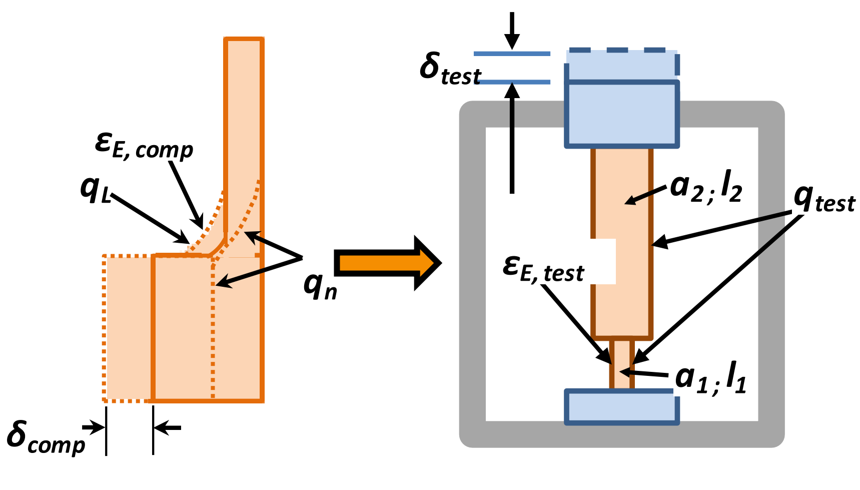
KEY FEATURE TEST RESULTS USED TO VERIFY E-PP METHODS

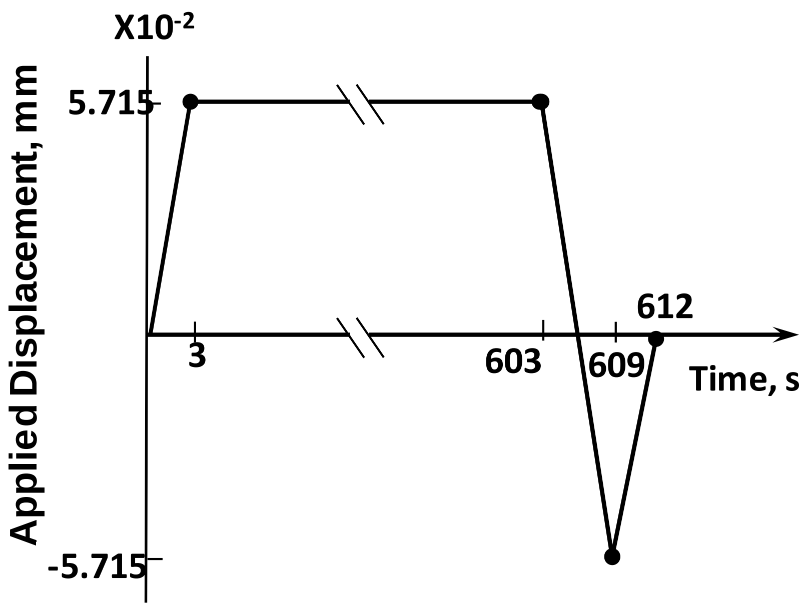
- Two bar test results used for strain limits



KEY FEATURE TEST RESULTS USED TO VERIFY E-PP METHODS

- SMT test results used for creep-fatigue





SUMMARY

- Alternative simplified rules for evaluation of cyclic loading
  - Address long term goal of SG-ETD – avoids stress classification
  - Current simplified rules deemed inapplicable to Alloy 617 at very high temperatures
- Proposed rules based on elastic-perfectly plastic (E-PP) analysis
  - Strain limits (Record # 14-1445)
  - Creep-fatigue damage (Record # 14-1446)
- Example problems and test data illustrate and verify applicability