Alternative Approaches for ASME Code Simplified Elastic-Plastic Analysis

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Background

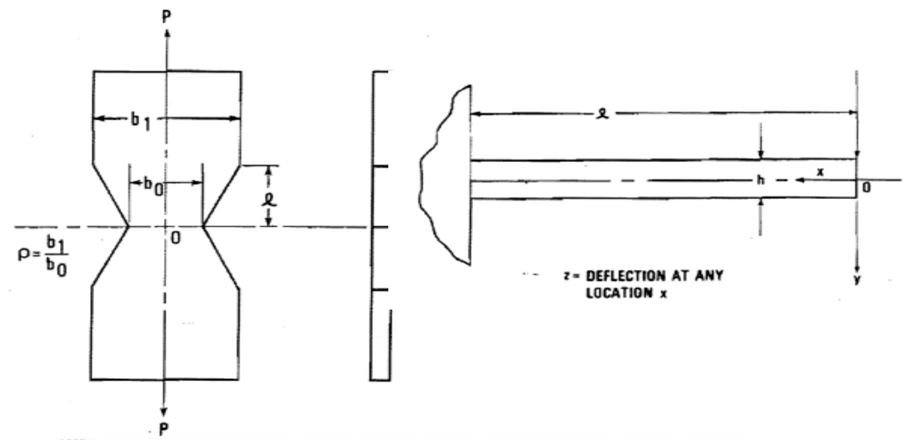
- NRC RG 1.207 requires the use of multipliers (F_{en}) on the cumulative usage factors (CUF) to account for the effects of environmentally assisted fatigue (EAF)
  - Application of RG-1.207 can increase the calculated CUF significantly, making it difficult to meet the CUF limits for new plants and plants with license renewal.
  - This can be exacerbated when higher number of cycles associated with flexible operation are considered.
  - In reality, there has been no field experience of cracking attributed to EAF; in the few cases where there has been cracking, it has been due to high cycle fatigue where EAF is not a factor.
  - On the other hand, EAF test data show a strong environmental effect; this is not consistent with the good field performance. While the F_{en} factors in RG 1.207 are consistent with test data, they still do not reflect the good EAF field performance.

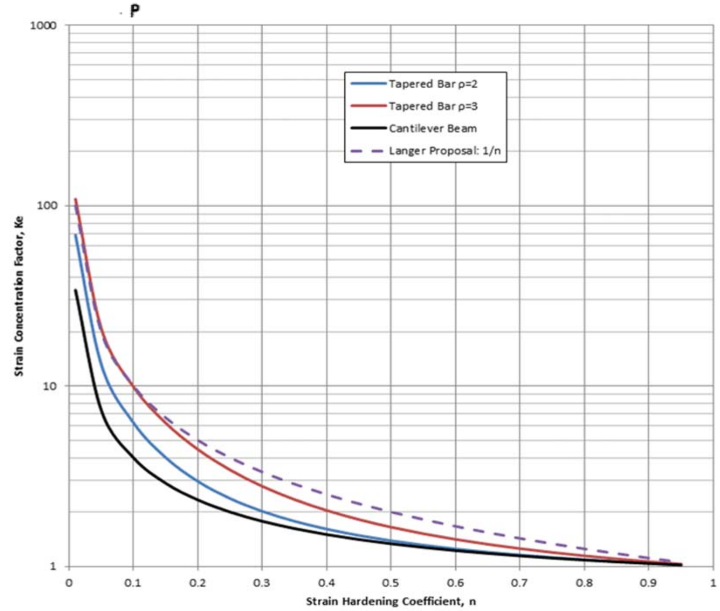
Background (cont.)

- One way of addressing the EAF problem is to examine the original CUF (without F_{en}) which may be over-conservative
  - Justify a lower CUF in the original analysis so that the fatigue usage multiplied by F_{en} is still acceptable.
- The use of the ASME Code simplified elastic-plastic analysis (NB-3228.5 or NG-3228.5) is often the biggest source of conservatism in fatigue analysis.
  - The focus of the EPRI project is to develop Alternative Approaches for ASME Code Simplified Elastic-Plastic Analysis
- There are two ways to update the high fatigue usage:
  - Use new elastic-plastic (EP) analysis; an expensive option that requires new finite element analysis; difficult to apply for piping. Also, the Code does not provide explicit rules on how EP analysis is performed
  - Propose a more realistic approach as an alternative to the NB-3228.5 (or NG-3228.5) rules for the Code simplified elastic plastic analysis.

Basis for Current Code K_e Equation

- Developed originally by Langer almost 50 years ago based on a simple model for a cantilever beam and tapered bar
- Bounded by the proposed $K_e = 1/n$ where n is the strain hardening coefficient
- Simple formulation, but overly conservative, especially for carbon steel and low alloy steel with low strain hardening coefficient
- Subsequently Modified with input from Tagart





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Current Code K_e Equation

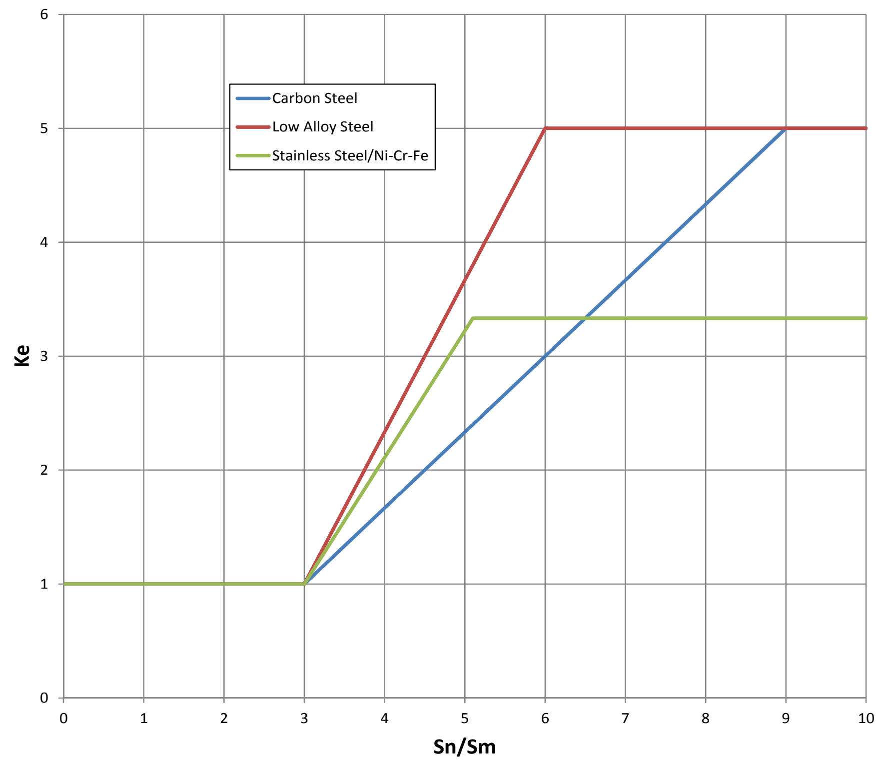
- $K_e = 1 \quad \text{for } S_n \leq 3S_m$

  $= 1 + \frac{(1-n)}{n(m-1)}\left\{\frac{S_n}{3S_m} - 1\right\} \quad \text{for } 3S_m \leq S_n \leq 3mS_m$

  $= 1/n \quad \text{for } S_n \geq 3mS_m$

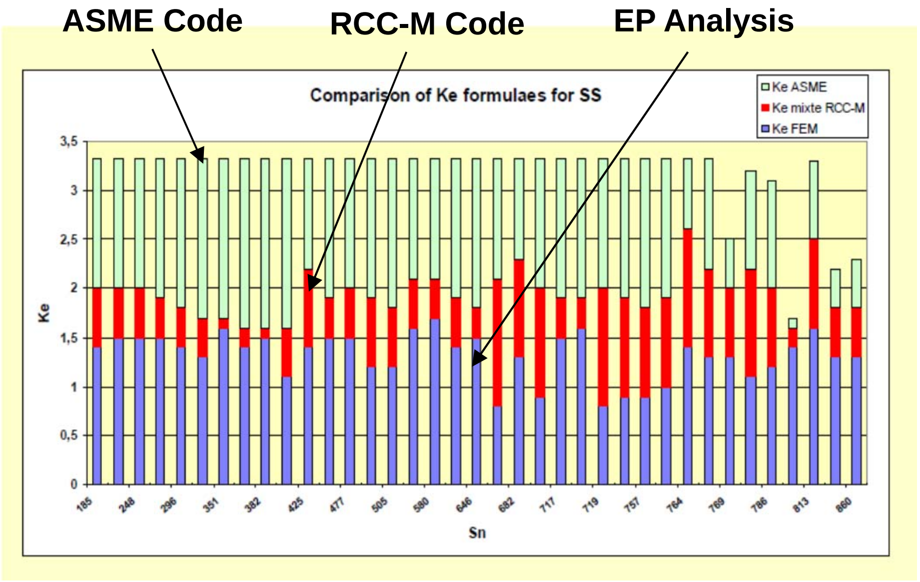
Materials	m	n
Carbon Steel	3.0	0.2
Low Alloy Steel	2.0	0.2
Austenitic Stainless Steel	1.7	0.3
Ni-Cr-Fe (Alloy 600)	1.7	0.3

- Comparison with the results from elastic plastic analysis show the conservatism in the Code K_e value
- A new approach that preserves the simplicity of the Code approach, but results in a more realistic CUF value is needed



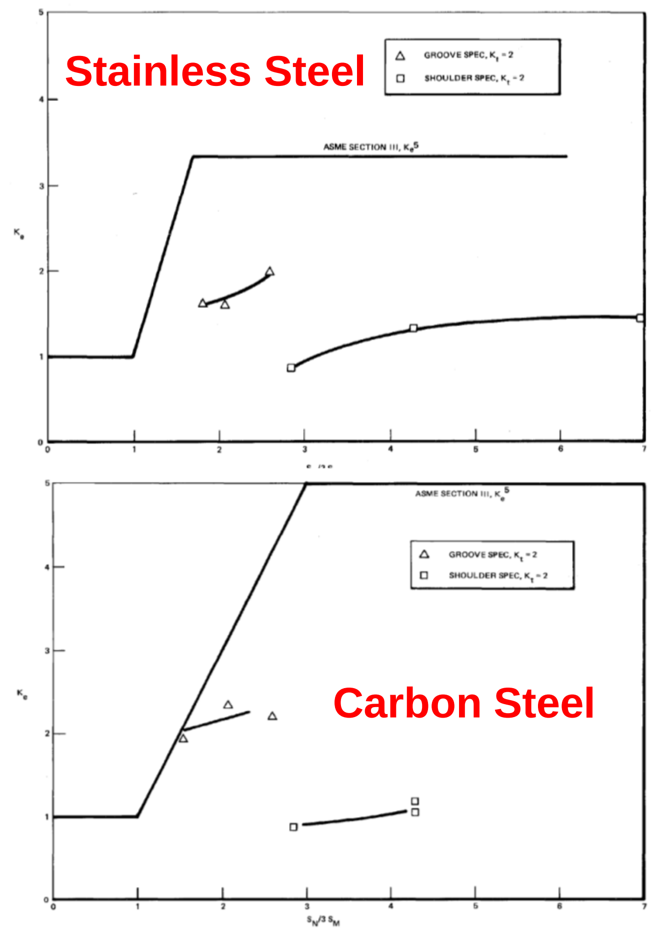
Conservatism in the Code K_e – Elastic-Plastic Analysis

- Comparison of the Code K_e value with the results of elastic-plastic analysis show that the Code value is conservative by a factor of two or higher.
- The higher Code K_e can result in an overestimate of 20-100 in fatigue usage.
- More realistic Code K_e factors can be significant in addressing license renewal and RG 1.207 EAF challenges



Conservatism in the Code K_e Equation – Air Test data

- Tests have also been done on notched carbon steel and stainless steel specimens in air to compare the Code K_e value with based on test data.
- Results confirm that the Code K_e values are conservative by factors well in excess of 2



TL Gerber, "Effect of Constraint and Loading Mode on Low Cycle fatigue Crack Initiation – Comparison with Code Design Rules" GEAP Report 20662, US AEC October 1974

K_e Formulation in WRC-361

- WRC-361 was one of the first efforts to examine the NB-3228.5 Code rules and offered alternate methods to determine K_e
- The K_e formulation in WRC-361 considers the following:
  - Effect of Poisson's ratio during plastic behavior. This is addressed by developing an equivalent $\nu{*}{=}0.5-\frac{E_s}{E}\,(0.5-\ \nu)$ and determining the ratio of stress intensity for elastic and elastic plastic behavior under strain controlled (e.g. thermal) loading. The stress intensity ratio is: $K_{\nu}{=}\ \frac{S_{int}{}^{Plastic}}{S_{int}{}^{Elastic}} = \frac{1-\nu}{1-\nu{*}}$. For v=0.3, the maximum value of K_{ν}=1.4
  - Elastic follow-up during mechanical load cycling; this is evaluated using the present Code K_e equation.
  - Notch strain redistribution based on Neuber analysis; the additional notch factor (over and above the stress concentration factor, K_T) is $K_n = K_T{}^{(1-n)/(1+n)}$
- The effective K_e value for the first two factors is determined by a weighted average of K_{ν} and K_e. This is then multiplied by the notch factor K_n.

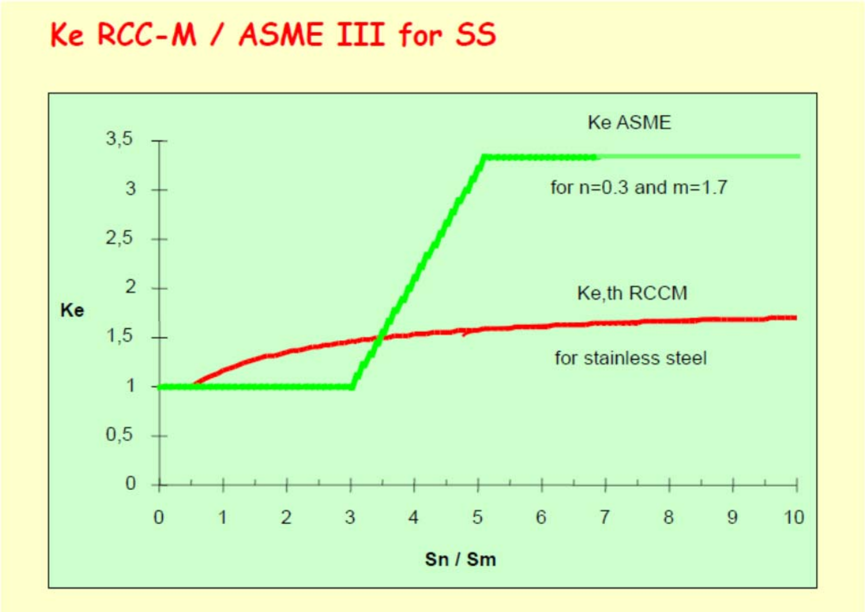
Application of WRC-361: French RCC-M Code

- There are several industry codes (e.g. EPRI Report TR-107533 in 1998) that attempt to adjust the Code conservatism; all based on WRC-361 concepts
- The RCC-M code includes the K_ν factor (Poisson's ratio effect)

$$S_a = 0.5\left({K_e}^{mech}{S_p}^{mech} + {K_e}^{ther}{S_p}^{ther}\right)$$

$${K_e}^{ther} = 1.86\left[1 - \frac{1}{1.66 + S_n/S_m}\right] \text{ but} \geq 1$$

- K_n (Neuber notch effect) is included in RCC-MR for high temperature reactors but not in RCC-M (for PWRs).
- Some disadvantages:
  - K_e correction even below $3S_m$
  - ${S_p}^{mech}$ and ${S_p}^{ther}$ are new stress terms that need new stress analysis
  - Potential Discontinuity in K_e at $3S_m$
- British Code similar to RCC-M



Code Case N-779

- Extends the work by Deardorf in EPRI Report TR-107533
- Combines contributions from three sources
  - Mechanical loading multiplied by the Code K_e
  - Thermal load multiplied by K_ν
  - Notch effect by including K_n
- Requires determination of stresses not currently available in ASME Code stress reports
- Somewhat difficult to use
- Identified as "Unacceptable" in RG 1.193

$$K_\nu = 1.4, \text{ for } S_p > 3S_m \text{ and } S_{p\text{-}tb\text{-}lt} \geq 3S_m$$
$$= 1.0 + 0.4\,(S_p - 3S_m) \,/\, (S_{tb+lt}), \text{ for } S_p > 3S_m \text{ and } S_{p\text{-}tb\text{-}lt} < 3S_m$$
$$= 1.0, \text{ for } S_p \leq 3S_m$$

and $K_\nu \leq K_e$

S_p = total stress intensity range

S_{tb+lt} = thermal bending plus local thermal stress intensity range

$S_{p\text{-}tb\text{-}lt}$ = total stress intensity range excluding thermal bending and local thermal stresses

$$K_n = 1.0 + \left[\left(\frac{S_{p-lt}}{S_n}\right)^{\left[\frac{1-n}{1+n}\right]} - 1\right]\left[\frac{(S_{p-lt}) - 3S_m}{S_{p-lt}}\right], \text{ for } (S_{p-lt}) > 3S_m$$
$$= 1.0 \text{ for } (S_{p-lt}) \leq 3S_m$$

and $K_n\, K_\nu \leq K_e$

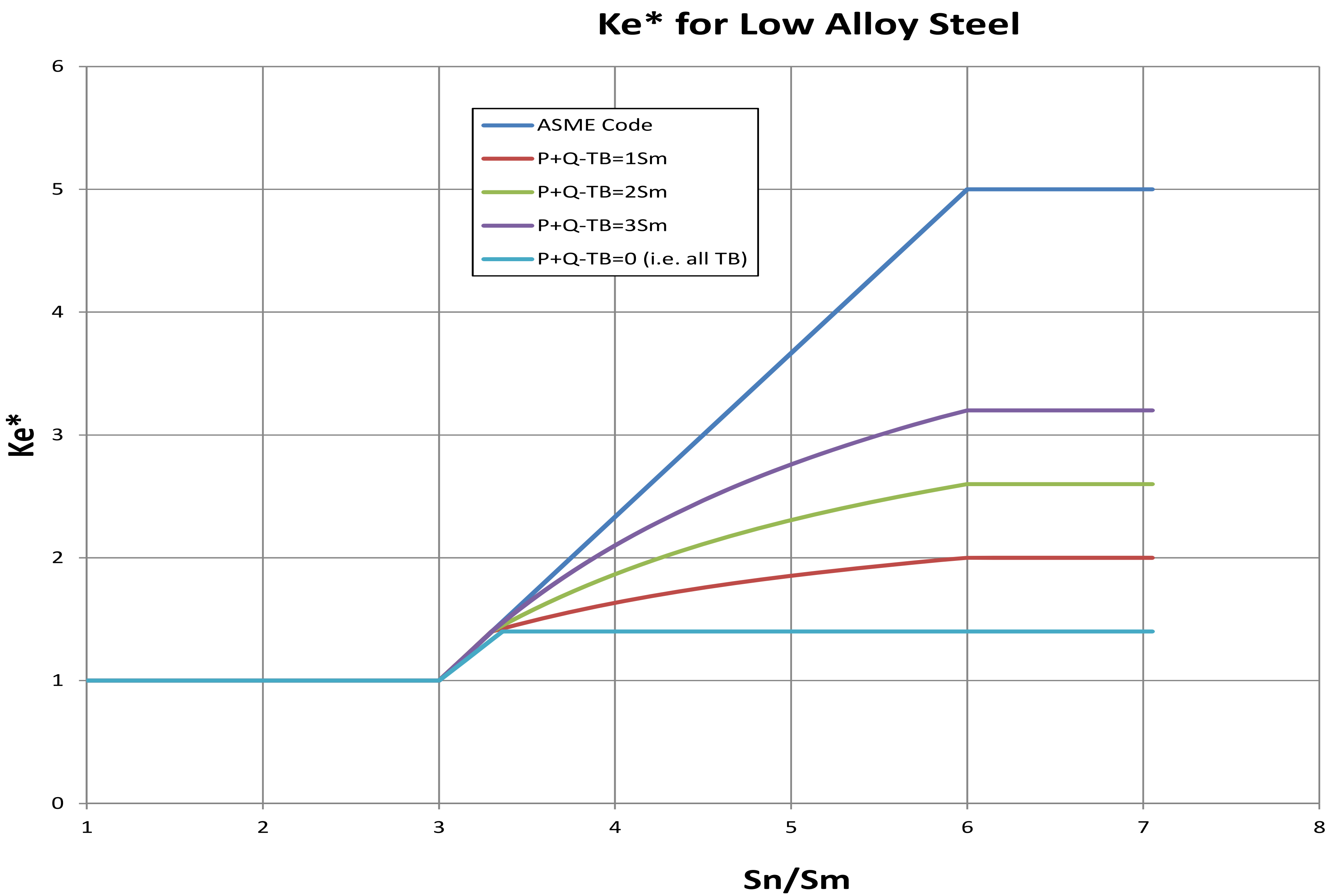
Why is a New K_e Relationship Needed?

- Most of the existing 'improved' K_e formulations require new stress analysis; if new analysis is performed, we might as well use new elastic-plastic (EP) analysis. However the Code does not specify rules for performing EP analysis; wide range of methods used.
- Some of the K_e factors may be more conservative than the Code value for stress ranges below $3S_m$ where the current rules are adequate
- There may be a discontinuity in K_e at $S_n=3S_m$ in many of the proposals.
- Some of the new K_e expressions may require new analysis and may be somewhat complex (e.g. Code Case 779).
- We need a new approach that uses existing information in current ASME Code stress reports and retains the simplicity of the current code but without the excessive conservatism.
  - The new approach should apply to pressure vessel components (NB-3200) as well as piping (NB-3600).
  - It should cover common structural materials- austenitic stainless steel, nickel based alloys, carbon steel and low alloy steel.

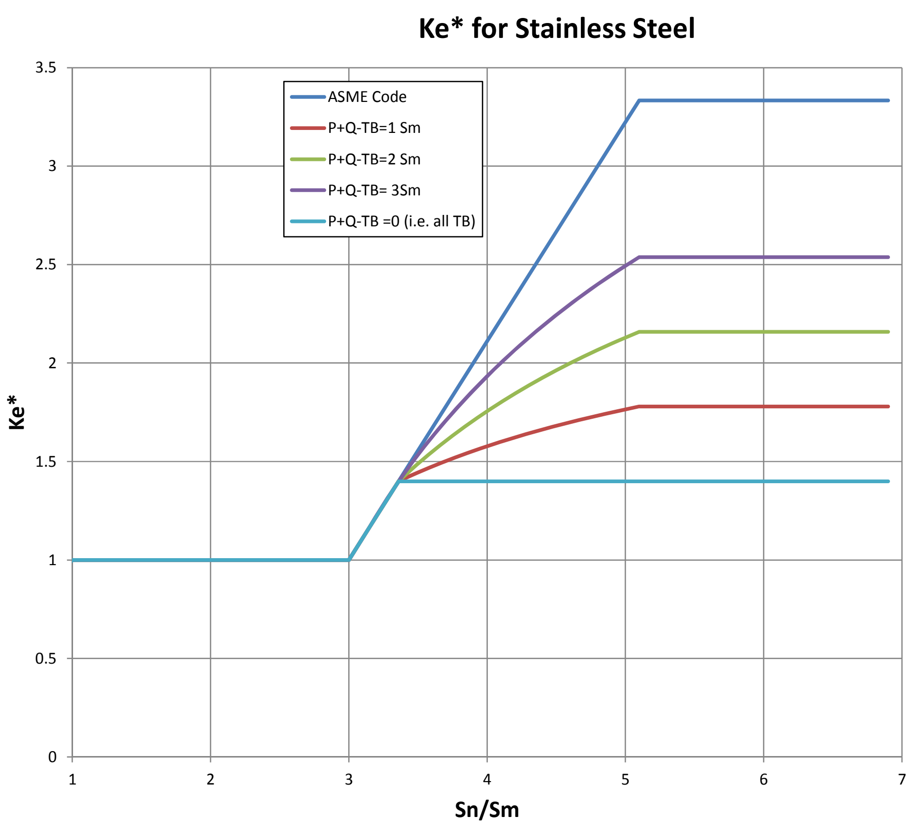
Proposed New K_e Formulation (w/o K_n Neuber Factor)

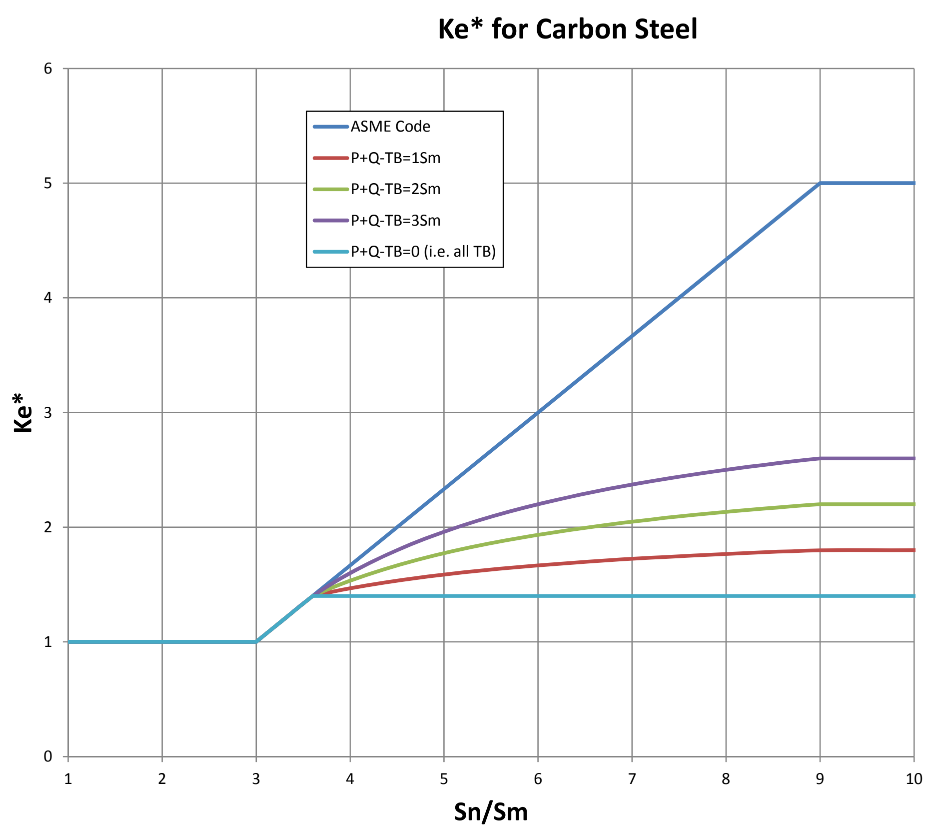
- Follows the WRC-361 method of using a weighted average approach for the thermal and mechanical load stresses
  - $K_e^* = K_\nu \frac{S_{n\,therm}}{S_n} + K_e \frac{S_{n\,mech}}{S_n}$
    - $S_{n\,mech}$ = Mechanical load: P+Q-Thermal Bending
    - $S_{n\,therm}$ = Thermal Load: Thermal Bending (TB)
  - K_ν is conservatively assumed to be 1.4 (corresponding to v=0.3)
  - $K_e^* = 1.4(1-R) + K_e R$ for $3S_m \leq P + Q \leq 3mS_m$; $R = \frac{P+Q-TB}{S_n}$, but not higher than K_e.
  - Eliminates the discontinuity at $S_n = 3S_m$
- The proposed K_e equation applied to piping also except that R is defined as:
  - $R = \frac{P+Q-TB}{S_n} = \frac{\text{Equation 13 of NB}-3653}{\text{Equation 10 of NB}-3653}$
  - S_n = P+Q = Equation 10 of NB-3653
  - P+Q-TB = Equation 13 of NB-3653

Proposed K_e* Factor for Low Alloy Steel



Proposed K_e* Factors for Stainless and Carbon Steels





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Consideration of Notch Effects

- WRC-361 recognizes Poisson's ratio effects and elastic follow-up effects by using a weighted approach of thermal and mechanical stresses and multiplies it by a notch factor based on Neuber analysis.
- WRC-361 specifies a Notch factor (over and above the standard stress concentration factor K_T used in elastic analysis)
  - The notch factor is given by: $K_n = K_T^{\left(\frac{1-n}{n+1}\right)}$
  - Depends on the strain hardening exponent n (equal to 0.3 for stainless steel and 0.2 for carbon and low alloy steel)
- The notch effects are first described here using Neuber Analysis. Since many Codes (e.g. RCC-M code) do not explicitly include the notch factor, example EP analysis is performed to determine whether there is a need to add the notch factor K_n.

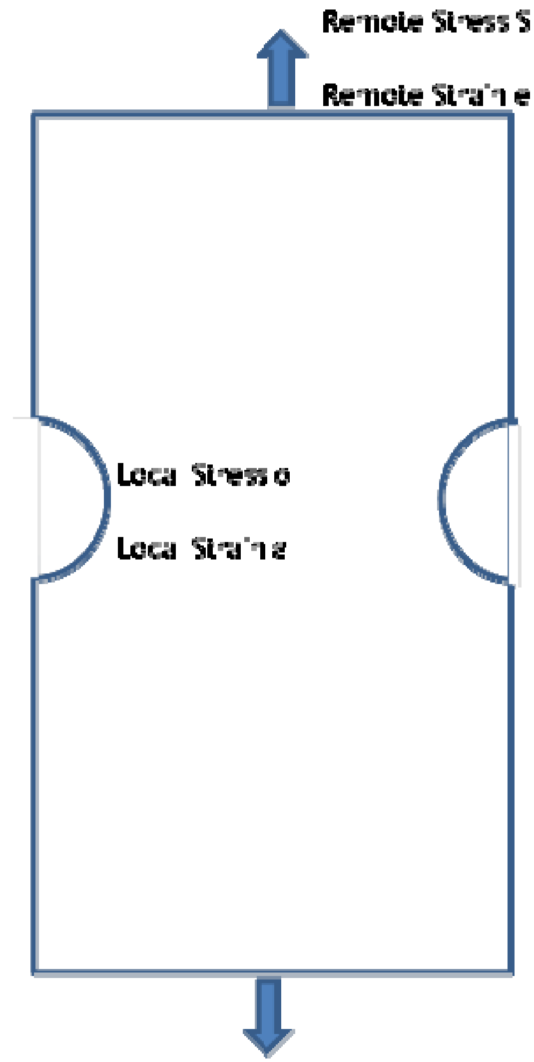
Notch Stress-Strain

- Analysis performed for stainless steel and carbon steel
- Remote stress and strain: S,e
- Local stress and strain: σ, ε
- Example considers the case K_T=2

$$K_t^2 = K_\sigma K_\epsilon$$

$$K_t^2 = \frac{\sigma}{S}\frac{\epsilon}{e}$$

$$K_t^2 = \frac{\sigma}{S}\frac{\epsilon E}{S}$$



Neuber Notch Analysis Approach

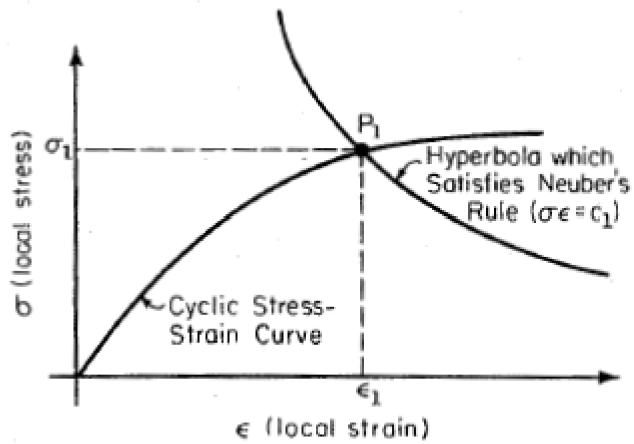
- Neuber analysis relates the stress and strain at the notch to the global stress and strain

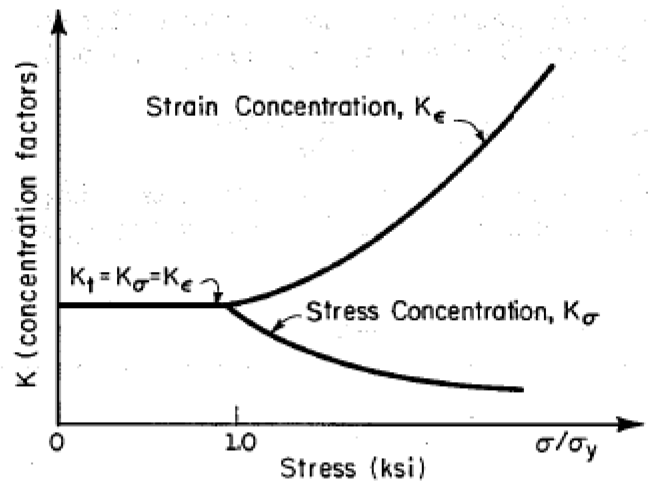
$$\underbrace{\frac{(K_t S)^2}{E}}_{\text{applied load}} = \underbrace{\sigma \epsilon}_{\text{notch response}}$$

$$K_t^2 = K_\sigma K_\epsilon$$

$$K_t^2 = \frac{\sigma}{S}\frac{\epsilon}{e}$$

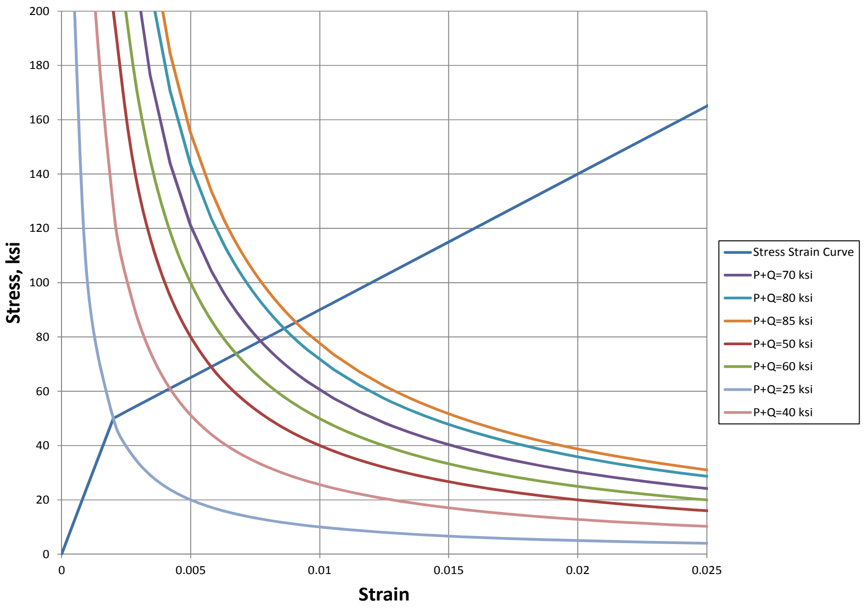
$$K_t^2 = \frac{\sigma}{S}\frac{\epsilon E}{S}$$

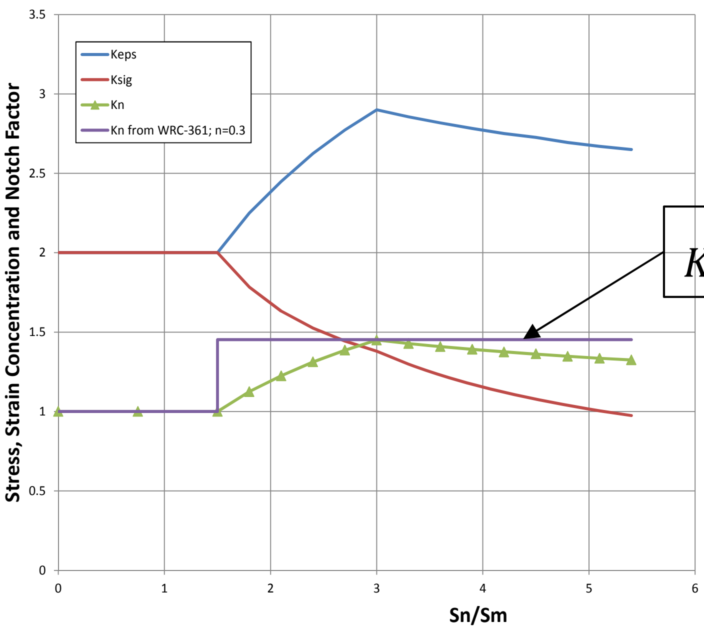




- A bilinear stress strain curve was fitted to the power law with n=0.3 for stainless steel and S_y= 50 ksi (close to $3S_m$=50.7 ksi for stainless steel at 550°F)

Example Results for Stainless Steel K_T=2





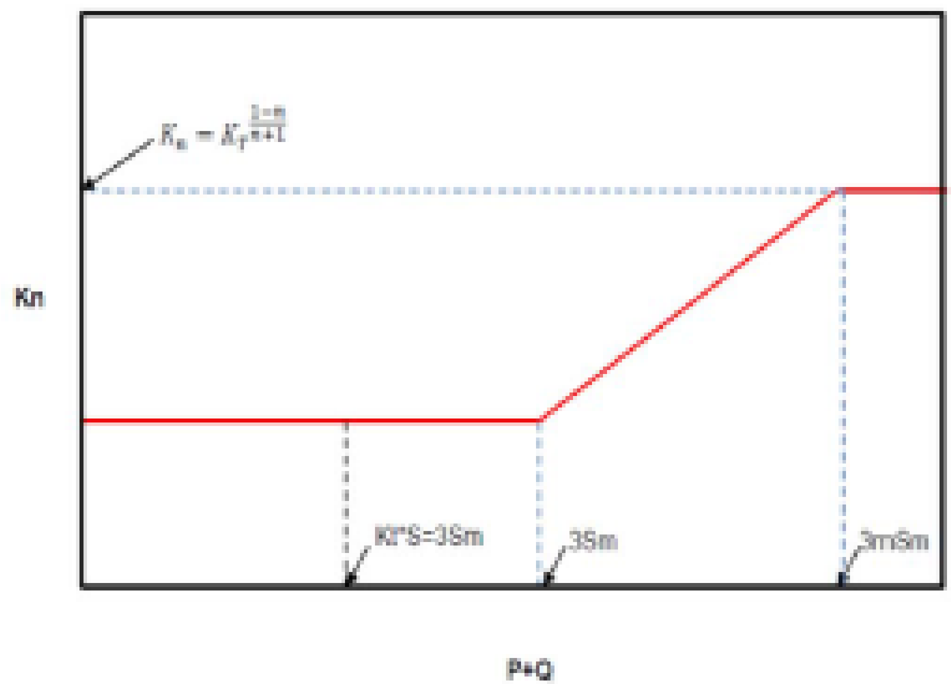
$$K_n = K_T^{\frac{1-n}{n+1}} = 1.45$$

Verification Problems for the Proposed K_e^*

- The objective of the verification problems was twofold:
  - Compare the prediction of the K_e^* equation with the results of elastic plastic analysis for unnotched geometry
  - Determine whether the additional notch factor K_n is needed for the evaluation of components with stress concentration factor (SCF), K_T
    - K_n is the additional factor over and above the K_T and accounts for local yielding in the SCF region
- Examples include notched and unnotched locations with a combined of mechanical (P+Q-TB) and thermal bending (TB)
  - Bettis stepped pipe test (no notch)
  - Notched (K_T=2.9) beam (both notch and unnotched locations) evaluated by Adams at KAPL
  - Axial groove in a pipe (K_T=3) with mechanical and thermal loading
  - Taper location in a pipe (K_T= 1.6)

Options Considered for Notches

- K_n is assumed to be constant and equal to 1.0; i.e. no additional notch strain factor over and above K_T
- Linear variation from 1.0 at S_n=3S_m and linear variation from 1.0 at S_n=3S_m to K_n at 3S_m<S_n<3S_m



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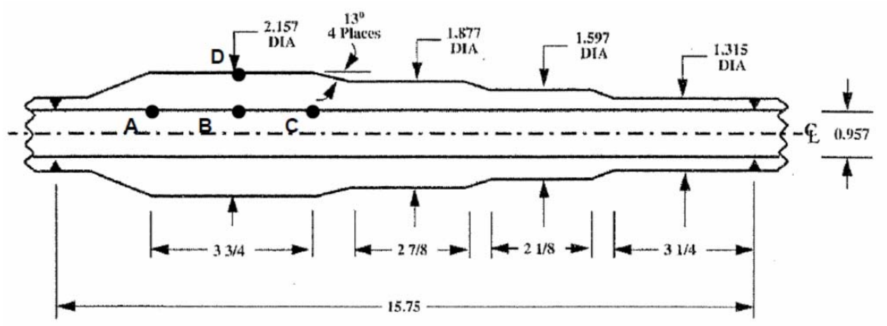
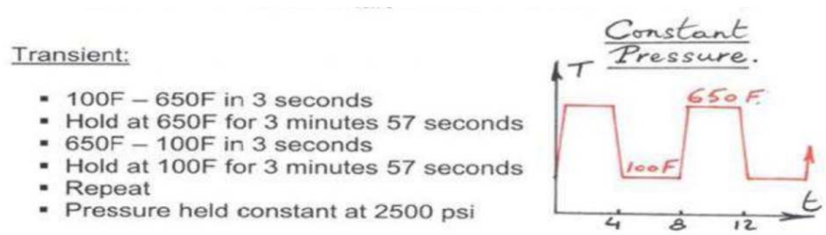
Example Problem: Bettis Stepped Pipe Test (SS)

- Test performed by Bettis to evaluate Environmental Fatigue effects in Piping
- Cycling from 100° to 650° F every four minutes; pressure held constant at 2500 psi
- Thermal analysis and elastic plastic stress analysis results published by Jones et al at Bettis (ASME PVP 2004-2748)



Thickness, inch	P+Q, ksi	Elastic Strain Amplitude, % (E=27E6 psi)	E-P analysis strain amplitude %	K_e based on Elastic Plastic analysis
0.6	147	0.54	0.815	1.50
0.46	137	0.51	0.735	1.45
0.32	120	0.44	0.675	1.52
0.179	79.8	0.30	0.37	1.25



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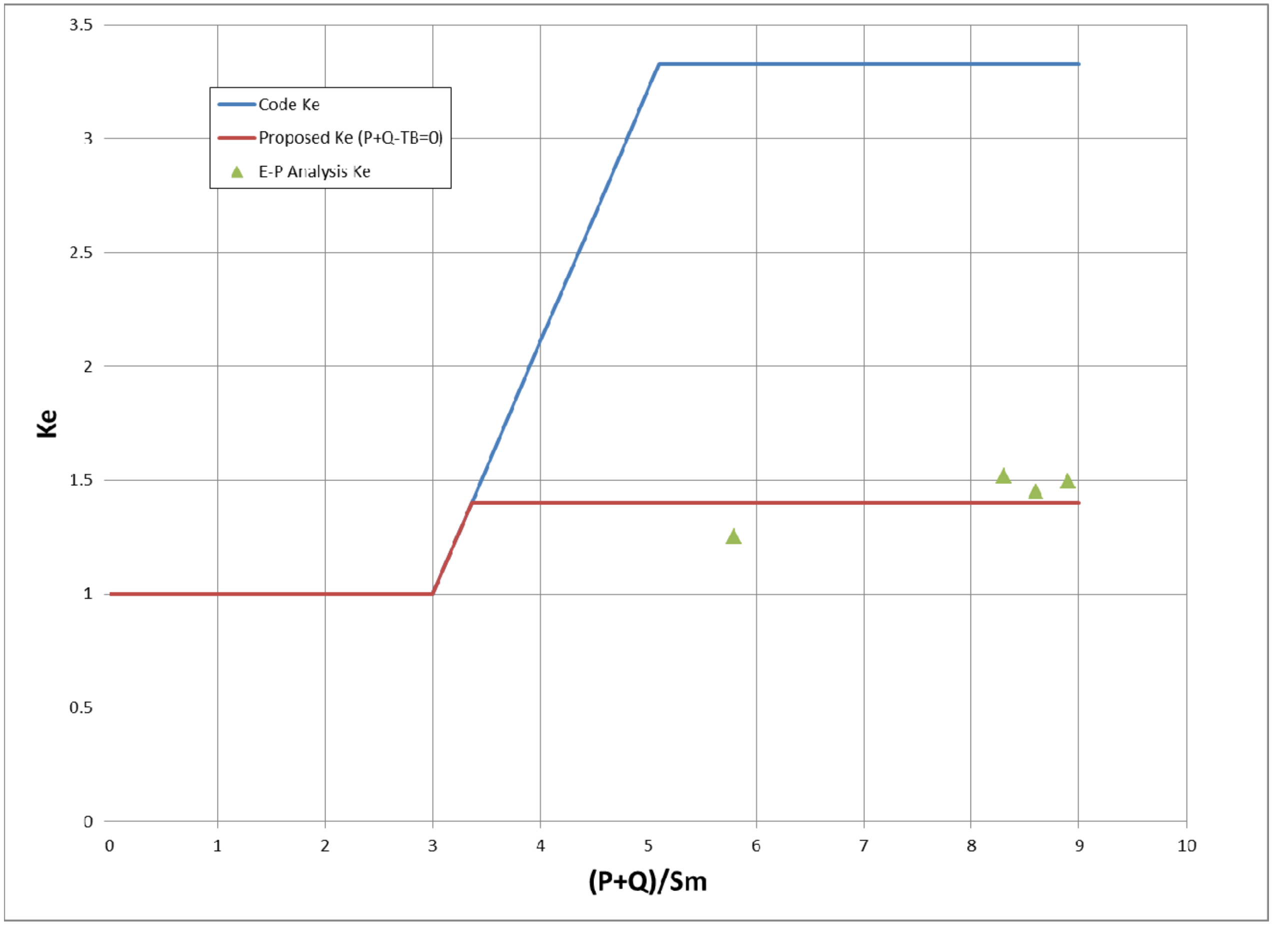
Ke Comparison: Elastic Plastic Analysis vs. Proposed K_e*



$$K_e^* = Lower\ of:$$

$$1.4\frac{TB}{S_n} + K_e\,\frac{P+Q-TB}{S_n} \text{ for } 3S_m \leq P + Q \leq 3mS_m \text{ or } K_e$$

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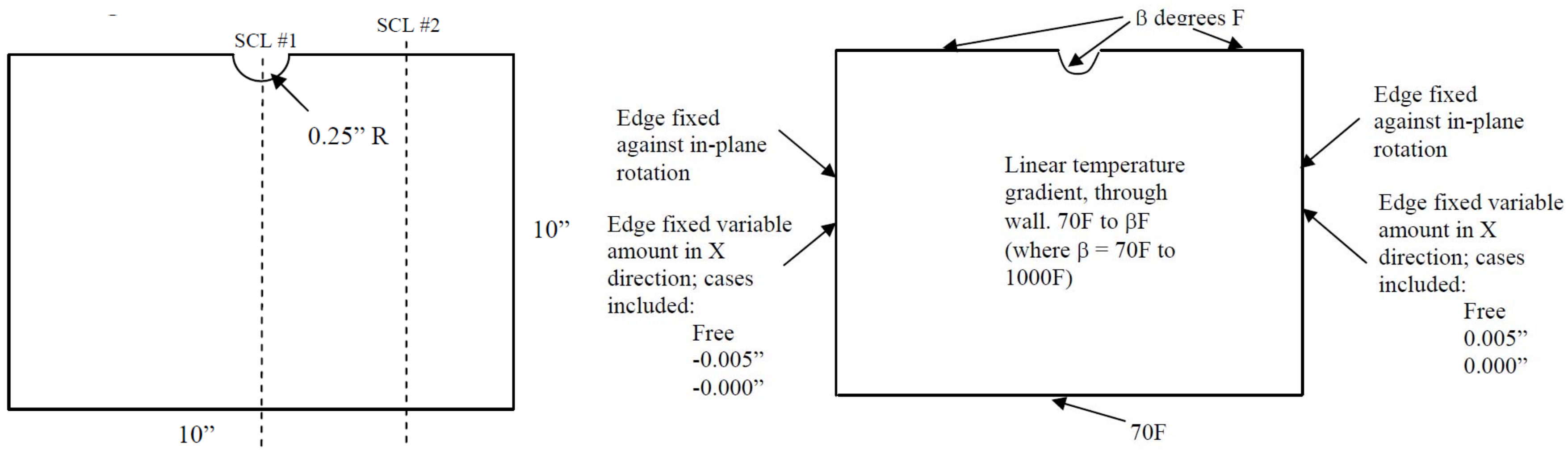
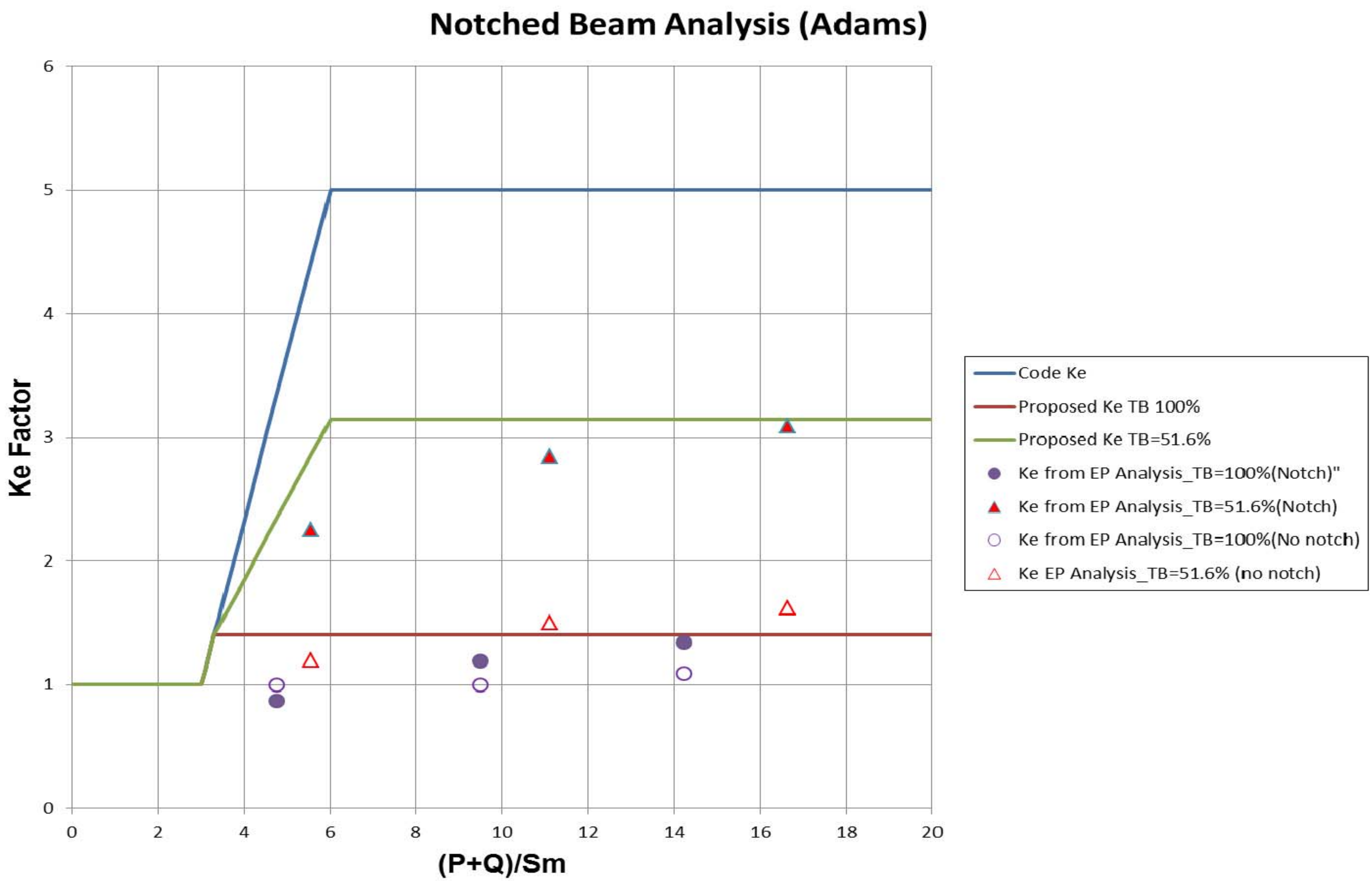
Notched Beam Example (Adams – KAPL)

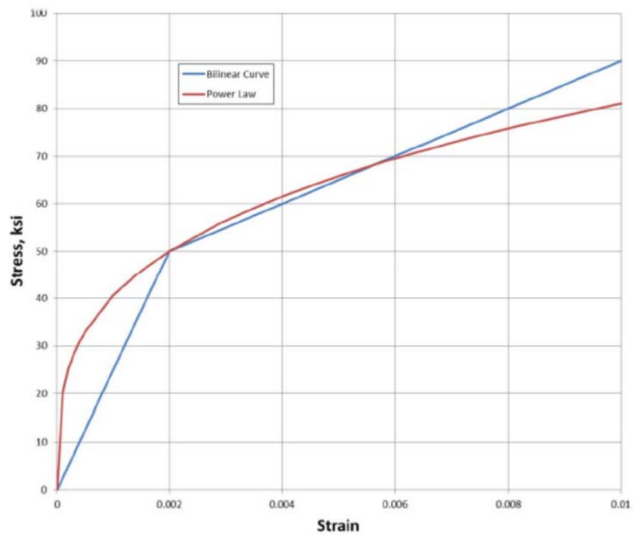


Low Alloy Steel Beam with Notch (K_T=2.9) subjected to Thermal Bending and Axial Loading

Notched Beam: Comparison with EP Analysis



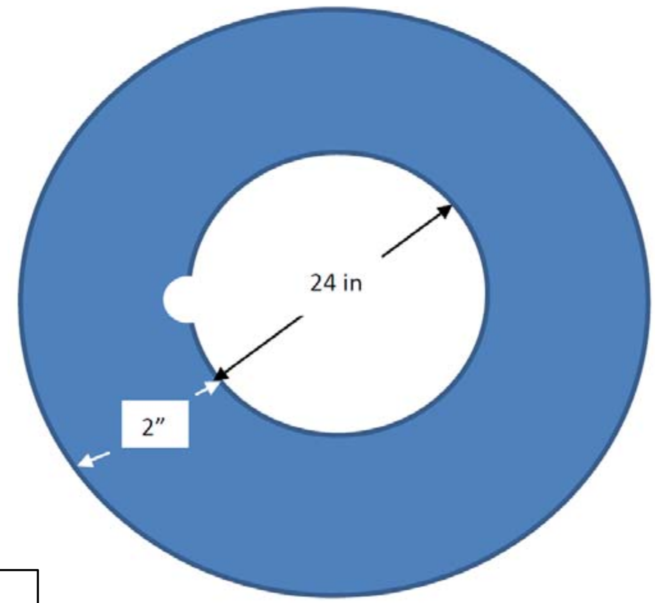
Example Problem: Axial Groove in a Pipe



Sy = 50 ksi (close to 3Sm at 550°F)

E=25x10^6 psi; Et=5x10^6 psi

Stainless Steel Pipe (K_T= 3)



E= 25E6 psi

α = 9E-6 /°F

Tref = 70°F

Pipe ID = 24 in.

Thickness = 2 in.

Axial semi-circular notch
¼ inch radius

Case 1: Pr=2000 psi; Metal To=550°F, Ti=100°F, ΔT=450°F

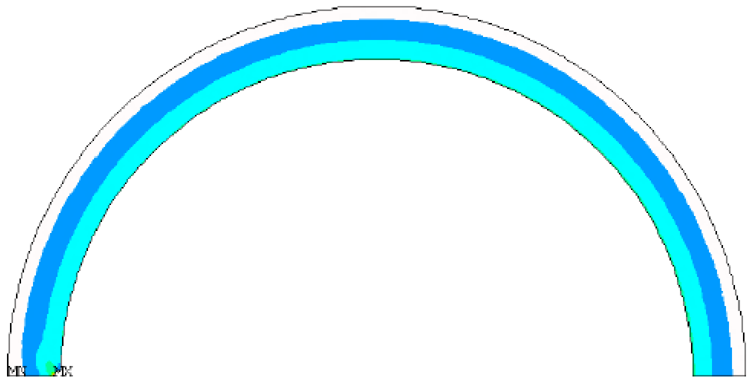
Case 2: Pr=1000 psi; Metal To=550°F, Ti=100°F, ΔT=450°F

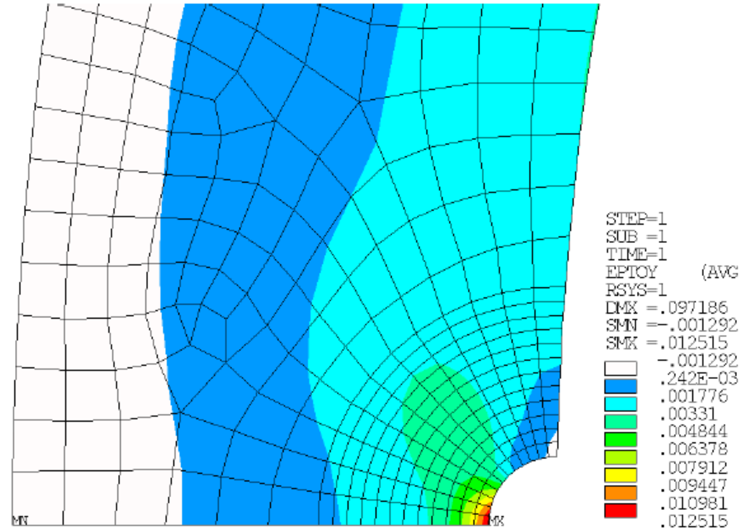
Case 3: Pr=2000 psi; Metal To=350°F, Ti=100°F, ΔT=250°F

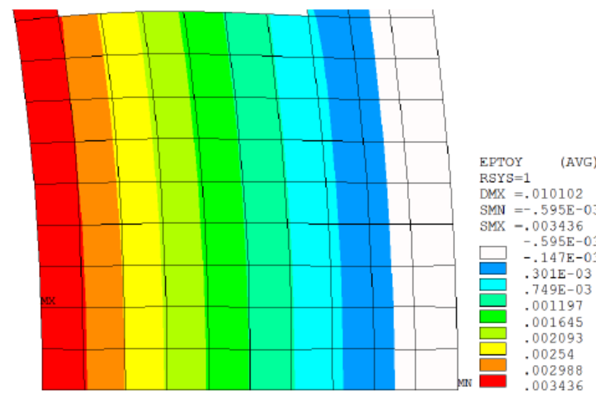
Case 4: Pr=0 psi; Metal To=550°F, Ti=100°F, ΔT=450°F

a) Elastic Analysis
b) Elastic-Plastic Analysis; Assume Bilinear stress strain curve, Kinematic hardening

Axial Groove Strain: Elastic Plastic Analysis







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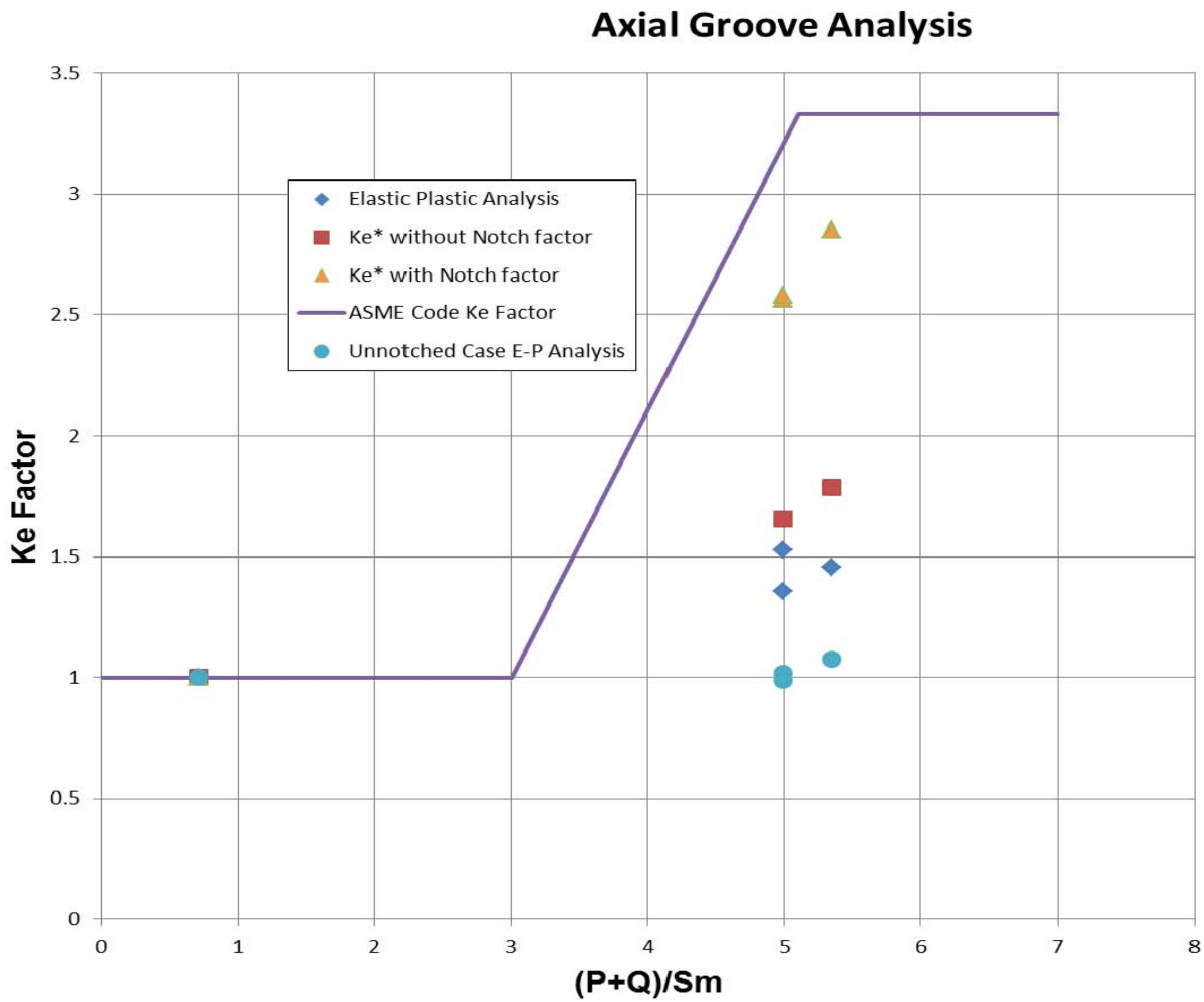
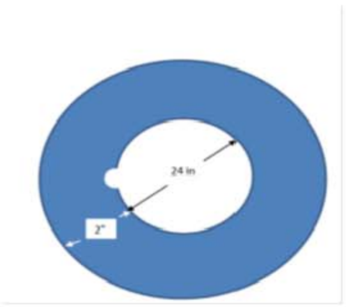
Axial Groove: Comparison with Elastic Plastic Analysis





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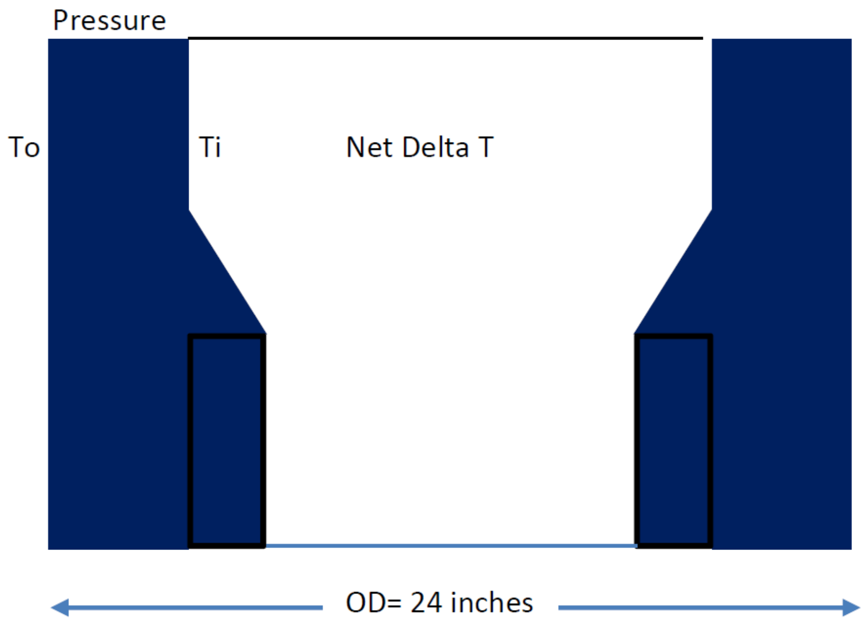
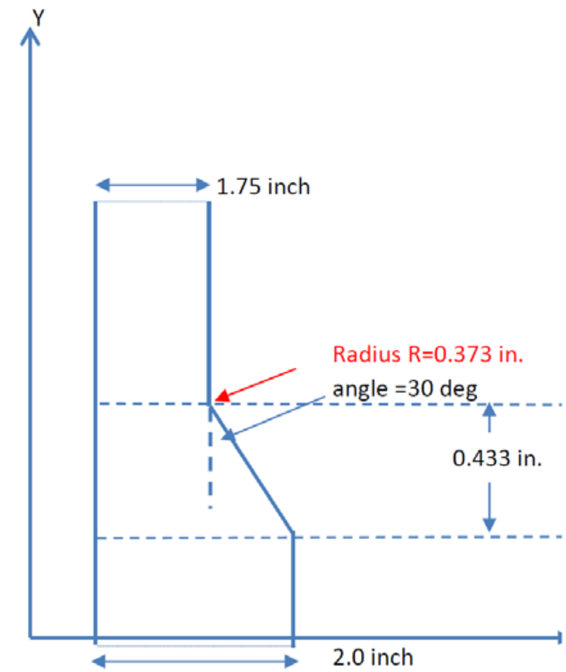
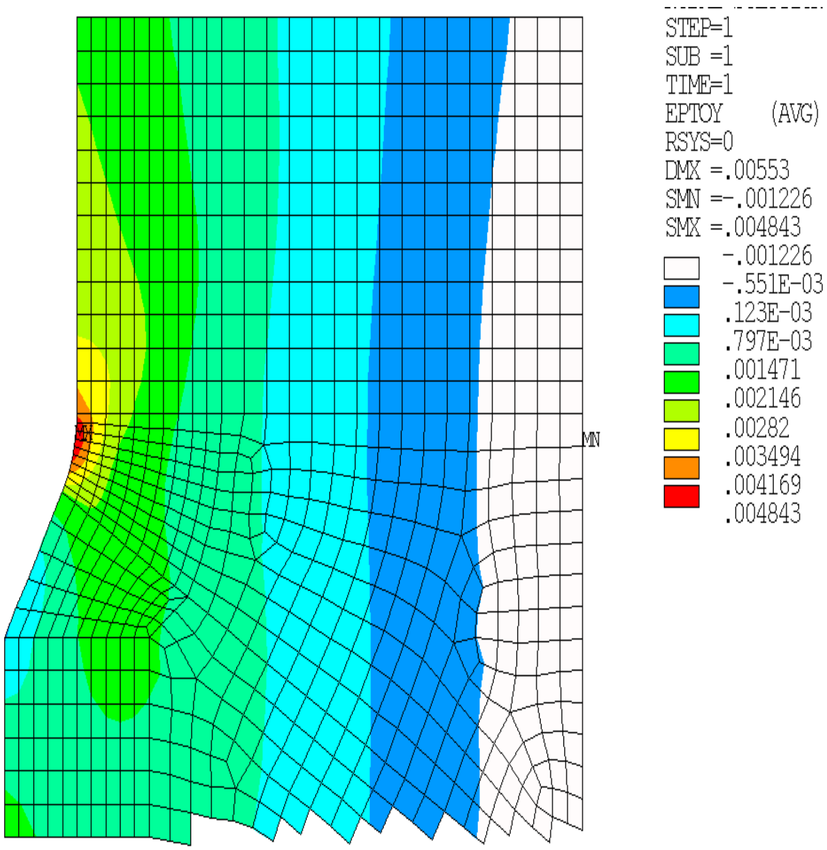
Example Problem: Tapered Shoulder in a Pipe

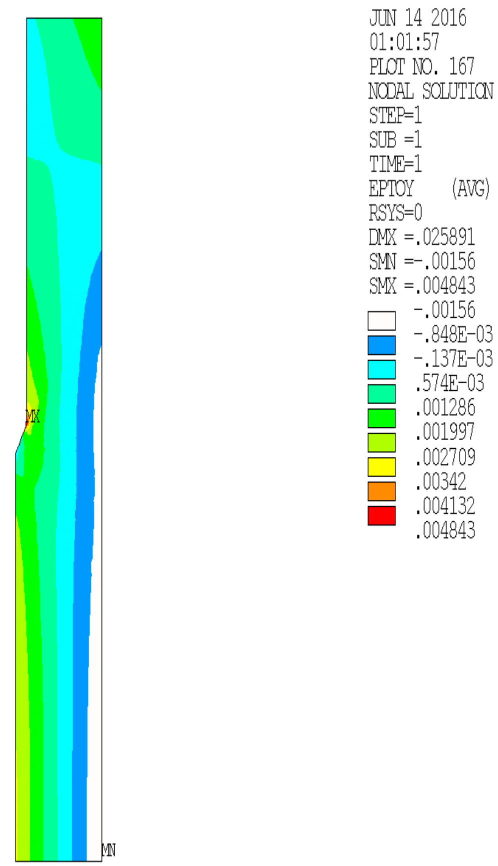




		Ti	Net Delta T	
Stainless steel stepped pipe				
Cases	Pressure	Ti	To	Delta T
	psi	Deg F	Deg F	Deg F
A	12000	100	550	450
B	18000	100	550	450
C	18000	100	400	300
D	12000	100	100	0

Tapered Shoulder in Pipe: Elastic Plastic Analysis





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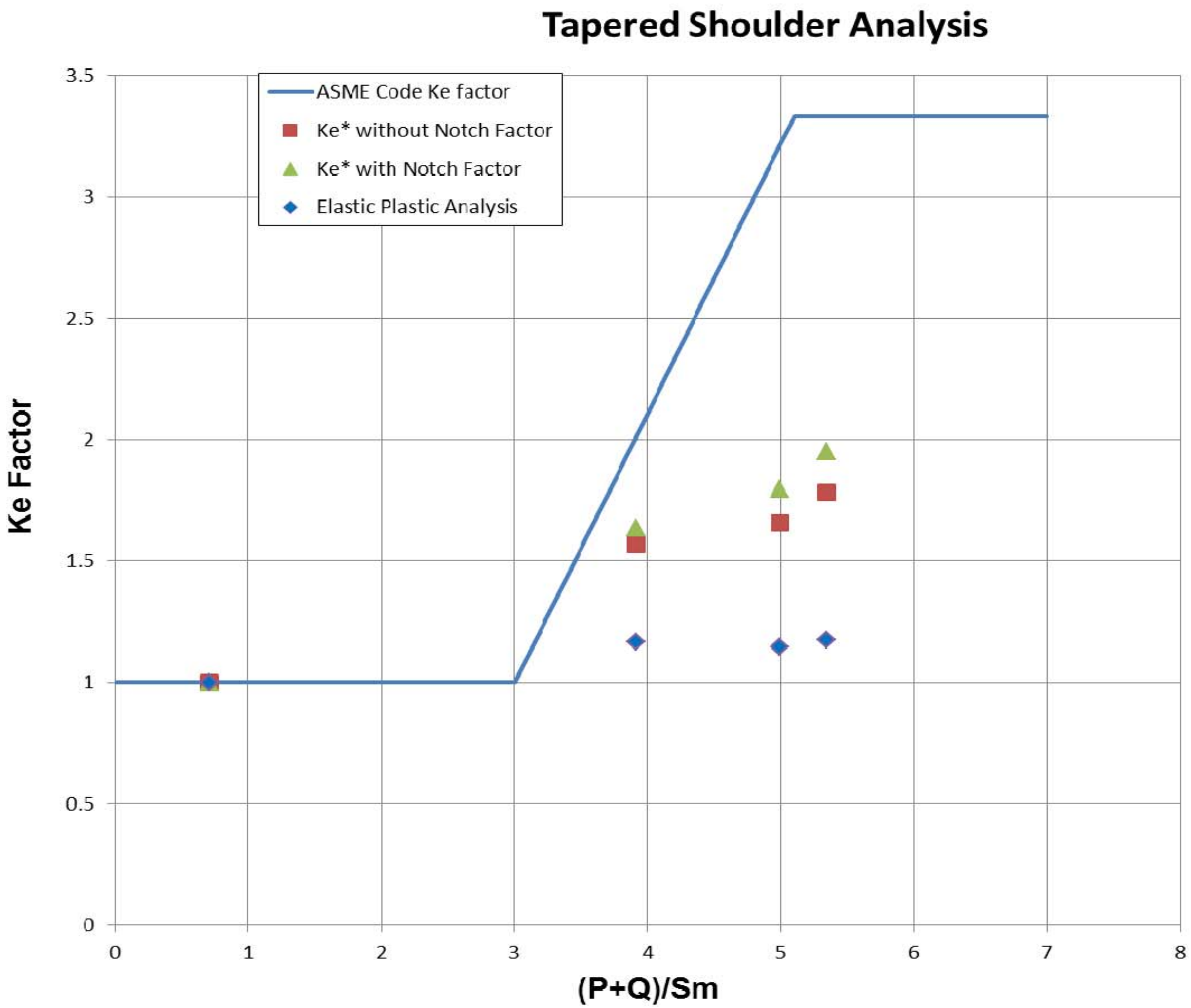
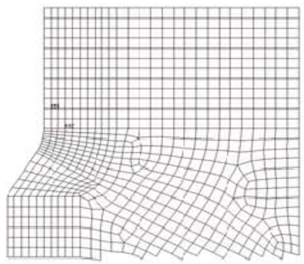
Tapered Shoulder: Comparison with Elastic Plastic Analysis





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Consideration of the Need for the Notch factor

- The EP analyses for the four example problems described here suggests that the $K_e{}^*$ equation (without the notch factor) proposed here bounds the results of the EP analysis for the cases described here.
- This suggests that no explicit K_n application is needed.
- There other justifications for not including the K_n factor:
  - Cyclic yield strength in in many materials (e.g. SS) is higher than $3S_m$
  - The theoretical stress concentration factor K_T is already included in the elastic analysis.
  - There are other conservatisms (e.g. K_ν of 1.4, use of the Code K_e for all other loads including mechanical and thermal membrane loading)

Recommendation: No K_n application

Summary and Recommendations

- The existing ASME Code simplified procedures for elastic plastic analysis have been shown to be overly conservative
- Several proposals have been made for modification of the ASME Code procedures but these proposals have been complicated and required new stress analyses
- A new proposal has been developed that:
  - Has been shown to be conservative relative to elastic-plastic analysis
  - Considers Poisson's ratio and elastic follow up (K_e) effects
  - Requires no new stress analysis
  - No application of Neuber notch factors over and above K_T
  - Has the potential to reduce CUF values
  - Will in most cases offset the need for elastic-plastic analyses

Next Step

- Submit a Code Case for consideration by the ASME Code

Proposed Code Case N-XXX

Alternative Rules for Simplified Elastic Plastic Analysis

Section III, Division 1

***Inquiry**:* What alternatives to NB-3228.5 in Section III, Subsection NB or NG-3228.5, Section III, Subsection NG, may be used for simplified elastic plastic analysis of components when the $3S_m$ limit on the range of primary plus secondary stress is exceeded?

Reply: It is the opinion of the committee that, as an alternative to NB-3228.5 in Section III, Subsection NB or NG-3228.5, Section III, Subsection NG, the $3S_m$ limit on the range of primary plus secondary stress intensity, P+Q, may be exceeded provided that the requirements of (a) through (c) below are met.

a) The range of primary plus secondary membrane plus bending stress intensity (P+Q), excluding thermal bending stresses (TB), shall be $\leq 3S_m$.

b) The value of S_a used for entering the design fatigue curve is multiplied by the factor K_e^*, where

$K_e^* = 1$ for $S_n \leq 3S_m$
= Smaller of K_e and $\{1.4(1-R) + K_e R)$ for $S_n \leq 3S_m \leq 3mS_m$
= $\{(1.4(1-R) + (1/n)R\}$ for $S_n \geq 3mS_m$

where R = (P+Q-TB)/(P+Q) and K_e, m and n are defined in NB-3228.5 or NG-3228.5 of Section III Subsection NB or NG respectively

c) The requirements of (c) through (f) of NB-3228.5 or NG-3228.5 are met

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