Alternative Approaches for ASME Code Simplified Elastic-Plastic Analysis

Sam Ranganath
XGEN engineering

Gary Stevens

EPRI

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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 and can make 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 Power Operation (load-following) 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 and EAF has not been 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 Fen factors in RG 1.207 are consistent with test data, they still do not reflect the good EAF field performance.

Background (cont.)

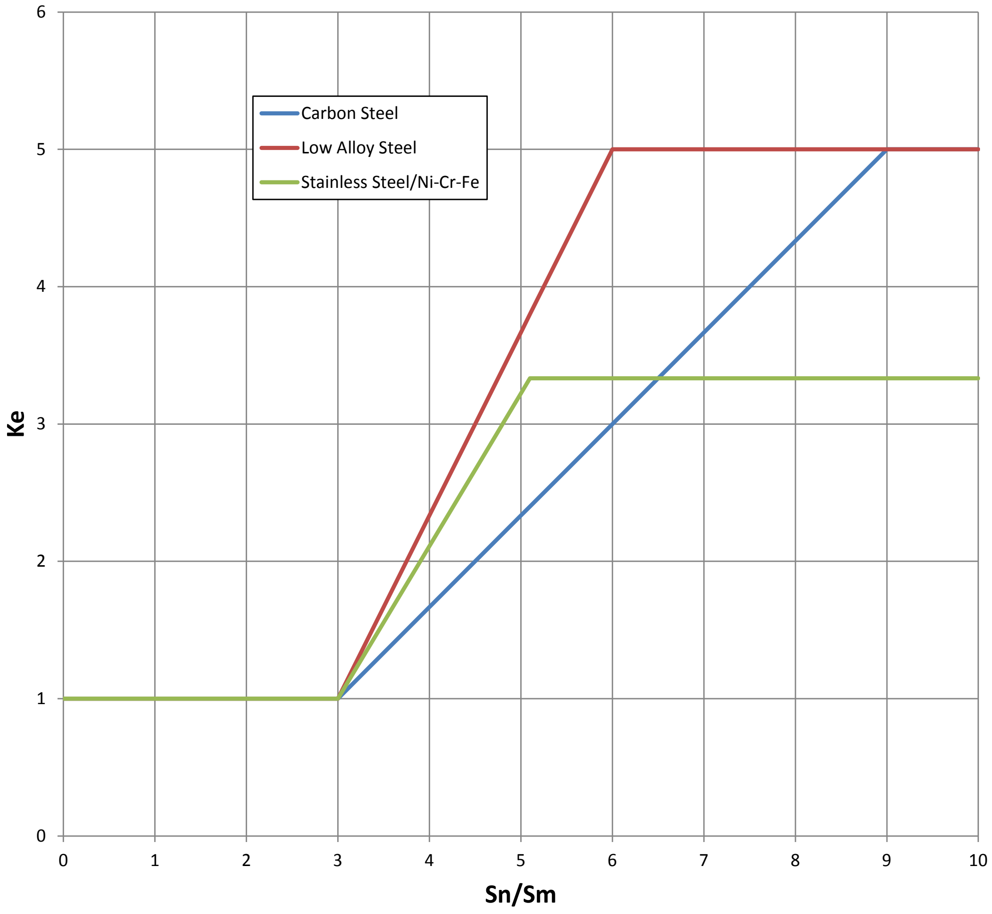
- One way of addressing the EAF problem is to examine the original CUF (without Fen) which may be over-conservative
  - Justify a lower CUF in the original analysis so that the fatigue usage multiplied by F_{en} is still acceptable.
- The use of the ASME Code simplified elastic-plastic analysis (NB-3228.5 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 rules for the Code simplified elastic plastic analysis.

Current Code K_e Equation

- $$\begin{aligned} K_e &= 1 \quad \text{for } S_n \leq 3S_m \\ &= 1 + \frac{(1-n)}{n(m-1)}\left\{\frac{S_n}{3S_m} - 1\right\} \quad \text{for } 3S_m \leq S_n \leq 3mS_m \\ &= 1/n \qquad \text{for } S_n \geq 3mS_m \end{aligned}$$

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

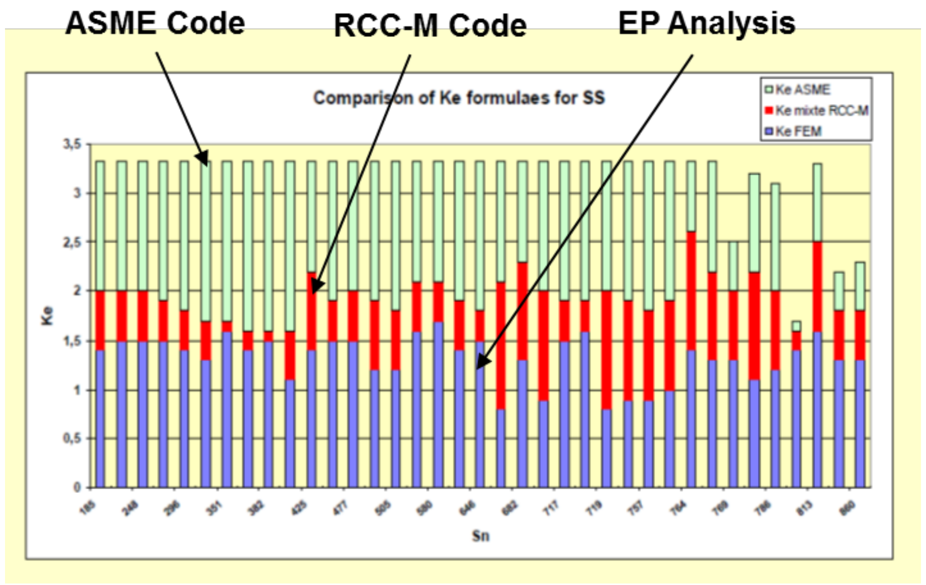
- Comparison with the results from elastic plastic analysis show the conservatism in the Code K_e value
- A new approach that preserves the simplicity of the Code approach, but results in a more realistic CUF value is needed

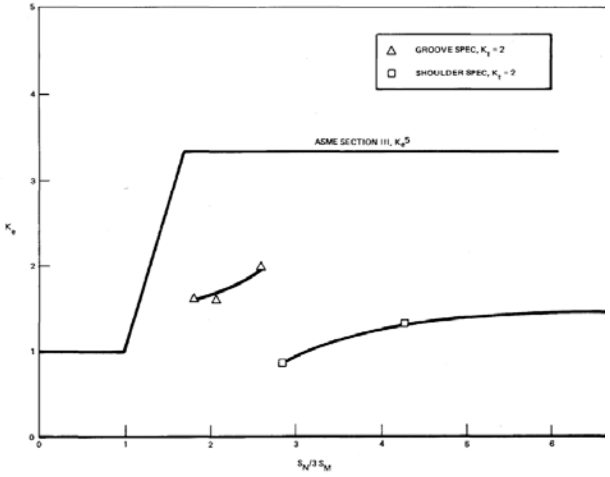


Conservatism in the Code K_e –Analysis and Test Data

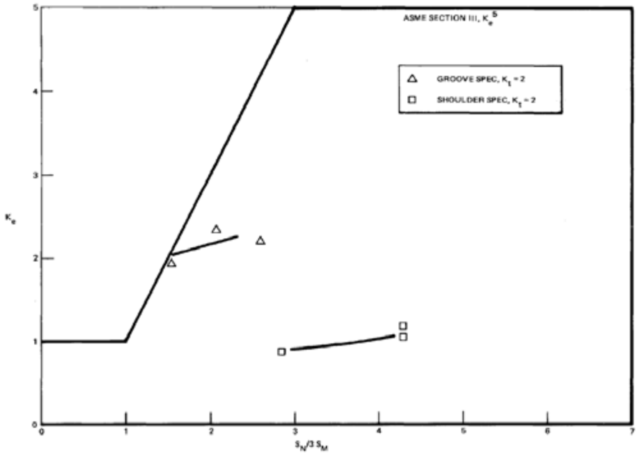
- Comparison of the Code K_e value with the results of elastic-plastic analysis show that the Code value is conservative by a factor of two or higher.
- The higher Code K_e can result in an overestimate of 20-100 in fatigue usage.
- More realistic Code K_e factors can be significant in addressing license renewal and RG 1.207 EAF challenges
- Tests[1] have also been done on notched carbon steel and stainless steel specimens in air to compare the Code K_e with test data
- Results confirm that the Code K_e values are conservative by factors well in excess of 2

[1] 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





Stainless Steel



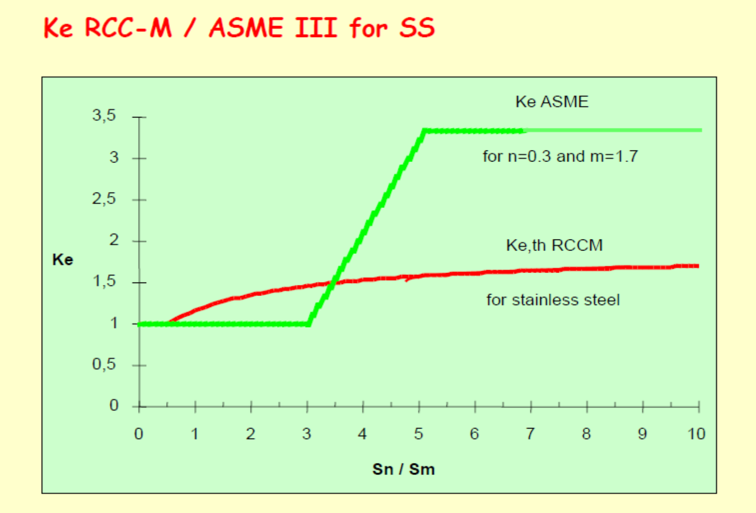
Carbon Steel

K_e Formulation in WRC-361

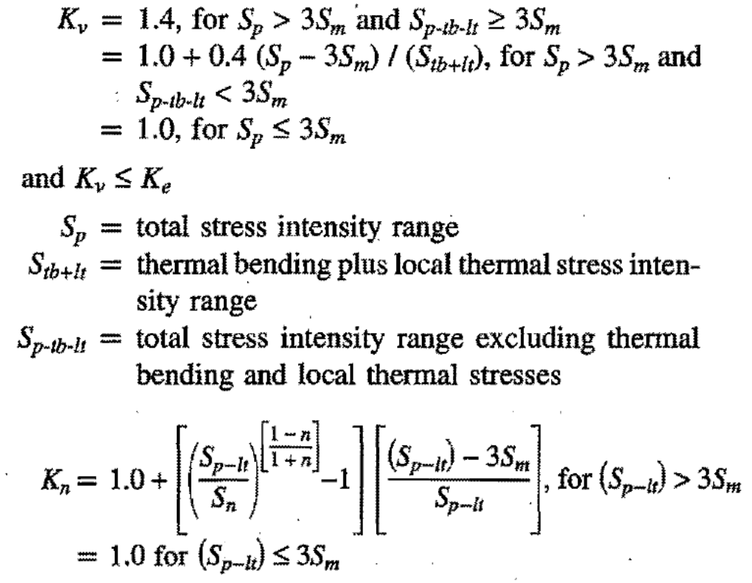
- WRC-361 was one of the first efforts to examine the NB-3228.5 Code rules and offered alternate methods to determine K_e
- The K_e formulation in WRC-361 considers the following:
  - Effect of Poisson's ratio during plastic behavior. This is addressed by developing an equivalent $\nu{*}=0.5-\frac{E_S}{E}(0.5-\nu)$ 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 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.

Other Available Options for Ke Analysis

- New elastic plastic analysis is an option
- There are Codes that reduce the conservatism in the ASME Code; some based on WRC-361 concepts
  - French, British and Japanese Codes
  - The RCC-M code includes the K_ν factor (Poisson's ratio effect). K_n (Neuber notch) is included in RCC-MR for high temperature reactors but not in RCC-M (for PWRs).
    - ASME Code Case N-779
- Some disadvantages:
  - $S_p{}^{mech}$ and $S_p{}^{ther}$ are new stress terms that need new stress analysis
  - Ke correction even below $3S_m$
  - Potential Discontinuity in K_e at $3S_m$
  - N-779 difficult to apply, especially for piping components
- Need for simple model that does not require new stress analysis and retains the simplicity of the current code but without the excessive conservatism.



CC N-779



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

and $K_\nu \leq K_e$

S_p = total stress intensity range

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

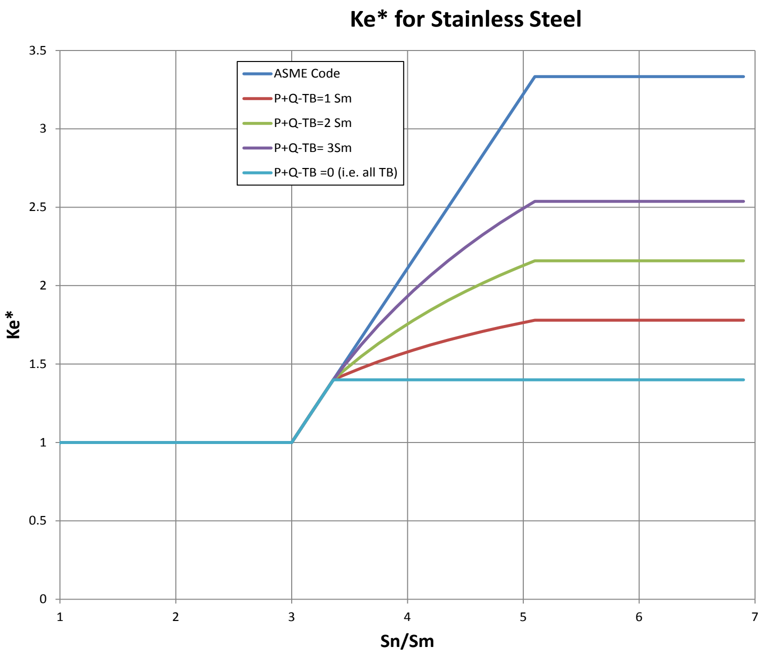
$S_{p\text{-}tb\text{-}lt}$ = total stress intensity range excluding thermal bending and local thermal stresses

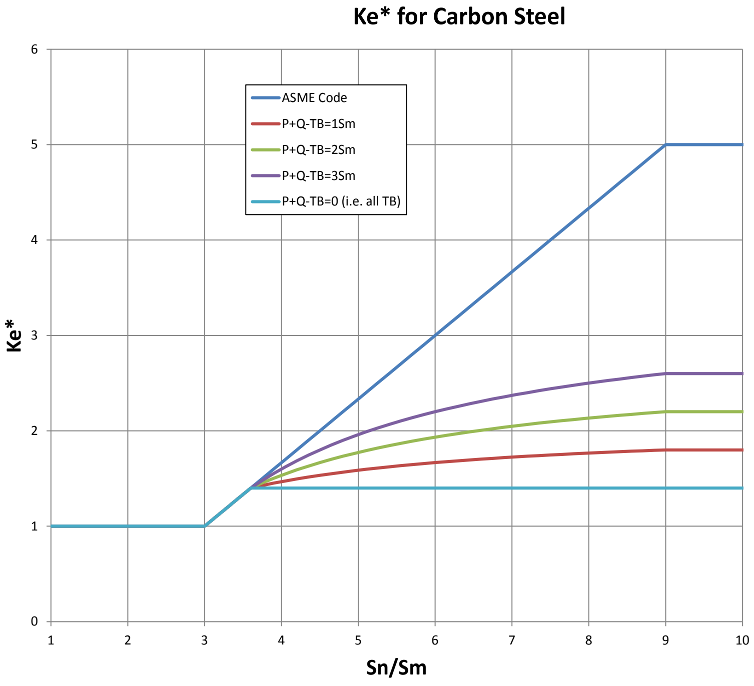
$$K_n = 1.0 + \left[\left(\frac{S_{p-lt}}{S_n}\right)^{\left[\frac{1-n}{1+n}\right]} - 1\right]\left[\frac{(S_{p-lt}) - 3S_m}{S_{p-lt}}\right], \text{ for } (S_{p-lt}) > 3S_m$$
$$= 1.0 \text{ for } (S_{p-lt}) \leq 3S_m$$

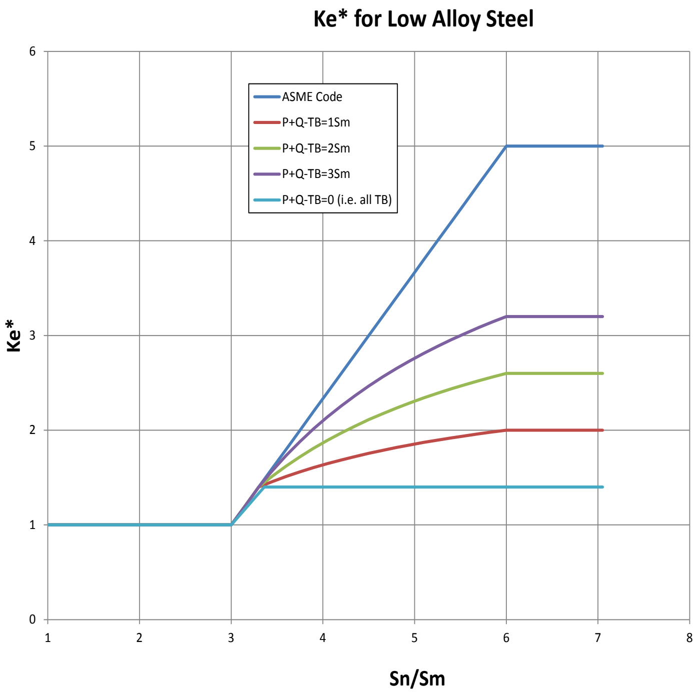
Proposed New K_e Formulation (NB-3200 and NG-3200)

- Follows the WRC-361 method of using a weighted average approach for the thermal and mechanical load stresses
  - $K_e{}^{*} = \left(K_\nu \frac{S_{n\,therm}}{S_n} + K_e \frac{S_{n\,mech}}{S_n}\right) K_n$
    - $S_{n\,mech}$ = Mechanical load: P+Q-Thermal Bending
    - $S_{n\,therm}$ = Thermal Load: Thermal Bending (TB)
    - K_n = Neuber notch factor = $K_T{}^{(1-n)/(1+n)}$
  - K_ν is conservatively assumed to be 1.4 (corresponding to v=0.3)
  - $K_e{}^{*} = (1.4(1-R) + K_e R)K_n$ for $3S_m \leq P + Q \leq 3mS_m$; $R = \frac{P+Q-TB}{S_n}$, but not higher than Ke.
  - Eliminates potential for a discontinuity at $S_n = 3S_m$
- The earlier proposal was to exclude the Neuber notch factor, $K_n = K_T{}^{(1-n)/(1+n)}$
  - Exclusion of K_n could be justified but Code members felt that this would result in too much reduction in conservatism. The proposal was revised to include the Neuber notch factor
- Vessels and Core Support structures (NB-3200 and NG-3200) are considered separately from Piping (NB-3600)

Proposed K_e* Factors for SS, CS and LAS (K_t=1)


Ke* for Stainless Steel


Ke* for Carbon Steel


Ke* for Low Alloy Steel

Consideration of Notch Effects

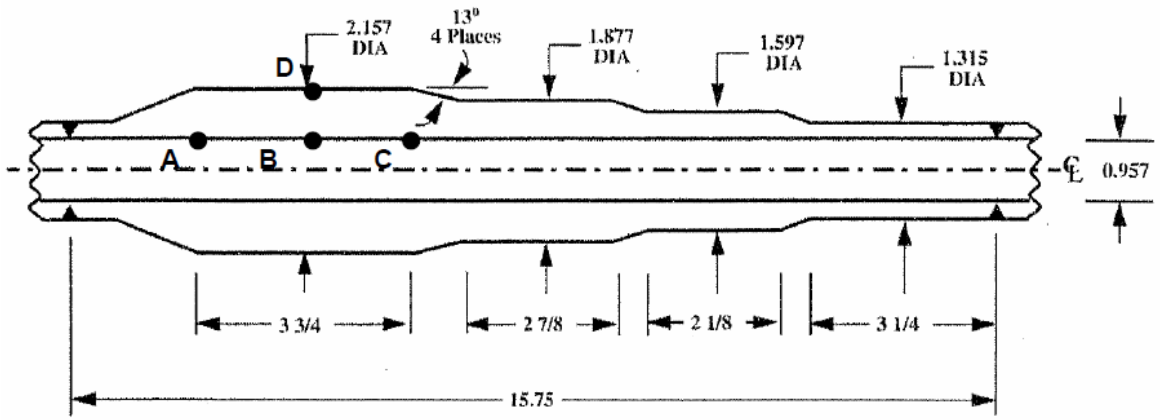
- WRC-361 recognizes Poisson’s ratio effects and elastic follow-up effects by using a weighted approach of thermal and mechanical stresses and multiplies it by a notch factor based on Neuber analysis.
- WRC-361 specifies a Notch factor (over and above the standard Kt factor used in elastic analysis)
  - 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)
- Since many Codes (e.g. RCC-M code) do not explicitly include the notch factor, example EP analysis is performed to determine the effect of the Neuber notch factor K_n.

Verification Problems for the Proposed K_e^*

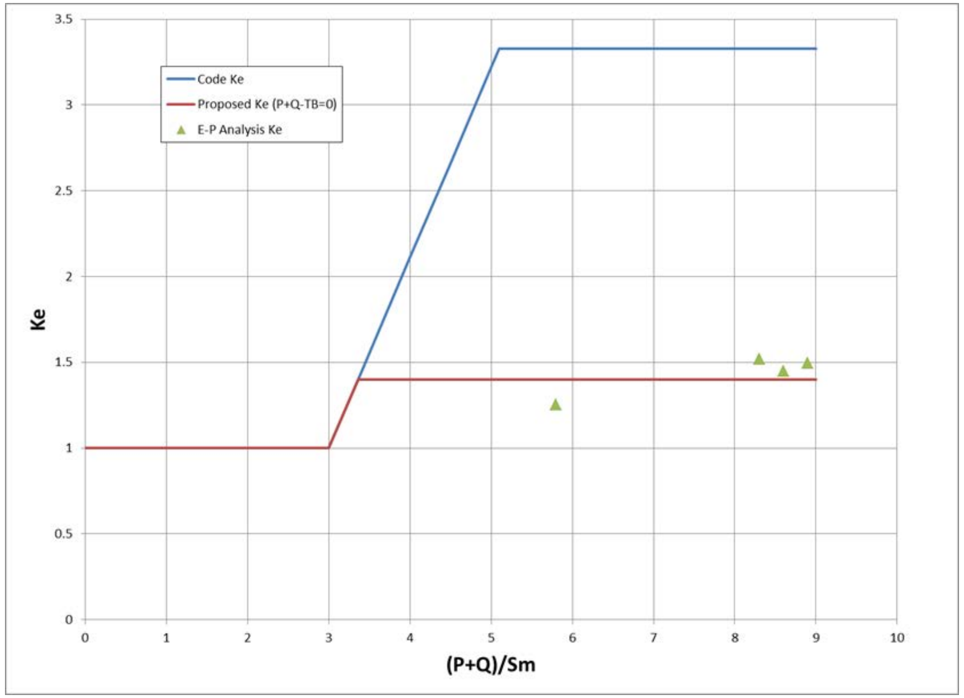
- The objective of the verification problems was twofold:
  - Compare the prediction of the K_e^* equation with the results of elastic plastic analysis for unnotched geometry
  - Determine the effect of additional notch factor K_n for the evaluation of components with stress concentration factor (SCF), 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) with mechanical and thermal loading

Example Problem: Bettis Stepped Pipe Test (SS)

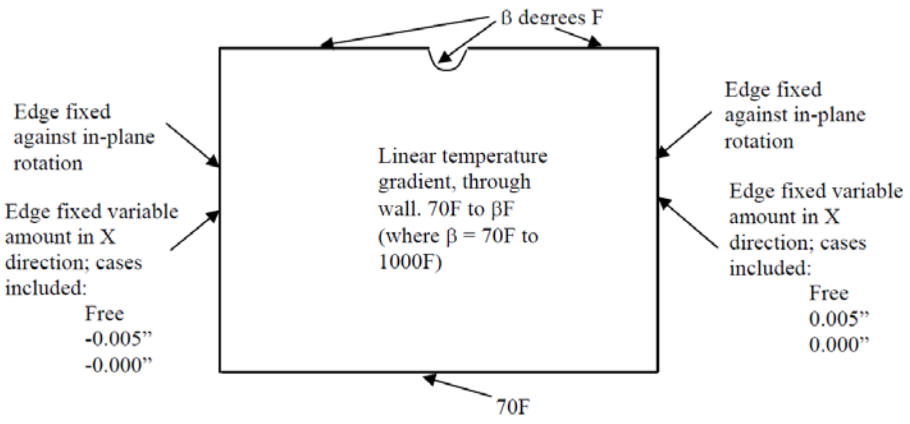
- Test performed by Bettis to evaluate Environmental Fatigue effects in Piping
- Cycling from 100° to 650° F every four minutes; pressure held constant at 2500 psi
- Thermal analysis and elastic plastic stress analysis results published by Jones et al at Bettis (ASME PVP 2004-2748)



Thickness, inch	P+Q, ksi	Elastic Strain Amplitude, %	E-P analysis strain amplitude %	Ke based on Elastic Plastic analysis
		(E=27E6 psi)		
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



Notched Beam Example (Adams – KAPL)



ß degrees F

Edge fixed against in-plane rotation

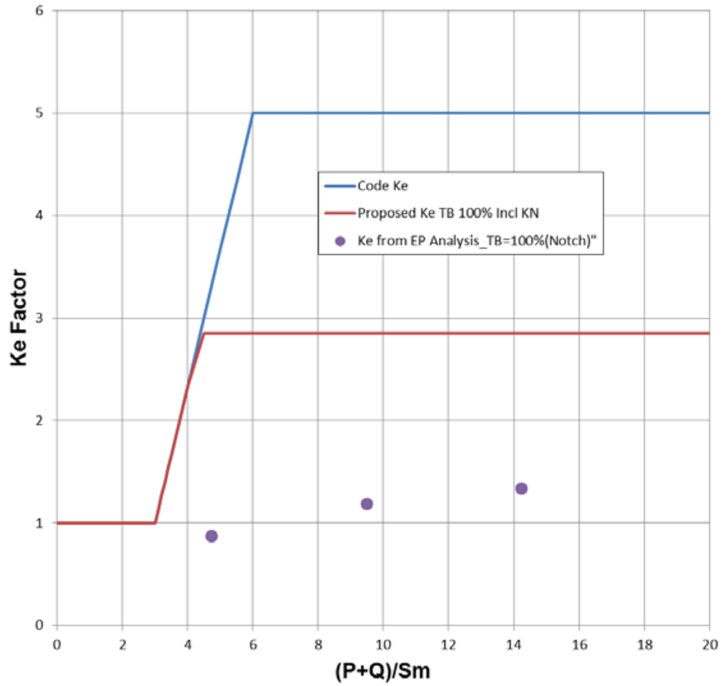
Edge fixed variable amount in X direction; cases included:
Free
-0.005”
-0.000”

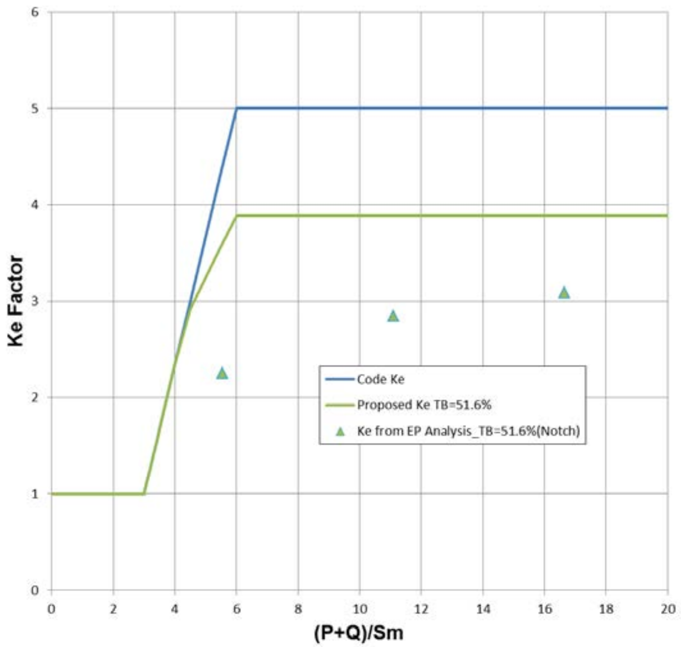
Linear temperature gradient, through wall. 70F to βF (where β = 70F to 1000F)

Edge fixed against in-plane rotation

Edge fixed variable amount in X direction; cases included:
Free
0.005”
0.000”

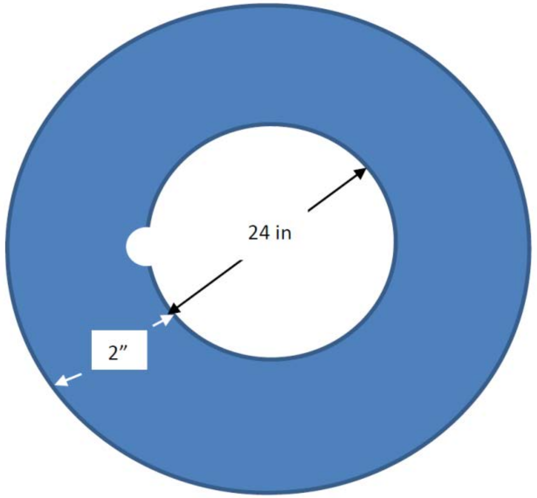
70F

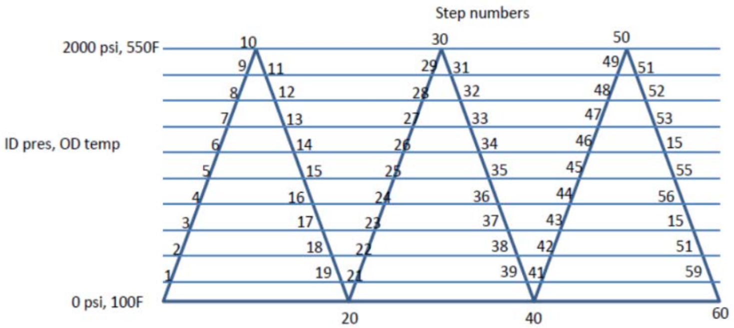




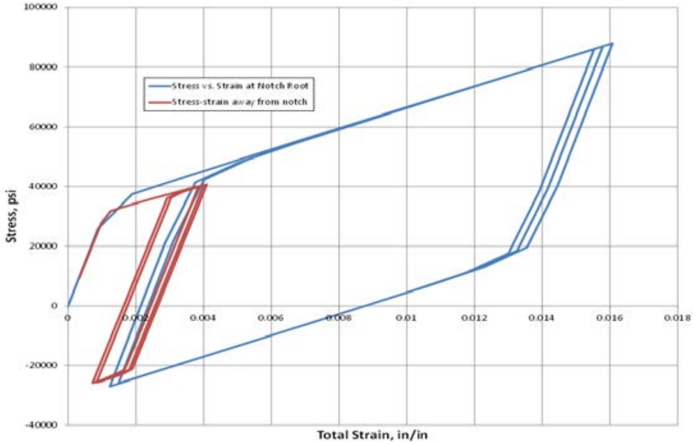
Low Alloy Steel Beam with Notch (Kt=2.9) subjected to Thermal Bending and Axial Loading

Axial Groove: Comparison with Elastic Plastic Analysis





Case	K_T	*P* psi (MPa)	ΔT °F (°C)	$(P+Q)/S_m$	K_e Code	K_e*	Elastic-Plastic Analysis	
							K_e No Notch	K_e Notch
1	2.78	2,000 (13.8)	450 (250)	5.09	3.32	2.57	1.00	1.62
2	2.78	2,000 (13.8)	400 (222.2)	4.62	2.79	2.49	1.00	1.59
3	2.78	2,000 (13.8)	350 (194.4)	4.14	2.26	2.40	1.00	1.54
4	2.78	2,000 (13.8)	300 (166.7)	3.66	1.74	2.27	1.00	1.47



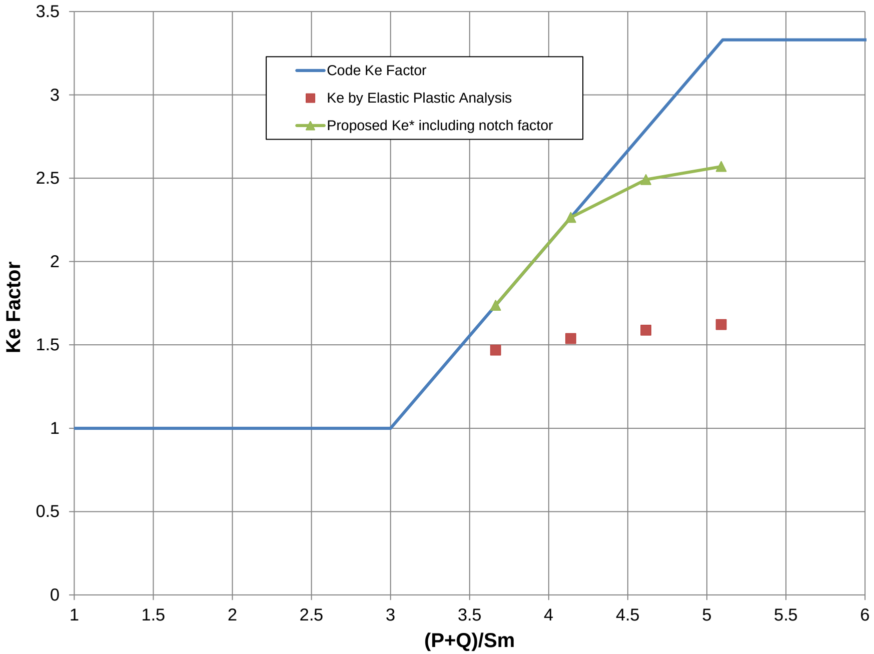
Case 1: Pr=2000 psi; Metal To=550°F, Ti=100°F, ΔT=450°F

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

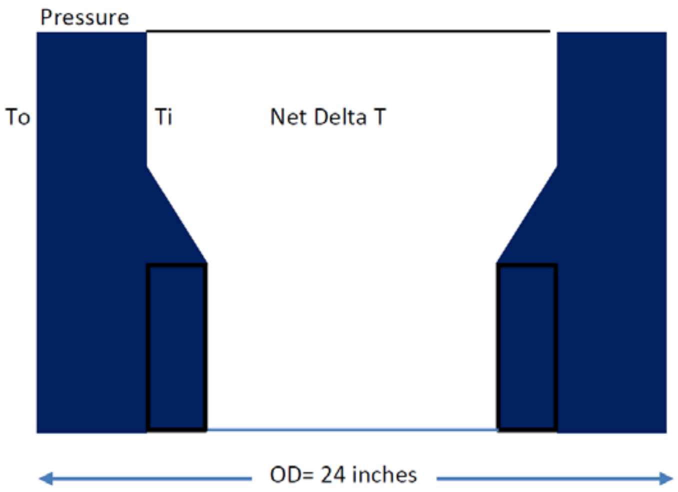
Case 3: Pr=2000 psi; Metal To=350°F, Ti=100°F, ΔT=250°F

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

Stainless Steel Pipe (Kt= 3)



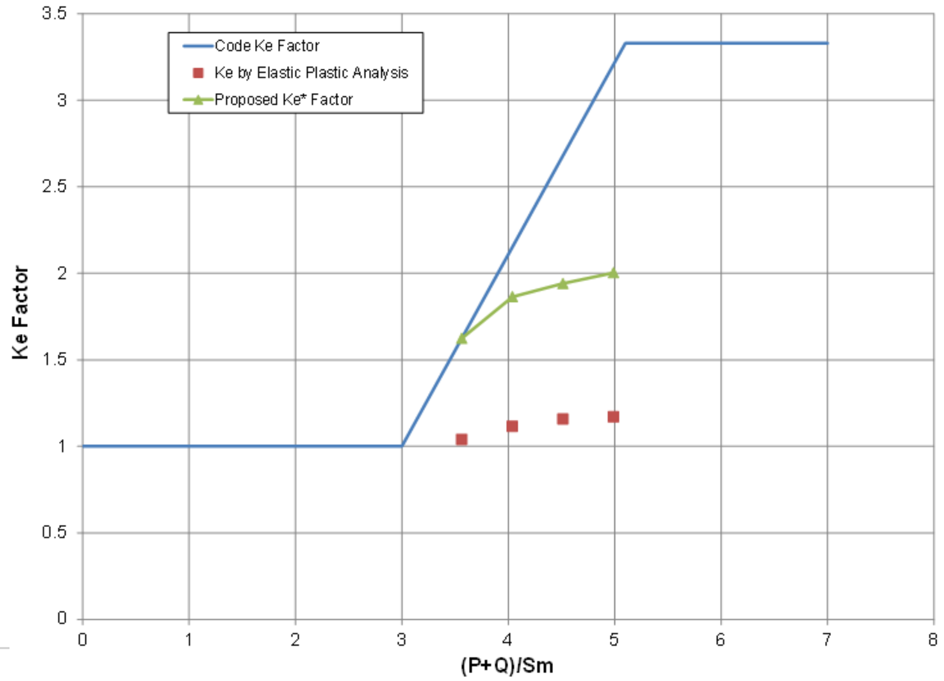
Tapered Shoulder: Comparison with Elastic Plastic Analysis



		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

Stainless Steel Pipe (K_t= 1.6)

Case	R	K_T	Stress, ksi (MPa)	ΔT °F (°C)	P+Q/S_m	K_e Code	K_e*	K_e by Elastic-Plastic Analysis
A	0.14	1.6	12 (82.7)	450 (250)	4.99	3.21	2.00	1.17
B	0.16	1.6	12 (82.7)	400 (222.2)	4.51	2.68	1.94	1.16
C	0.18	1.6	12 (82.7)	350 (194.4)	4.04	2.15	1.86	1.12
D	0.20	1.6	12 (82.7)	300 (166.7)	3.56	1.62	1.62	1.04



Conclusions from the NB-3200 (Vessel) Analysis

- The existing ASME Code simplified procedures for elastic plastic analysis have been shown to be overly conservative
- The new proposal for K_e*:
  - Reduces the conservatism in the existing ASME Code approach
  - Considers Poisson’s ratio and elastic follow up (K_ν and K_e) effects and includes Neuber notch factors over and above K_t
  - Requires no new stress analysis
  - Has the potential to significantly reduce CUF values
  - Will in most cases, show that even with the inclusion of the Fen factors in RG 1.207, acceptable fatigue usage can be demonstrated

Piping Analysis (NB-3600)

- The rules of NB-3200 can also be used for piping, but because of the large number of piping components and the high cost and time involved, this is not feasible.
- The preferred alternative is to use the equation in NB-3650 which includes:
  - Equation 9 of NB-3652 (primary stress limits),
  - Equation 10 of NB-3653.1 (primary plus secondary stress limits)
  - Equation 11 of NB-3653.2 (peak stress intensity range) for use in fatigue usage analysis
  - Equation 12 of NB-3653.6 (limits on stress due to thermal expansion and anchor movement)
  - Equation 13 of NB-3653.6 (limits on The primary plus secondary membrane plus bending stress intensity, excluding thermal bending and thermal expansion stresses
  - Equation 14 (alternating stress for use in fatigue analysis)
  - Thermal ratchet limit on ΔT as given in NB-3653.7
- A key difference between NB-3200 and NB-3600 is that the through thickness ΔT stress is classified as a peak stress for piping whereas it is secondary for the vessel
  - The ΔT stress is not included in the P+Q calculation and does not affect the Code K_e value
  - Consistent with this, the original proposal for K_e^* did not include the peak stress, but many Code members felt that this would lead to a reduction in the overall conservatism
  - As in the NB-3200 case, the members felt that the Neuber factor should also be included
  - The revised approach in this presentation includes the ΔT stress and the Neuber factor.

Proposed K_e^* for Piping (NB-3600)

Starting with the WRC-361 equation:

$$K_e^{\,*} = K_\nu \frac{S_{\text{n therm}}}{S_{\text{nV}}} + K_e \frac{S_{\text{n mech}}}{S_{\text{nV}}}$$

$$S_{\text{n therm}} = S_{\Delta T1} + \left(C_3 - C_3{}'\right)S_{\text{Ta}-\text{Tb}}\ ;\ \ S_{\Delta T1} = \frac{E\alpha\lfloor\Delta T1\rfloor}{2(1-\nu)}$$

$S_{\text{n mech}} = C_1 S_{\text{Pr}} + C_2 S_{\text{Mom}} + C_3{}' S_{\text{Ta}-\text{Tb}}$ = Eq. 13+Eq 12

$S_{\text{n,v}} = S_{\text{n,piping}} + S_{\Delta T1}$= Eq. 10 + $S_{\Delta T1}$

Expressing $K_e^{\,*}$ in terms of R and R_1:

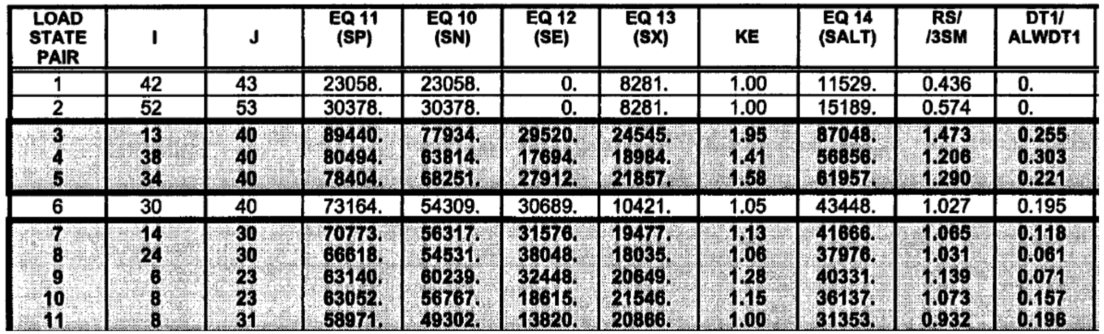
$$K_e^* = 1.4\,R_1 K_3^{\frac{1-n}{1+n}} + K_e R$$

where $R = \frac{Eq.13+Eq.12}{S_{n,piping}+S_{\Delta T1}}$ $R_1 = \frac{S_{\Delta T1}+(Eq.10-(Eq.13+Eq.12))}{Eq.10+S_{\Delta T1}}$ $S_{\Delta T1} = \frac{E\alpha\Delta T_1}{2(1-\nu)}$

E, α and ν are the Young’s Modulus, thermal expansion coefficient and Poisson’s ratio respectively

Example Problem for Piping-1

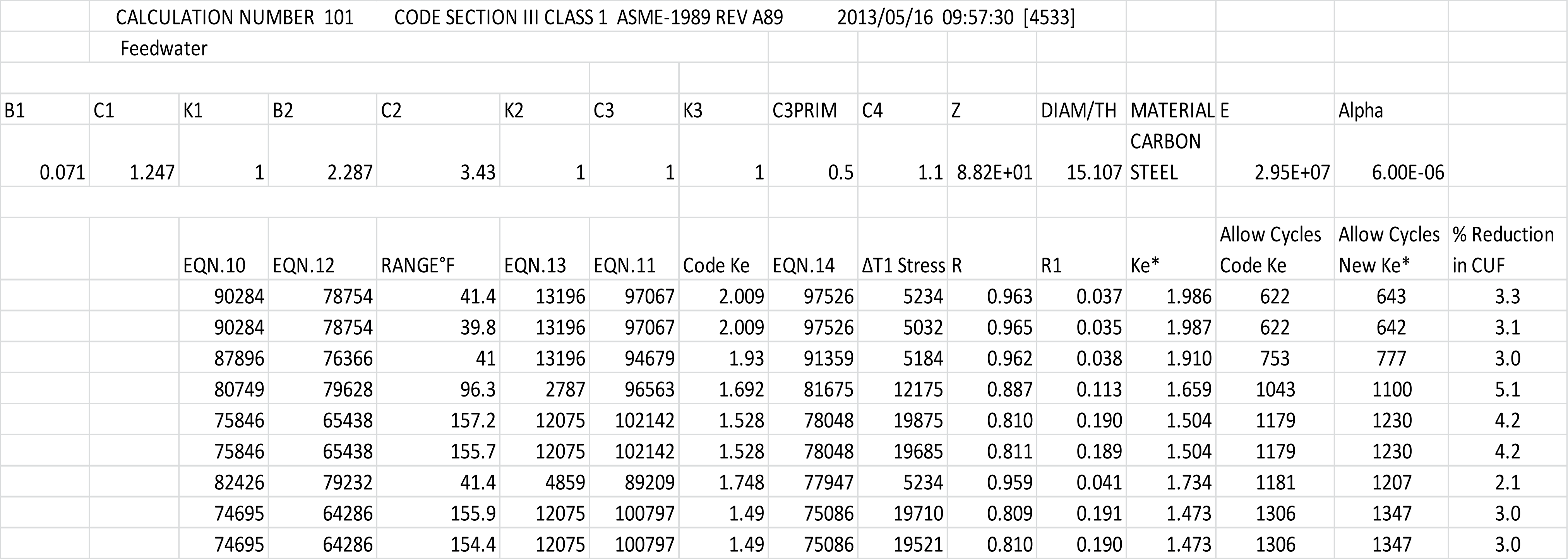
BWR FW Piping



LOAD STATE PAIR	I	J	EQ 11 (SP)	EQ 10 (SN)	EQ 12 (SE)	EQ 13 (SX)	KE	EQ 14 (SALT)	RS/ /3SM	DT1/ ALWDT1
1	42	43	23058.	23058.	0.	8281.	1.00	11529.	0.436	0.
2	52	53	30378.	30378.	0.	8281.	1.00	15189.	0.574	0.
3	13	40	89440.	77934.	29520.	24545.	1.95	87048.	1.473	0.255
4	38	40	80494.	63814.	17694.	18984.	1.41	56856.	1.206	0.303
5	34	40	78404.	68251.	27912.	21857.	1.58	61957.	1.290	0.221
6	30	40	73164.	54309.	30689.	10421.	1.05	43448.	1.027	0.195
7	14	30	70773.	56317.	31576.	19477.	1.13	41666.	1.065	0.118
8	24	30	66618.	54531.	38048.	18035.	1.06	37976.	1.031	0.061
9	6	23	63140.	60239.	32448.	20649.	1.28	40331.	1.139	0.071
10	8	23	63052.	56767.	18615.	21546.	1.15	36137.	1.073	0.157
11	8	31	58971.	49302.	13820.	20866.	1.00	31353.	0.932	0.196

Load Pair	Eq 10 Sn	Eq 11	Eq 12	Eq 13	Eq 14Salt	Ke Code	DT1	DT1 stress	New R	New R1	New Ke*	New Ke*/Ke	New cycles	Code cycles
3	78	89	29.5	24.5	87	1.95	205	28.6	0.507	0.5	1.68	0.86	1325	878
4	63.8	80.5	17.7	19	56.8	1.41	244	34.0	0.375	0.6	1.40	0.99	2968	2916
5	68.3	78.4	27.9	21.9	62	1.58	178	24.8	0.535	0.5	1.50	0.95	2632	2208
6	54.3	73.2	30.7	10.4	43.4	1.05	157	21.9	0.54	0.5	1.05	1.00	9582	9582
7	56.3	70.8	31.6	19.5	41.7	1.13	95	13.2	0.735	0.3	1.13	1.00	8611	8611
8	54.5	66.6	38	18	38	1.06	49	6.8	0.913	0.1	1.06	1.00	12818	12818
9	60.2	63.1	32.4	20.6	40.3	1.28	57	8.0	0.778	0.2	1.28	1.00	8418	8418
10	56.8	63.1	18.6	21.6	36.1	1.15	126	17.6	0.54	0.5	1.15	1.00	11780	11780

Example Problem for Piping-2



	CALCULATION NUMBER 101 CODE SECTION III CLASS 1 ASME-1989 REV A89 2013/05/16 09:57:30 [4533]														
	Feedwater														
B1	C1	K1	B2	C2	K2	C3	K3	C3PRIM	C4	Z	DIAM/TH	MATERIAL	E	Alpha	
0.071	1.247	1	2.287	3.43	1	1	1	0.5	1.1	8.82E+01	15.107	CARBON STEEL	2.95E+07	6.00E-06	
		EQN.10	EQN.12	RANGE°F	EQN.13	EQN.11	Code Ke	EQN.14	ΔT1 Stress	R	R1	Ke*	Allow Cycles Code Ke	Allow Cycles New Ke*	% Reduction in CUF
		90284	78754	41.4	13196	97067	2.009	97526	5234	0.963	0.037	1.986	622	643	3.3
		90284	78754	39.8	13196	97067	2.009	97526	5032	0.965	0.035	1.987	622	642	3.1
		87896	76366	41	13196	94679	1.93	91359	5184	0.962	0.038	1.910	753	777	3.0
		80749	79628	96.3	2787	96563	1.692	81675	12175	0.887	0.113	1.659	1043	1100	5.1
		75846	65438	157.2	12075	102142	1.528	78048	19875	0.810	0.190	1.504	1179	1230	4.2
		75846	65438	155.7	12075	102142	1.528	78048	19685	0.811	0.189	1.504	1179	1230	4.2
		82426	79232	41.4	4859	89209	1.748	77947	5234	0.959	0.041	1.734	1181	1207	2.1
		74695	64286	155.9	12075	100797	1.49	75086	19710	0.809	0.191	1.473	1306	1347	3.0
		74695	64286	154.4	12075	100797	1.49	75086	19521	0.810	0.190	1.473	1306	1347	3.0

- **Extent of Benefit varies from case to case**
- **Modest reduction in K_e with some reduction in fatigue usage (adding the ΔT stress and the Neuber factor limits the potential benefit). The proposal is still conservative**
- **All the information needed to calculate K_e^* is available in piping stress reports; no new analysis is needed**

Summary of Revised Code Case

For Vessels and Core Support Structures

$$K_e^* = 1 \quad \text{for } S_n \le 3S_m$$

$$= \text{Smaller of } K_e \text{ and } \left\{1.4(1-R)K_T^{\frac{1-n}{n+1}} + K_e\,R\right\} \text{ for } 3S_m \le S_n < 3mS_m$$

$$= \text{Smaller of } \; 1/n \text{ and } \left\{1.4(1-R)K_T^{\frac{1-n}{n+1}} + K_e R\right\} \text{ for } S_n \ge 3mS_m$$

$$R = \frac{(Sn - TB)}{Sn}$$

$$S_{\text{alt}} = K_e^*\,S_p/2$$

For Piping Components

$$K_e^* = 1 \quad \text{for } S_n \le 3S_m$$

$$= \text{Smaller of } K_e \text{ and } \left\{1.4R_1K_3^{\frac{1-n}{n+1}} + K_e\,R\right\} \text{ for } 3S_m \le S_n < 3mS_m$$

$$= \text{Smaller of } \; 1/n \text{ and } \left\{1.4R_1K_3^{\frac{1-n}{n+1}} + K_e\,R\right\} \text{ for } S_n \ge 3mS_m$$

$$S_{\Delta T1} = \frac{C_3 E\alpha|\Delta T_1|}{2(1-\nu)}$$

$$R = \frac{Eq.13 + Eq.12}{Eq.10 + S_{\Delta T1}}$$

$$R_1 = \frac{S_{\Delta T1} + Eq.10 - (Eq.13 + Eq.12)}{Eq.10 + S_{\Delta T1}}$$

$$S_{\text{alt}} = K_e^*\,S_p/2$$

Status of the Proposed Code Case

- The code case (especially the piping part) has been discussed extensively in several WG-Piping meetings and most of the important comments have been addressed
- Technical basis document and the revised Code Case have been completed. They will be uploaded to the ASME code web site with the expectation of a letter ballot by the November meeting at Atlanta
  - Voting by WG-Piping, WG-Design Methodology and WG-Core Support Structures and subsequently by SG-Component Design and SG-Design Methodology

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