Using Component Test Data to Assist in Establishing Code Criteria to Achieve the Desired Seismic Capacity Margin (EPRI and Japanese Test Data)

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Seismic Capacity Margin R_{CP}

$$R_{CP} = F_S F_{NL} F_{Red}$$

F_S = Strength Margin

F_{NL} = Nonlinear Dynamic Margin

F_{Red} = Redundancy Margin

$$R_{CP_{1\%}} = F_{S_{1\%}} (F_{NL} F_{Red})_{cons.}$$

Goal

$$R_{CP_{1\%}} = 2.0$$

$$F_{S_{1\%}} = \frac{2.0}{(F_{NL} F_{Red})_{cons.}}$$

$(F_{NL} F_{Red})_{CONS.}$	$F_{S_{1\%}}$
1.33	1.5
1.5	1.33
1.8	1.1

Strength Margin F_S

- Can be directly estimated from component test data with minimum controversy

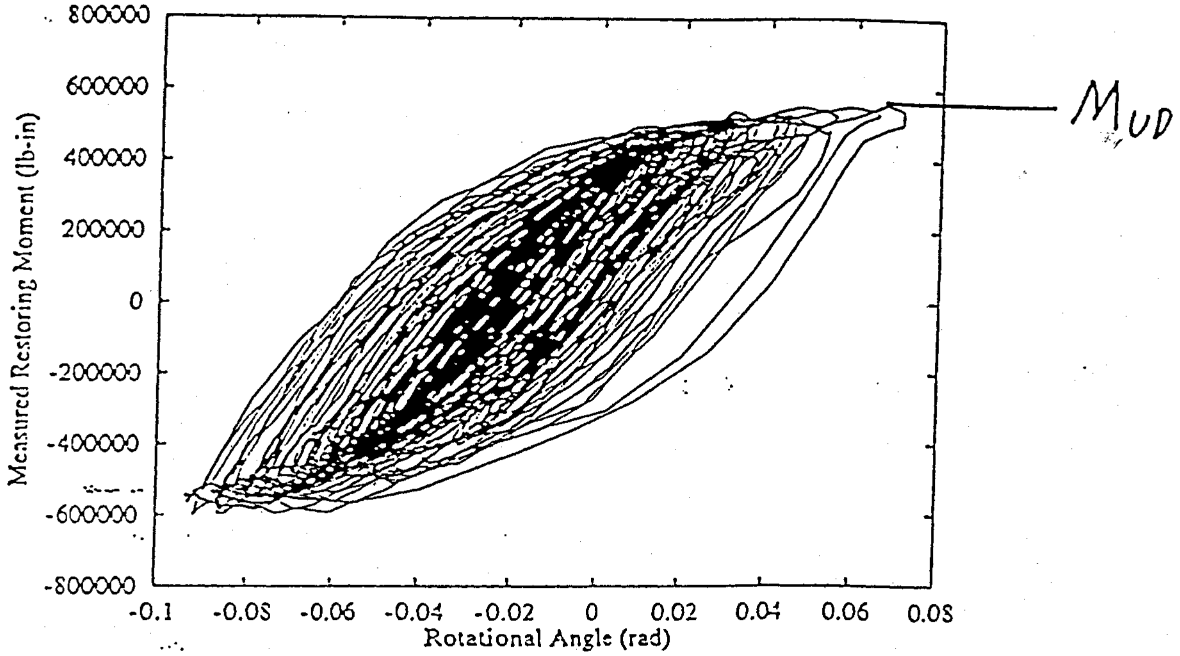
$$F_S = \frac{M_{UD}}{M_{CODE}}$$

M_{UD} = Ultimate moment achieved in component under dynamic cyclic loading prior to failure

M_{CODE} = Code Permissible Moment

$$M_{CODE} = \left[3S_M - \frac{B_1'PD}{2t}\right]\frac{Z_N}{B_2'}$$

B_1', B_2' = Cyclic Dynamic Stress Indices



M_{UD}

Figure 1: Measured hysteretic loops for ANCO Test 14, Run 6

Elbows, Bends and Tees

$$B_2' = \left(\tfrac{2}{3}\right) B_2 \geq 1.0$$

$$B_1' = \begin{cases} 0 & \text{Elbows and Bends} \\ 0.5 & \text{Tees} \end{cases}$$

Weld Region Connecting Fittings to Pipe or Other Location of Abrupt Stiffness Change

$$B_2' = \left(\tfrac{4}{3}\right)$$

$$B_1' = 0.5$$

Other Fittings Where Data To Justify A Reduction Is Unavailable

$$B_2' = B_2$$

$$B_1' = B_1$$

Straight Pipe

$$B_2' = 1.0$$

$$B_1' = 0.5$$

Table 1: EPRI Dynamic Component Test Data*

Component	Mtl.	Z_N in^3	$\frac{PD_0}{2t}$ ksi	B_1	B_2	M_{UD} kip-inch	M_{CODE} kip-inch	F_S
Elbow								
3 EL,10,LR	SS	4.35	9.89	0	5.51	142	71	2.00
4 EL,40,LR	CS	8.50	11.83	0	3.27	381	234	1.63
5 EL,40,LR	CS	8.50	20.11	0	3.27	478	234	2.05
6 EL,40,LR	SS	8.50	20.11	0	3.27	469	234	2.01
7 EL,40,LR	SS	8.50	11.83	0	3.27	454	234	1.94
8 EL,40,LR	SS	8.50	0	0	3.27	456	234	1.95
13 EL,40,SR	CS	8.50	11.83	0	4.29	322	178	1.81
19 EL,40,SR	SS	8.50	29.58	0	3.27	579	234	2.47
30 EL,10,LR	SS	4.35	9.89	0	5.51	130	71	1.83
31 EL,10,LR	SS	4.35	9.89	0	5.51	188	71	2.65
35 EL,40,LR	CS	8.50	20.11	0	3.27	465	234	1.99
37 EL,10,LR	SS	4.35	0	0	5.51	70	71	0.99**
41 EL,40,LR	CS	8.50	20.11	0	3.27	499	234	2.13
Non Elbow								
9 Tee, 40	SS	8.50	20.11	0.5	1.0	629	318	1.98
10 Tee, 40	SS	8.50	11.83	0.5	1.0	635	345	1.84
11 Tee, 10	SS	4.35	9.89	0.5	1.0	369	180	2.05
12 Tee, 40	SS	8.50	20.11	0.5	1.0	719	318	2.26
14 Tee, 40	CS	8.50	20.11	0.5	1.0	617	318	1.94
15 Red, 40	SS	3.21	16.14	0.5	1.0	333	125	2.66
16 Red, 40	CS	3.21	16.14	0.5	1.0	385	125	3.08
34 Pipe, 40	CS	8.50	11.83	0.5	1.0	759	345	2.20
36 Tee, 40	CS	8.50	20.11	0.5	1.0	700	318	2.20
38 Tee, 40	SS	8.50	20.11	0.5	2.02	643	315	2.04
39 Tee, 40	SS	8.50	0	0.5	2.02	623	379	1.64
40 Red, 40	SS	3.21	0	0.5	1.0	314	144	2.17

*S_M = 20 ksi all cases

**Component 37 is an outlier not included in statistical comparison

Table 2: Japanese Dynamic Component Test Data

Component	Mtl.	S_M N/mm^2	Z_N mm^3	$\frac{PD_0}{2t}$ MP_a	B_1	B_2	M_{UD} kNm	M_{CODE} kNm	F_S
Bends									
1	CS	110.3	52530	126.7	0	2.16	31.80	12.07	2.63
2	SS	137.9	52530	142.9	0	2.16	45.20	15.09	3.00
3	CS	110.3	96712	69.0	0	1.14	58.28	24.00	2.43
4	CS	110.3	52530	70.5	0	2.16	29.50	12.07	2.44
5	CS	110.3	52530	17.1	0	2.16	25.00	12.07	2.07
7	CS	110.3	52530	125.7	0	2.16	21.31	12.07	1.77
8	CS	110.3	52530	127.6	0	2.16	26.35	12.07	2.18
10	CS	110.3	52530	129.5	0	2.16	34.40	12.07	2.85
Tees									
11	CS	110.3	55243	125.7	0.5	2.17	24.17	10.24	2.36
12	CS	110.3	20635	95.4	0.5	1.0	10.00	4.38	2.28
13	CS	110.3	55243	130.5	0.5	1.0	21.79	11.01	1.98
Pipe									
14	CS	110.3	52530	122.9	0.5	1.0	23.65	10.62	2.23
15	CS	110.3	52530	135.3	0.5	1.0	21.21	10.37	2.04

Table 3: Japanese Cyclic Static Component Test Data

Component	Mtl.	S_M N/mm^2	Z_N mm^3	$\frac{PD_0}{2t}$ MP_a	B_1	B_2	M_{UD} kNm	M_{CODE} kNm	F_S
Bends									
1	CS	110.3	52530	126.7	0	2.16	32.86	12.07	2.72
2	SS	137.9	52530	136.2	0	2.16	34.28	15.09	2.27
3	CS	110.3	96712	66.5	0	1.14	69.36	24.00	2.89
4	CS	110.3	52530	61.0	0	2.16	27.84	12.07	2.31
5	CS	110.3	52530	3.8	0	2.16	24.99	12.07	2.07
7	CS	110.3	52530	124.8	0	2.16	18.64	12.07	1.54
8	CS	110.3	52530	127.6	0	2.16	28.95	12.07	2.40
9	CS	110.3	52530	127.6	0	2.16	32.82	12.07	2.73
11	CS	110.3	52530	125.7	0	2.16	30.61	12.07	2.54
Tees									
12	CS	110.3	55243	125.7	0.5	2.17	25.95	10.24	2.54
13	CS	110.3	20635	95.4	0.5	1.0	11.43	4.38	2.61
14	CS	110.3	55243	123.8	0.5	1.0	27.38	11.15	2.46
Pipe									
15	CS	110.3	52530	123.8	0.5	1.0	23.90	10.60	2.26

- Assuming data reasonably fits lognormal distribution

$$F_{S_{1\%}} = F_{S_{50\%}} e^{-2.326\beta_{FS}}$$

$$F_{S_{50\%}} = \text{Median of Data}$$

$$\beta_{FS} = \text{Log. Std. Dev. of Data}$$

- Must check lognormal distribution assumption

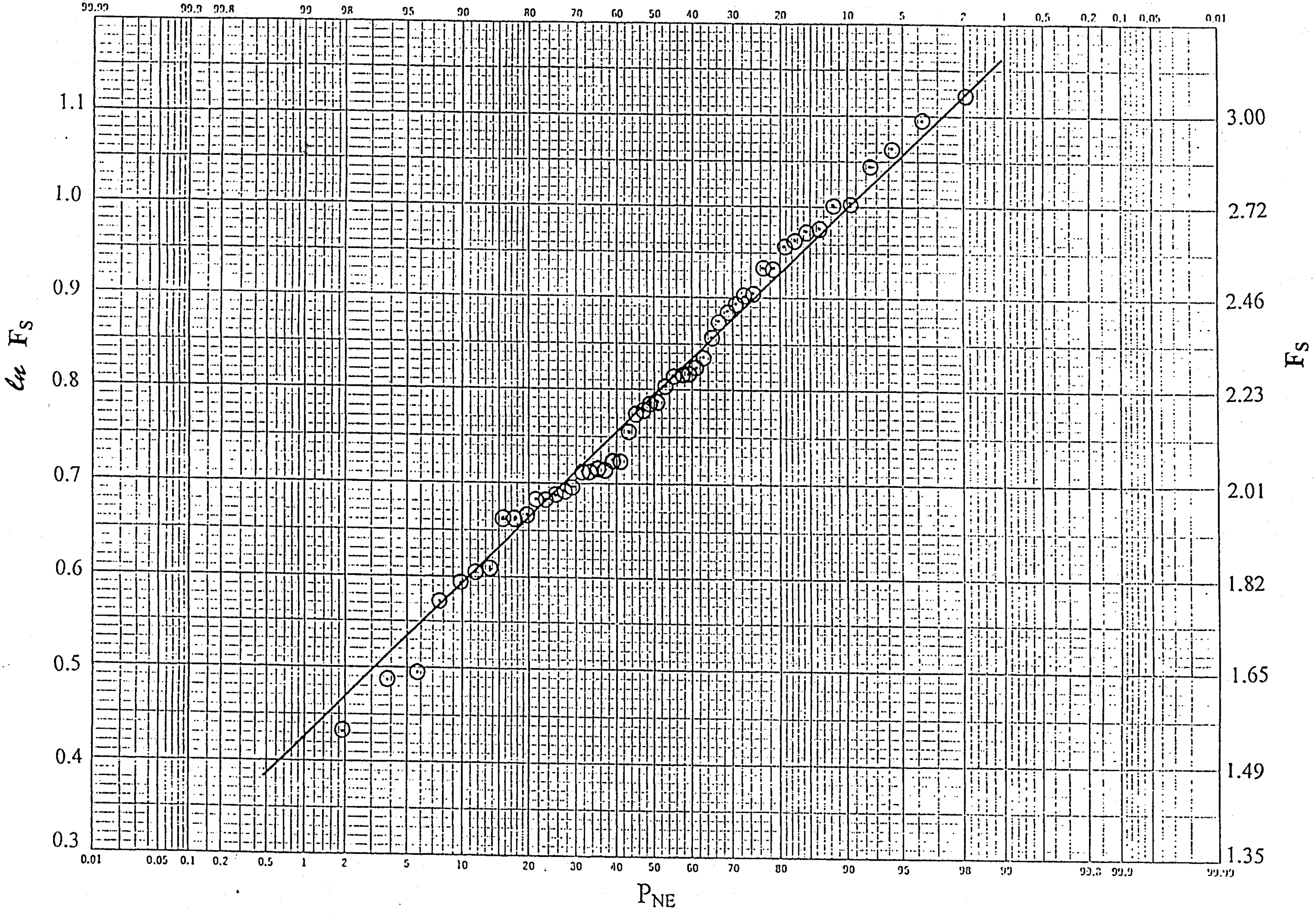


Figure 4: Cumulative Normal Probability L_N of Strength Factor

Table 4: Comparison of Statistical Distribution for EPRI and Japanese Test Data

	EPRI Dynamic	Japanese		Combined
		Dynamic	Cyclic Static	
Number of Tests	24	13	13	50
$F_{S_{50\%}}$	2.08	2.30	2.38	2.21
β_S	0.15	0.15	0.16	0.16
$F_{S_{1\%}}$	1.47	1.63	1.64	1.53

Table 5: Comparison of Statistical Distributions for Fitting Body Failures Versus Near Weld Failures

	Fitting Body (Eqn. 5a)	Near Weld (Eqn. 5b)	Combined
Number of Tests	33	17	50
$F_{S_{50\%}}$	2.21	2.23	2.21
β_S	0.18	0.13	0.16
$F_{S_{1\%}}$	1.47	1.65	1.53

Table 6: Comparison of Statistical Distribution for Carbon Steel Versus Stainless Steel Components

	Carbon Steel CS	Stainless Steel SS	Combined
Number of Tests	33	17	50
$F_{S_{50\%}}$	2.26	2.14	2.21
β_S	0.16	0.16	0.16
$F_{S_{1\%}}$	1.55	1.49	1.53

Component Test Nonlinear Factor F_{NL_C} Can Be Estimated From Cal Tech Nonlinear Studies

- Studies Present (M_r/B_2) Versus R_W

$$F_{NLC} = \frac{B_2}{F_S}\left(\frac{M_r}{B_2}\right)F_C$$

Elbows, Bends, and Tees: $F_C = 1.0$ to 1.07
Weld Region Connecting Fittings: $F_C = 2.0$ to 2.14

Component	$F_C\ B_2/F_S$
14	4.10
40	0.92

- Therefore For Components 14 and 40

$$F_{NLC} \approx \left(\frac{M_r}{B_2}\right)$$

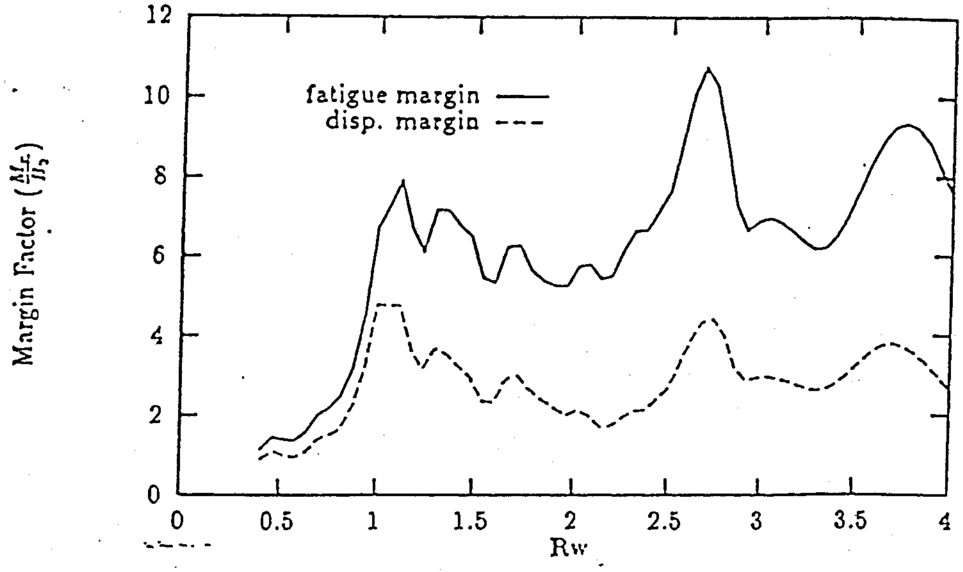


Figure 2: Component 14 Parametric Models, PFDR input; fatigue margin spectrum and displacement margin spectrum, αw = 0%, ς3 = 2.5% Sequential Method (From Ref. 2)

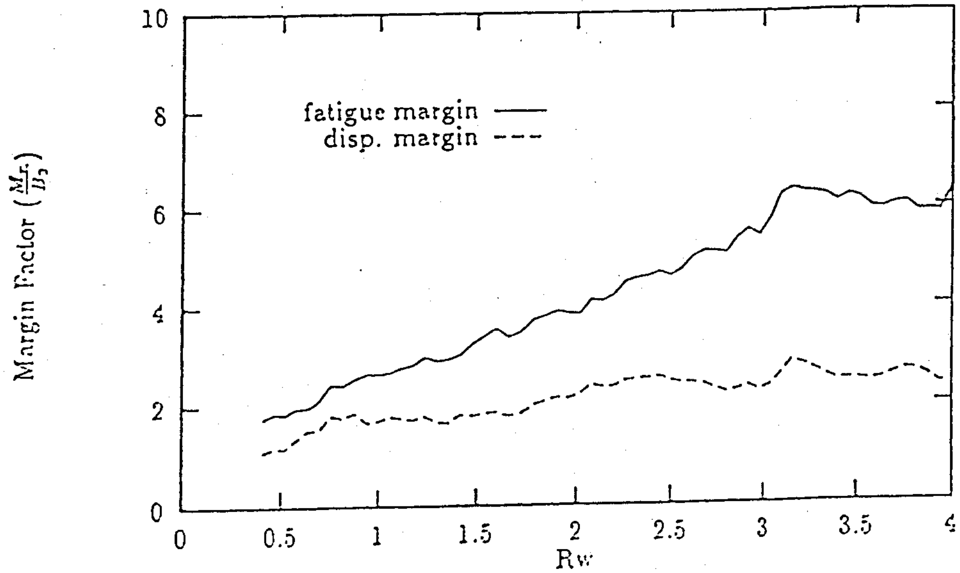


Figure 3: Component 14, Parametric Models, Reg. 1.60 input: fatigue margin spectrum and displacement margin spectrum, αw = 0%, ς3 = 2.5% Sequential Method (From Ref. 2)

Nonlinear Factor F_{NLc} for SDOF Component

- F_{NLc} is highly variable and strongly dependent on both the ratio R_W of the central frequency of input to the component natural frequency and the breadth of input frequency content
- As $R_W \to 0$: $F_{NLc} \approx 1.0$
- $R_W > 0$: $F_{NLc} \approx 1.0$ to 8.0
- At $R_W \approx 1.0$: $F_{NLc} \approx 2.0$ to 8.0
- Cannot establish any simple relationship between R_W and F_{NLc}

Redundancy Factor F_{red}

- Cantilever Component Tests

$$F_{Red_C} = 1.0$$

- Piping Systems
  - Example : Uniform Fixed Beam Subjected to Uniform Load

$$F_{Red_s} = \frac{16}{12} = 1.33$$

Conclusions

- Proposed Code Rules Achieve a 1% Non Exceedance Probability (NEP) Strength Margin $F_{S_{1\%}} \approx 1.5$

- So Long As ($F_{NL} \bullet F_{Red}$) is About 1.33 or Greater, the Proposed Code Rules Will Achieve a 1% NEP Seismic Capacity Margin $R_{CP_{1\%}}$ of About 2.0 or Greater

- Typical Piping Systems Are Likely to Have ($F_{NL} \bullet F_{Red}$) Much Greater Than 1.33, So That $R_{CP_{1\%}}$ Is Likely To Be Much Greater Than 2.0 For Typical Piping Systems