Tutorial for Fatigue Evaluation of Piping Systems using CAEPIPE

The following are the Steps for performing “Fatigue Evaluation” using CAEPIPE.

General

Fatigue analysis is an essential aspect of evaluating the long-term reliability of piping systems, especially those exposed to cyclic loading. Over time, repeated stress fluctuations - whether due to changes in temperature, pressure, or mechanical/flow-induced vibrations - can lead to the initiation of microscopic cracks, propagation of the cracks and eventual failure. The study of fatigue is essential for ensuring the reliability and longevity of piping components in various applications such as process, power, nuclear, aerospace, etc.

Starting Version 13.00, CAEPIPE (built into CAEPIPE 3D+) simplifies the fatigue analysis process by automatically checking against design codes and providing fatigue life estimates based on thermal cyclic loads the piping system will encounter. ASME Section VIII Division 2 provides guidelines for applying fatigue evaluation rules to piping and other pressure-retaining equipment. Wherever applicable, these guidelines have been followed in the methodology implemented in CAEPIPE. CAEPIPE has the ability to perform both detailed and simplified fatigue evaluation. Below are the details related to Fatigue Evaluation in CAEPIPE.

Detailed Fatigue Evaluation

Detailed Fatigue Evaluation is performed as per Miner’s Rule (Damage Accumulation Theory) which is based on Cumulative Damage Theory.

Miner’s Rule is based on the concept that fatigue damage accumulates over time and that failure occurs when the accumulated damage reaches a critical value, typically set to 1. The rule is expressed mathematically as:

$$D = \sum \frac{n_i}{N_i} \qquad (1)$$

where, D = Total cumulative damage, n_i = Actual number of cycles at stress level i, N_i = Number of cycles to Failure at stress level i (from the S-N curve).

When the total damage D equals or exceeds 1.0, then according to Miner’s Rule, the fatigue failure of the system could occur.

The number of cycles to failure (N_i) is found from the S-N curves (Wöhler Curves) available in ASME Section VIII, Division 2 (2021). The current version of CAEPIPE is supplied with 7 Fatigue Curves corresponding to the Figures 3-F.1 through 3-F.7 of ASME Section VIII, Division 2 (2021). Users can even add their own Fatigue curves and import into CAEPIPE. Please refer to CAEPIPE User’s Manual for further information.

Note:

1. *When the Cumulative Damage as calculated by the above conservative approach is less than 1.0, then it implies that no further node-by-node Fatigue Evaluation needs to be carried out. On the other hand, when the Cumulative Damage as calculated above exceeds 1.0, then user needs to perform the Detailed Fatigue Evaluation manually at each node (outside of CAEPIPE by exporting ‘Element Forces’ results in .csv format) to make sure that the Cumulative Damage at each node is less than 1.0. If not, user needs to make appropriate changes to the layout and its support scheme in order to make sure the cyclic thermal stresses are reduced at all relevant nodes to such extents that the above Fatigue requirement is met.*

2. *In a future version of CAEPIPE, the stress amplitudes at each node will be used to determine the corresponding allowable number of cycles from S-N Curve which will result in cumulative damage factor at each node, which will not be as conservative as currently being done in this version of CAEPIPE.*

Simplified Fatigue Evaluation

Given below is the equation used in computing the total number of "equivalent reference displacement stress range cycles (N)" for Simplified Fatigue Evaluation.

$$N = N_E + \sum (q_i^x . N_i) \ for \ i = 1,2,\dots,n \tag{2}$$

Where N_E = number of cycles of the reference displacement stress range, S_E

N_i = number of cycles associated with the displacement stress range, S_i

$q_i = {}^{S_i}/_{S_E}$

S_E = reference displacement stress range, psi (kPa) = maximum stress range computed among the displacement stress ranges selected by the user for Simplified Fatigue Evaluation.

S_i = maximum computed stress range for the ith displacement stress range.

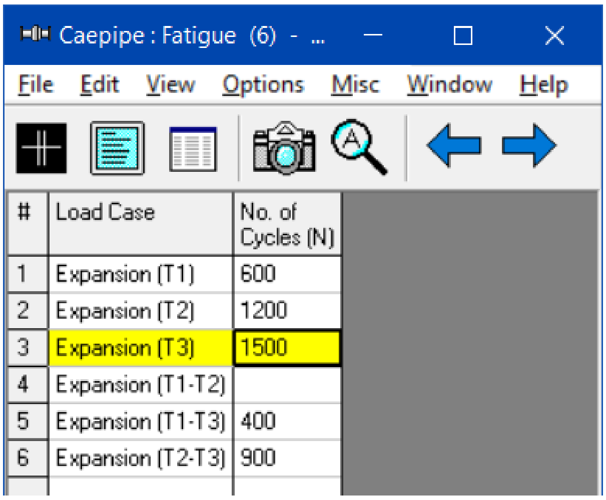
x = 1 or 3 or 5 based on the analysis Code selected. Please refer to CAEPIPE Code Compliance Manual for further details.

Once the "equivalent reference displacement stress range cycles (N)" is computed, then CAEPIPE uses this "N" to compute the Stress Range Reduction Factor (f or U) as per the piping code selected for analysis.

When the Simplified Fatigue Evaluation is turned ON, then the 'equivalent reference displacement stress range cycles (N)' computed as per Simplified Fatigue Evaluation will internally overwrite the Number of Thermal Cycles (N) that was input through Options > Analysis > Temperature (= 7000 by default) for computing the Expansion Allowable Stress.

Actual Number of Cycles to be Input for Detailed and Simplified Fatigue Analyses:

In CAEPIPE, the actual number of cycles associated with each selected expansion load case can be entered as shown below. When Simplified or Detailed Fatigue Analysis is enabled, CAEPIPE utilizes this table (containing the actual number of cycles for the selected load cases) to perform both Simplified and Detailed Fatigue Analysis. Please note, when any of the load cases is not to be included in the Fatigue Evaluation, then leave the 'Number of Cycles (N)' field for that load case BLANK as shown below.



#	Load Case	No. of Cycles (N)
1	Expansion (T1)	600
2	Expansion (T2)	1200
3	Expansion (T3)	1500
4	Expansion (T1-T2)	
5	Expansion (T1-T3)	400
6	Expansion (T2-T3)	900

When the Detailed Fatigue Analysis is turned ON, CAEPIPE uses the “No. of Cycles” input by the user through Layout Window > Misc > Fatigue Cycles to compute the “Cumulative Damage (D)” as outlined above under the section titled ‘Detailed Fatigue Evaluation’.

Similarly, *when Simplified Fatigue Analysis is turned ON*, CAEPIPE uses the “No. of Cycles” input by the user through Layout Window > Misc > Fatigue Cycles for calculating the “equivalent reference displacement stress range cycles (N)”, which then is used to compute the stress range reduction factor (‘f’ or ‘U’) as detailed above under the section titled ‘Simplified Fatigue Evaluation’.

For better clarity, refer to the example given below to input the Fatigue Cycles table:

Consider a piping system that operates at three different temperature levels, each with a corresponding number of cycles over its service life and with the reference temperature of 70^0F.

2000 cycles of $T_1 = Expansion\ (T_1) = T_1 - T_{ref} = 370^0F - 70^0F = 300^0F$

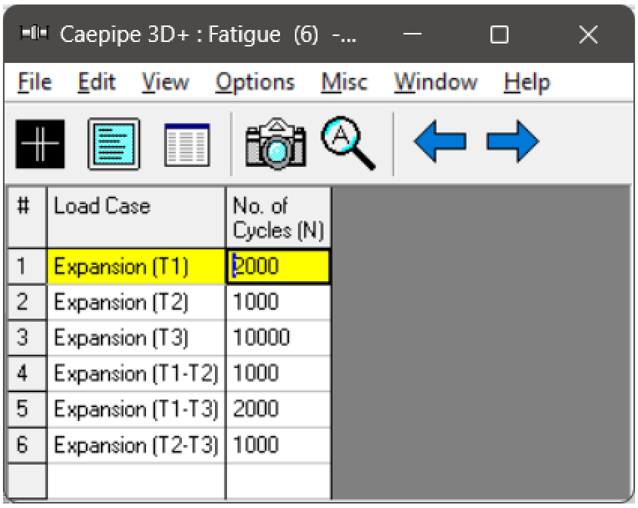
1000 cycles of $T_2 = Expansion\ (T_2) = T_2 - T_{ref} = -150^0F - 70^0F = -220^0F$

10000 cycles of $T_3 = Expansion\ (T_3) = T_3 - T_{ref} = -100^0F - 70^0F = -170^0F$

With reference to the above temperature ranges, the number of cycles that can be entered in CAEPIPE for each load case are as follows.

- For Expansion (T_1), the number of cycles=2000
- For Expansion (T_2), the number of cycles=1000
- For Expansion (T_3), the number of cycles=10000
- For Expansion $(T_1 - T_2)$, the number of cycles = Min(T_1, T_2) = Min(2000,1000) = 1000
- For Expansion $(T_1 - T_3)$, the number of cycles = Min(T_1, T_3) = Min(2000,10000) = 2000
- For Expansion $(T_2 - T_3)$, the number of cycles = Min(T_2, T_3) = Min(1000,10000) = 1000

Accordingly, the Fatigue Cycles table in CAEPIPE is to be input as shown below.



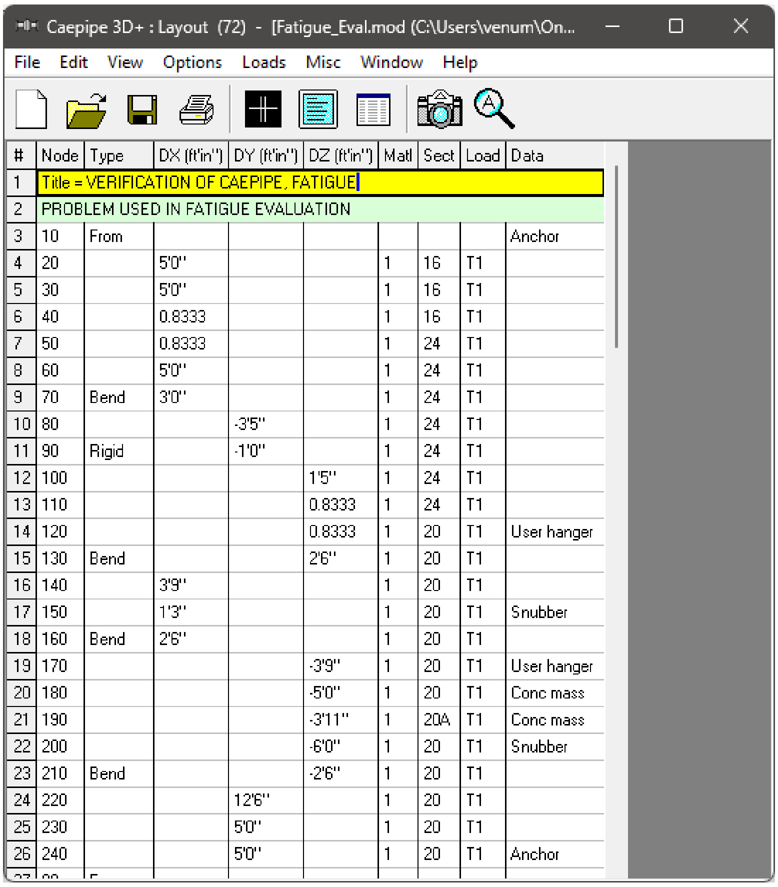
#	Load Case	No. of Cycles (N)
1	Expansion (T1)	2000
2	Expansion (T2)	1000
3	Expansion (T3)	10000
4	Expansion (T1-T2)	1000
5	Expansion (T1-T3)	2000
6	Expansion (T2-T3)	1000

The above approach to input the number of cycles is conservative as the sum of the Number of Cycles input is greater than the sum of actual number of cycles (i.e., [17000 = 2000+1000+10000+1000+2000+1000] > [13000 = 2000+1000+10000]). **There may be alternate ways to input the number of cycles, such as “combining” or "lumping" the ranges of variations to produce the maximum effect as stated in Clause NB-3553 ‘Fatigue Usage’ of ASME Section III, Subsection NB (2021).**

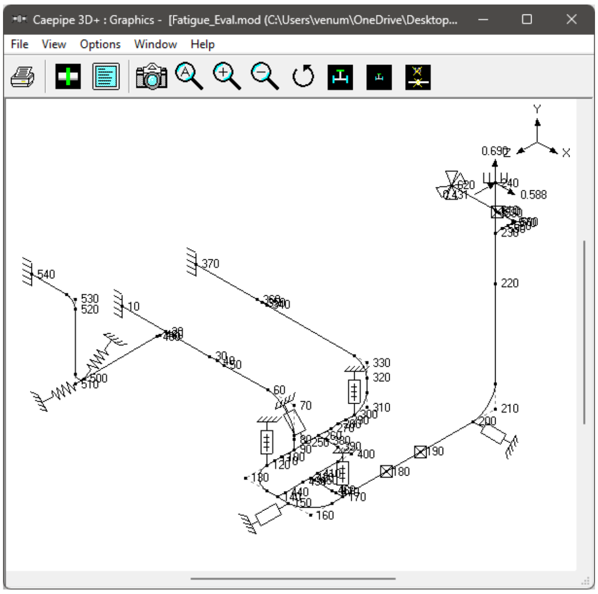
Tutorial:

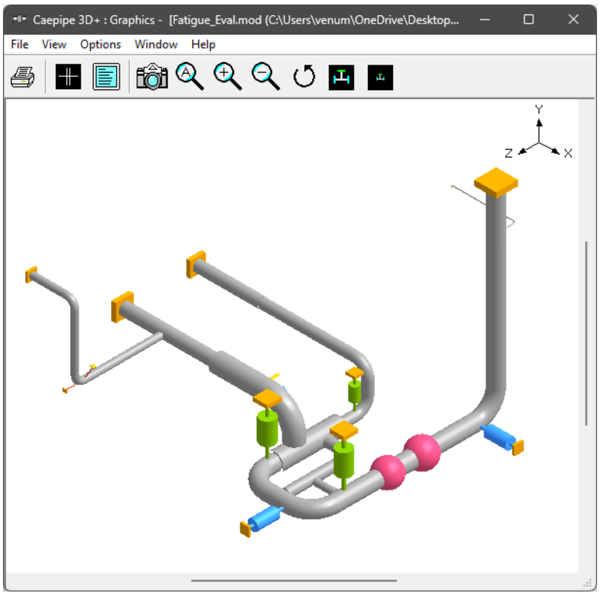
Step 1:

Snapshots shown below are from a sample CAEPIPE Stress layout that is used for Detailed and Simplified Fatigue Evaluation (see the “Fatigue_Eval.mod” file).



#	Node	Type	DX (ft'in")	DY (ft'in")	DZ (ft'in")	Matl	Sect	Load	Data
1	Title = VERIFICATION OF CAEPIPE, FATIGUE								
2	PROBLEM USED IN FATIGUE EVALUATION								
3	10	From							Anchor
4	20		5'0"			1	16	T1	
5	30		5'0"			1	16	T1	
6	40		0.8333			1	16	T1	
7	50		0.8333			1	24	T1	
8	60		5'0"			1	24	T1	
9	70	Bend	3'0"			1	24	T1	
10	80			-3'5"		1	24	T1	
11	90	Rigid		-1'0"		1	24	T1	
12	100				1'5"	1	24	T1	
13	110				0.8333	1	24	T1	
14	120				0.8333	1	20	T1	User hanger
15	130	Bend			2'6"	1	20	T1	
16	140		3'9"			1	20	T1	
17	150		1'3"			1	20	T1	Snubber
18	160	Bend	2'6"			1	20	T1	
19	170				-3'9"	1	20	T1	User hanger
20	180				-5'0"	1	20	T1	Conc mass
21	190				-3'11"	1	20A	T1	Conc mass
22	200				-6'0"	1	20	T1	Snubber
23	210	Bend			-2'6"	1	20	T1	
24	220			12'6"		1	20	T1	
25	230			5'0"		1	20	T1	
26	240			5'0"		1	20	T1	Anchor



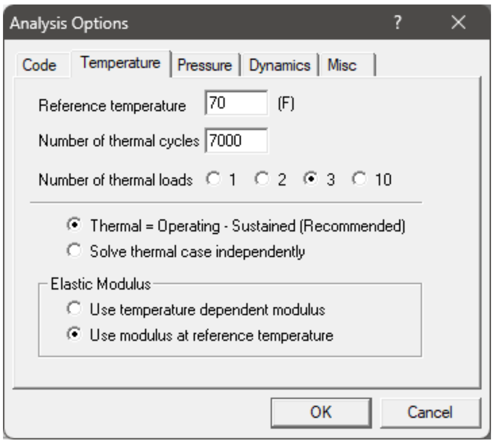


The piping code selected for the analysis is ASME B31.1 (2022) for which $'x'$ in Eq. (2) is 5.

Step 2:

As explained above, this stress layout is assumed to be operating at three different temperature levels T1, T2 and T3 as 370 deg.F, -150 deg.F and -100 deg.F respectively with the reference temperature as $70^0 F$ and all Pressures P1, P2 and P3 as 100 psi. These loads can be input into CAEPIPE as follows.

- Select the "Number of thermal loads" as 3 through Layout Window > Options > Analysis > Temperature.



Reference temperature 70 (F)

Number of thermal cycles 7000

Number of thermal loads ○ 1 ○ 2 ● 3 ○ 10

● Thermal = Operating - Sustained (Recommended)

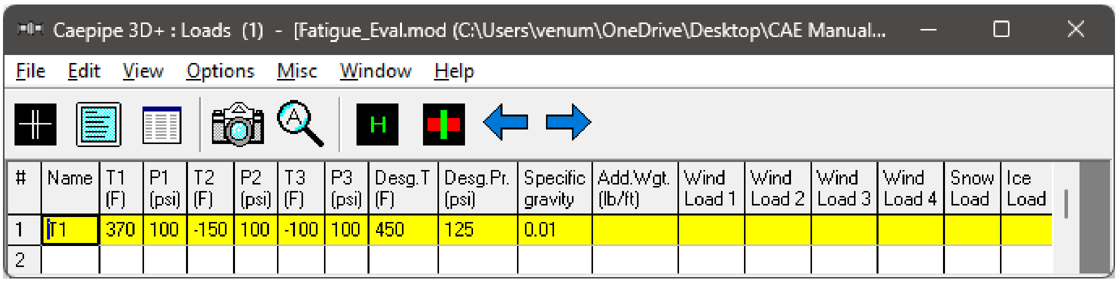
○ Solve thermal case independently

Elastic Modulus

○ Use temperature dependent modulus

● Use modulus at reference temperature

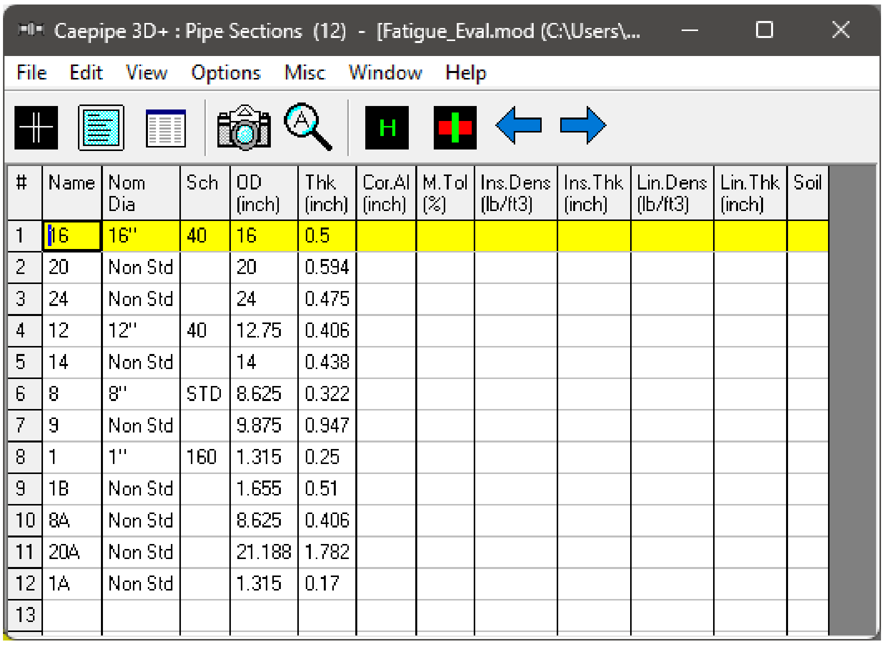
- Input the Temperatures and Pressures for Operating and Design load cases as given below through Layout Window > Misc > Loads.



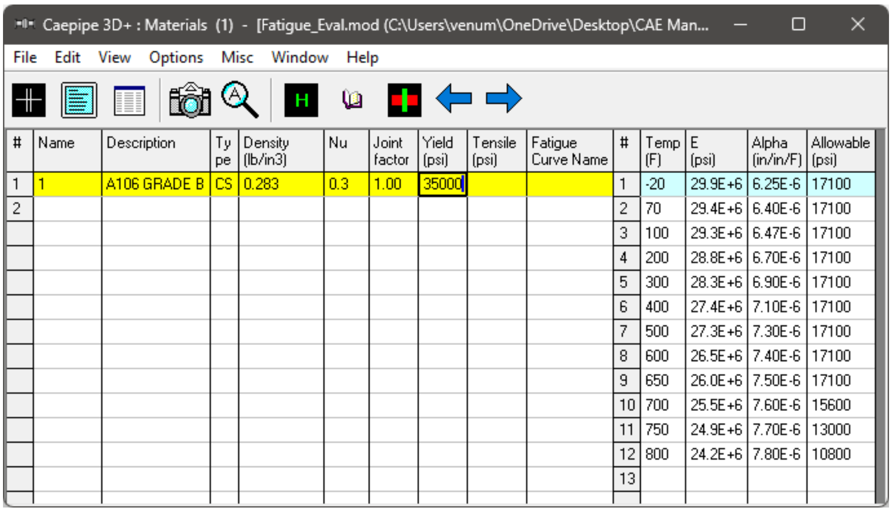
#	Name	T1 (F)	P1 (psi)	T2 (F)	P2 (psi)	T3 (F)	P3 (psi)	Desg.T (F)	Desg.Pr. (psi)	Specific gravity	Add.Wgt. (lb/ft)	Wind Load 1	Wind Load 2	Wind Load 3	Wind Load 4	Snow Load	Ice Load
1	T1	370	100	-150	100	-100	100	450	125	0.01							
2																	

Step 3:

Section properties and Material used for this stress layout are given below.



#	Name	Nom Dia	Sch	OD (inch)	Thk (inch)	Cor.Al (inch)	M.Tol (%)	Ins.Dens (lb/ft3)	Ins.Thk (inch)	Lin.Dens (lb/ft3)	Lin.Thk (inch)	Soil
1	16	16"	40	16	0.5							
2	20	Non Std		20	0.594							
3	24	Non Std		24	0.475							
4	12	12"	40	12.75	0.406							
5	14	Non Std		14	0.438							
6	8	8"	STD	8.625	0.322							
7	9	Non Std		9.875	0.947							
8	1	1"	160	1.315	0.25							
9	1B	Non Std		1.655	0.51							
10	8A	Non Std		8.625	0.406							
11	20A	Non Std		21.188	1.782							
12	1A	Non Std		1.315	0.17							
13												



#	Name	Description	Type	Density (lb/in3)	Nu	Joint factor	Yield (psi)	Tensile (psi)	Fatigue Curve Name
1	1	A106 GRADE B	CS	0.283	0.3	1.00	35000		
2									

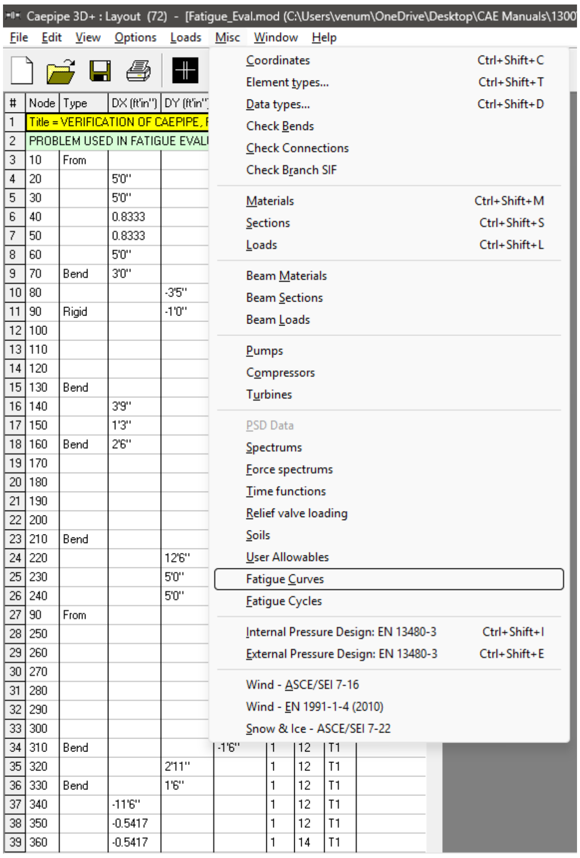
#	Temp (F)	E (psi)	Alpha (in/in/F)	Allowable (psi)
1	-20	29.9E+6	6.25E-6	17100
2	70	29.4E+6	6.40E-6	17100
3	100	29.3E+6	6.47E-6	17100
4	200	28.8E+6	6.70E-6	17100
5	300	28.3E+6	6.90E-6	17100
6	400	27.4E+6	7.10E-6	17100
7	500	27.3E+6	7.30E-6	17100
8	600	26.5E+6	7.40E-6	17100
9	650	26.0E+6	7.50E-6	17100
10	700	25.5E+6	7.60E-6	15600
11	750	24.9E+6	7.70E-6	13000
12	800	24.2E+6	7.80E-6	10800
13				

Step 4:

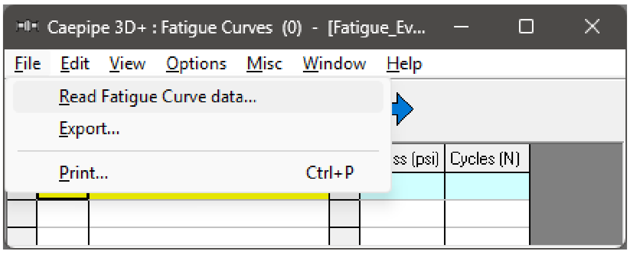
Import / Read the Fatigue Curve into CAEPIPE for Fatigue Evaluation.

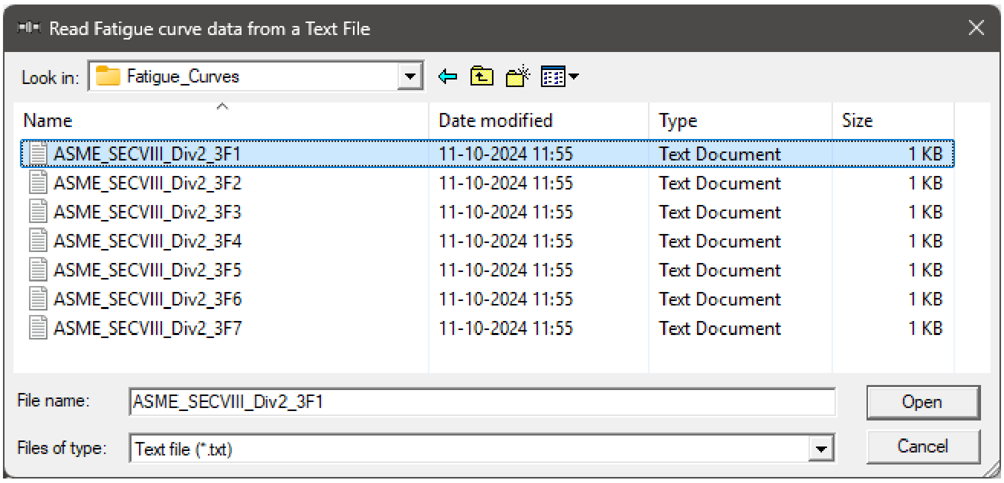
CAEPIPE is supplied with seven (7) Fatigue Curves corresponding to Figures 3-F.1 through 3-F.7 of ASME Section VIII, Division 2 (2021). These Fatigue Curves are available inside the folder “Fatigue_Curves” of CAEPIPE installation directory.

A Fatigue curve from the file ‘ASME_SECVIII_DIV2_3F1’ available in Fatigue Curves folder corresponding to ‘*Carbon, Low Alloy, Series 4XX, High Alloy, and High Tensile Strength Steels for Temperatures Not Exceeding 700 deg. F - UTS <= 80 Ksi from* ASME Section VIII, Division 2 (2021)’ supplied with CAEPIPE is used for Fatigue Evaluation. This fatigue curve is imported into CAEPIPE by selecting the file ‘ASME_SECVIII_DIV2_3F1’ available in Fatigue Curves folder through “Layout Window > Misc > Fatigue Curves > File Menu > Read Fatigue curve data” as shown in the snapshots below.



#	Node	Type	DX (ft'in")	DY (ft'in"				
1	Title = VERIFICATION OF CAEPIPE, F							
2	PROBLEM USED IN FATIGUE EVALI							
3	10	From						
4	20		5'0"					
5	30		5'0"					
6	40		0.8333					
7	50		0.8333					
8	60		5'0"					
9	70	Bend	3'0"					
10	80			-3'5"				
11	90	Rigid		-1'0"				
12	100							
13	110							
14	120							
15	130	Bend						
16	140		3'9"					
17	150		1'3"					
18	160	Bend	2'6"					
19	170							
20	180							
21	190							
22	200							
23	210	Bend						
24	220			12'6"				
25	230			5'0"				
26	240			5'0"				
27	90	From						
28	250							
29	260							
30	270							
31	280							
32	290							
33	300							
34	310	Bend			-1'6"	1	12	T1
35	320			2'11"		1	12	T1
36	330	Bend		1'6"		1	12	T1
37	340		-11'6"			1	12	T1
38	350		-0.5417			1	12	T1
39	360		-0.5417			1	14	T1

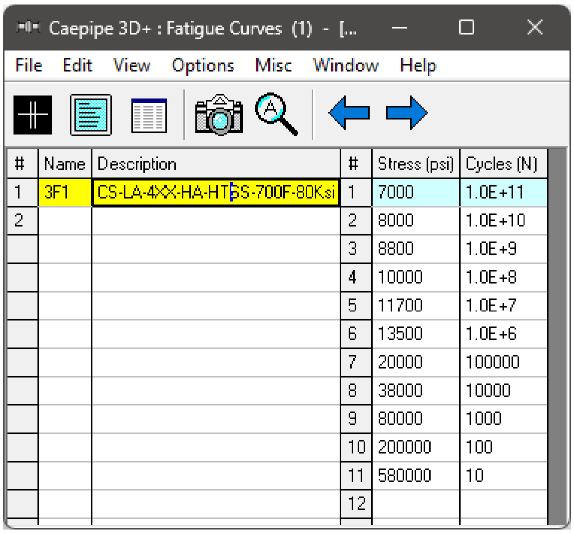




Name	Date modified	Type	Size
ASME_SECVIII_Div2_3F1	11-10-2024 11:55	Text Document	1 KB
ASME_SECVIII_Div2_3F2	11-10-2024 11:55	Text Document	1 KB
ASME_SECVIII_Div2_3F3	11-10-2024 11:55	Text Document	1 KB
ASME_SECVIII_Div2_3F4	11-10-2024 11:55	Text Document	1 KB
ASME_SECVIII_Div2_3F5	11-10-2024 11:55	Text Document	1 KB
ASME_SECVIII_Div2_3F6	11-10-2024 11:55	Text Document	1 KB
ASME_SECVIII_Div2_3F7	11-10-2024 11:55	Text Document	1 KB

File name: ASME_SECVIII_Div2_3F1

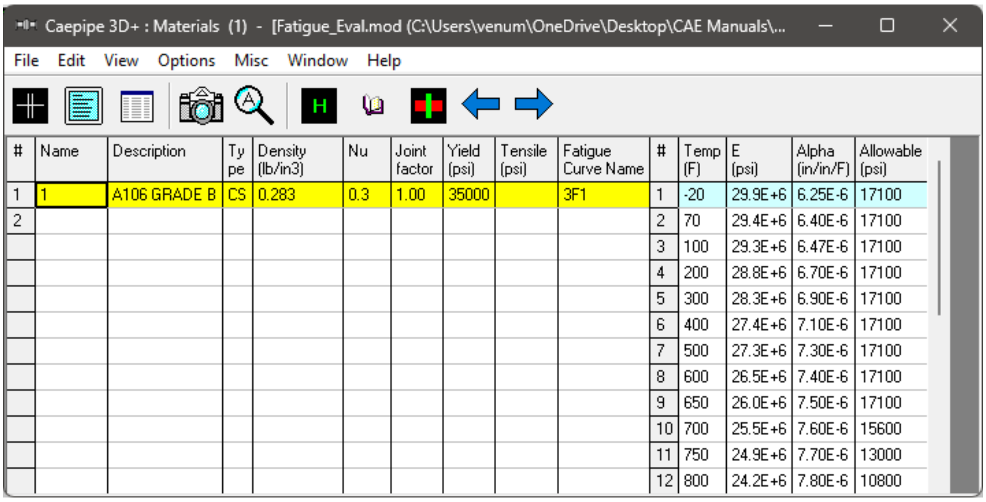
Files of type: Text file (*.txt)



#	Name	Description	#	Stress (psi)	Cycles (N)
1	3F1	CS-LA-4XX-HA-HTS-700F-80Ksi	1	7000	1.0E+11
2			2	8000	1.0E+10
			3	8800	1.0E+9
			4	10000	1.0E+8
			5	11700	1.0E+7
			6	13500	1.0E+6
			7	20000	100000
			8	38000	10000
			9	80000	1000
			10	200000	100
			11	580000	10
			12		

Step 5:

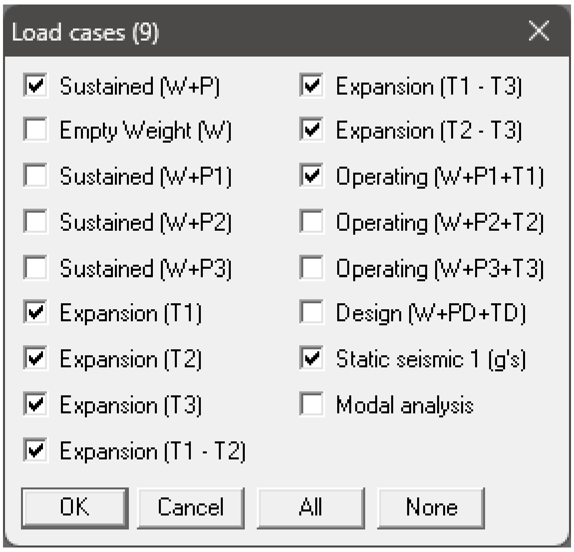
Assign Fatigue Curve to the Material through “Layout Window > Misc > Materials > Fatigue Curve Name” as shown below.



#	Name	Description	Type	Density (lb/in3)	Nu	Joint factor	Yield (psi)	Tensile (psi)	Fatigue Curve Name	#	Temp (F)	E (psi)	Alpha (in/in/F)	Allowable (psi)
1	1	A106 GRADE B	CS	0.283	0.3	1.00	35000		3F1	1	-20	29.9E+6	6.25E-6	17100
2										2	70	29.4E+6	6.40E-6	17100
										3	100	29.3E+6	6.47E-6	17100
										4	200	28.8E+6	6.70E-6	17100
										5	300	28.3E+6	6.90E-6	17100
										6	400	27.4E+6	7.10E-6	17100
										7	500	27.3E+6	7.30E-6	17100
										8	600	26.5E+6	7.40E-6	17100
										9	650	26.0E+6	7.50E-6	17100
										10	700	25.5E+6	7.60E-6	15600
										11	750	24.9E+6	7.70E-6	13000
										12	800	24.2E+6	7.80E-6	10800

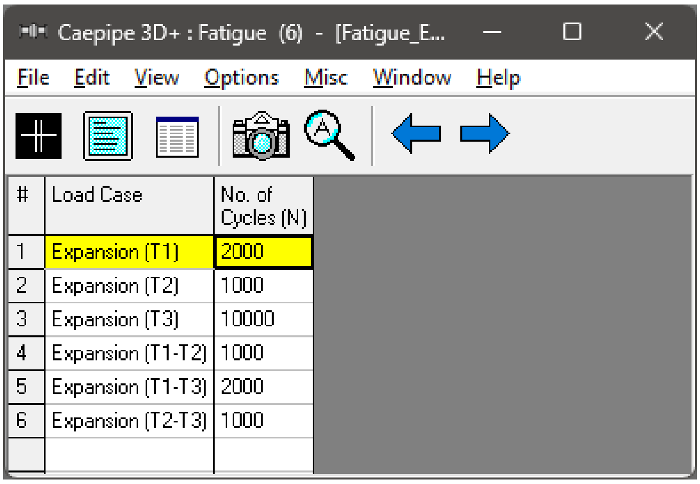
Step 6:

For inputting the Actual Number of Fatigue cycles, select the required Expansion load cases through "Layout Window > Loads > Load cases" as shown below.



☑ Sustained (W+P)
☐ Empty Weight (W)
☐ Sustained (W+P1)
☐ Sustained (W+P2)
☐ Sustained (W+P3)
☑ Expansion (T1)
☑ Expansion (T2)
☑ Expansion (T3)
☑ Expansion (T1 - T2)
☑ Expansion (T1 - T3)
☑ Expansion (T2 - T3)
☑ Operating (W+P1+T1)
☐ Operating (W+P2+T2)
☐ Operating (W+P3+T3)
☐ Design (W+PD+TD)
☑ Static seismic 1 (g's)
☐ Modal analysis

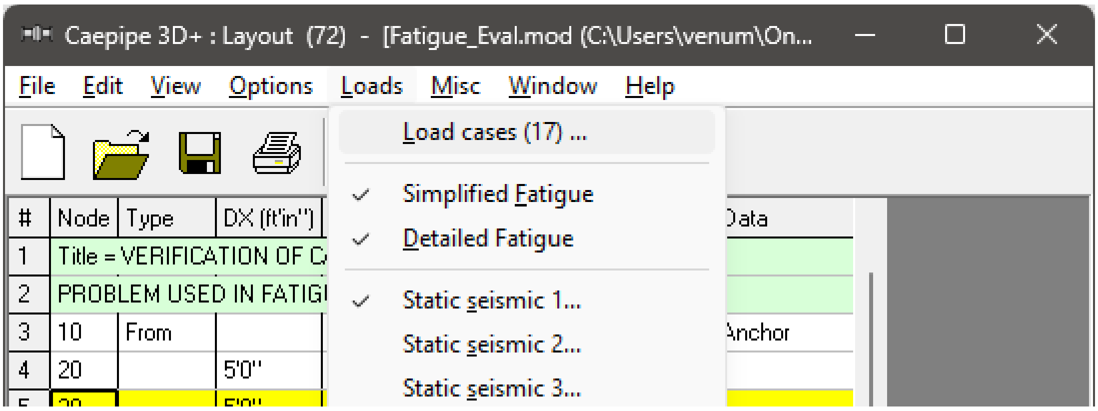
Once the required load cases are selected, input the Actual Number of Cycles (N) as detailed above under the Section titled "Actual Number of Cycles to be Input for Detailed and Simplified Fatigue Analysis" in this tutorial for the selected Expansion load cases through "Layout Window > Misc > Fatigue Cycles" as shown below.



#	Load Case	No. of Cycles (N)
1	Expansion (T1)	2000
2	Expansion (T2)	1000
3	Expansion (T3)	10000
4	Expansion (T1-T2)	1000
5	Expansion (T1-T3)	2000
6	Expansion (T2-T3)	1000

Step 7:

Turn ON (tick) the Simplified and Detailed Fatigue load cases through Layout Window > Loads.

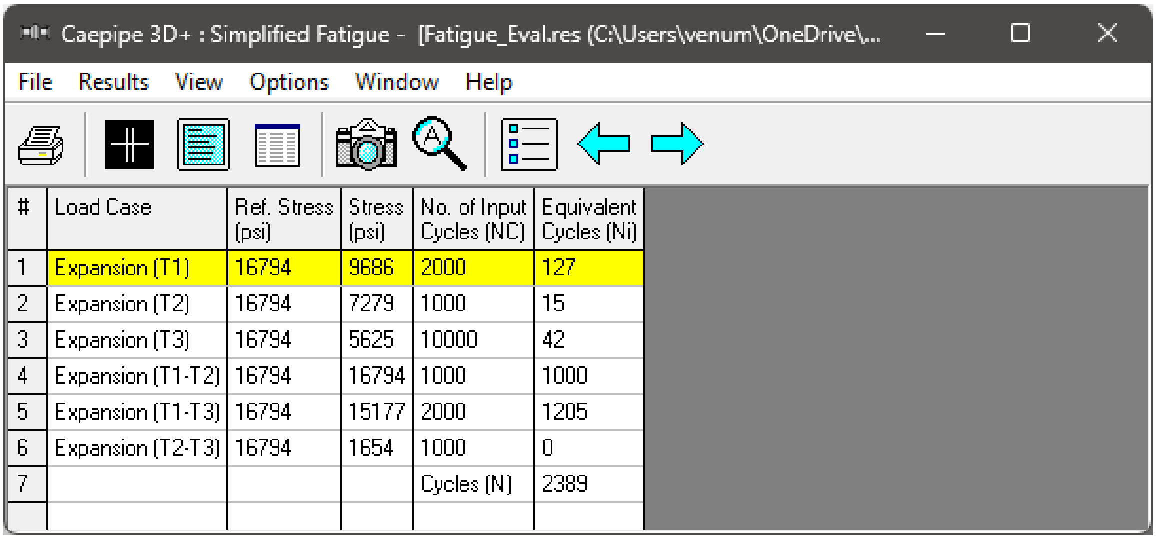


Step 8:

Save the model and perform the Analysis through “Layout Window > File > Analyze”.

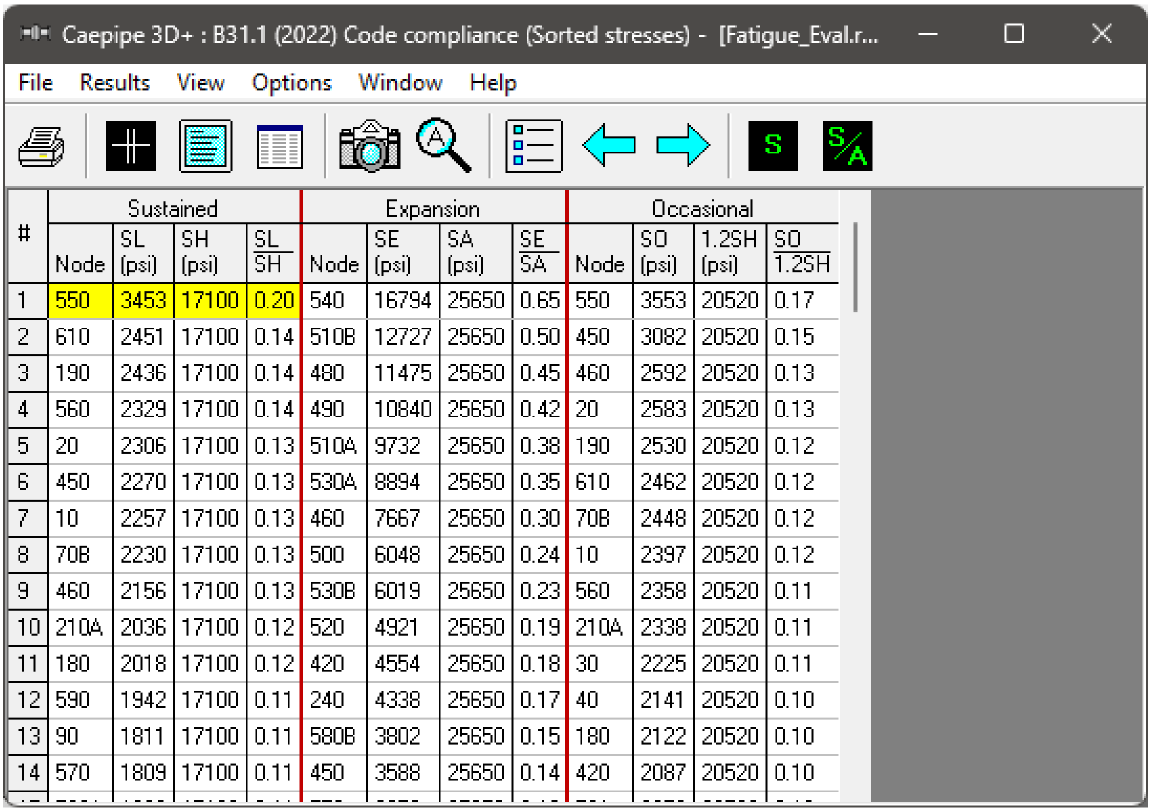
Step 9:

Review the Simplified Fatigue Evaluation Results by selecting the option “Simplified Fatigue” through “Results Window > Results”.



#	Load Case	Ref. Stress (psi)	Stress (psi)	No. of Input Cycles (NC)	Equivalent Cycles (Ni)
1	Expansion (T1)	16794	9686	2000	127
2	Expansion (T2)	16794	7279	1000	15
3	Expansion (T3)	16794	5625	10000	42
4	Expansion (T1-T2)	16794	16794	1000	1000
5	Expansion (T1-T3)	16794	15177	2000	1205
6	Expansion (T2-T3)	16794	1654	1000	0
7				Cycles (N)	2389

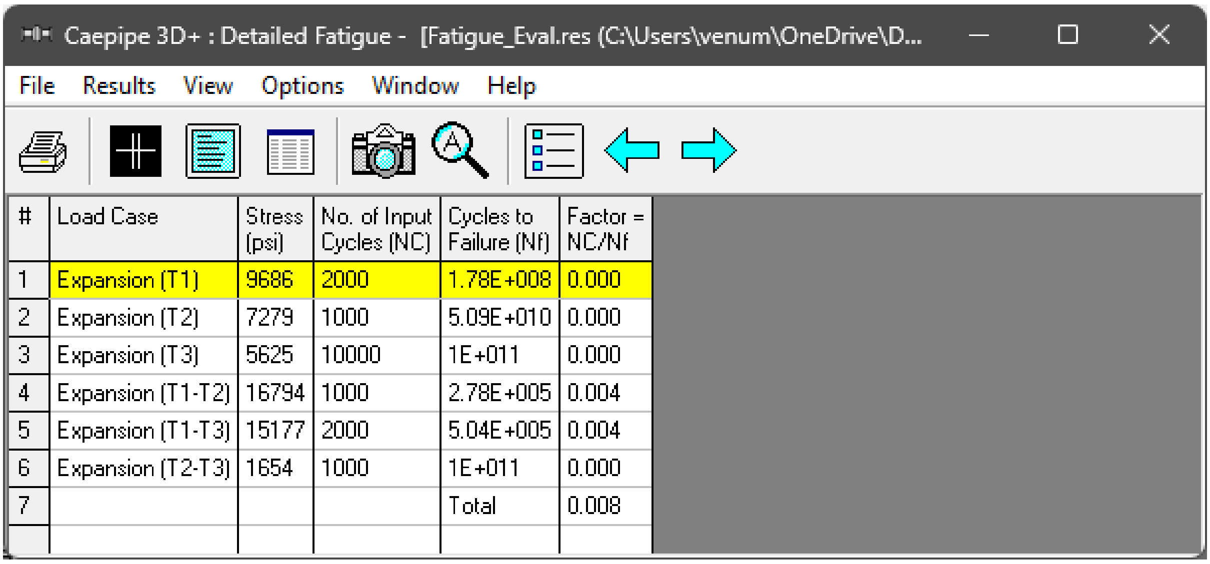
CAEPIPE uses the above computed equivalent number of reference displacement stress range cycles (N_i = 2389) to determine the Stress Range Reduction Factor (f) using Eq. (2) with $x = 5$ corresponding to the piping code ASME B31.1 (2022) selected for analysis. This Factor (f) is then used in computing the Expansion Allowable Stress (SA) shown under Sorted Stresses and Code Compliance results of CAEPIPE.



#	Sustained				Expansion				Occasional			
	Node	SL (psi)	SH (psi)	SL / SH	Node	SE (psi)	SA (psi)	SE / SA	Node	SO (psi)	1.2SH (psi)	SO / 1.2SH
1	550	3453	17100	0.20	540	16794	25650	0.65	550	3553	20520	0.17
2	610	2451	17100	0.14	510B	12727	25650	0.50	450	3082	20520	0.15
3	190	2436	17100	0.14	480	11475	25650	0.45	460	2592	20520	0.13
4	560	2329	17100	0.14	490	10840	25650	0.42	20	2583	20520	0.13
5	20	2306	17100	0.13	510A	9732	25650	0.38	190	2530	20520	0.12
6	450	2270	17100	0.13	530A	8894	25650	0.35	610	2462	20520	0.12
7	10	2257	17100	0.13	460	7667	25650	0.30	70B	2448	20520	0.12
8	70B	2230	17100	0.13	500	6048	25650	0.24	10	2397	20520	0.12
9	460	2156	17100	0.13	530B	6019	25650	0.23	560	2358	20520	0.11
10	210A	2036	17100	0.12	520	4921	25650	0.19	210A	2338	20520	0.11
11	180	2018	17100	0.12	420	4554	25650	0.18	30	2225	20520	0.11
12	590	1942	17100	0.11	240	4338	25650	0.17	40	2141	20520	0.10
13	90	1811	17100	0.11	580B	3802	25650	0.15	180	2122	20520	0.10
14	570	1809	17100	0.11	450	3588	25650	0.14	420	2087	20520	0.10

Step 10:

Review the Detailed Fatigue Evaluation Results through "Results Window > Results > Detailed Fatigue" as shown below.



#	Load Case	Stress (psi)	No. of Input Cycles (NC)	Cycles to Failure (Nf)	Factor = NC/Nf
1	Expansion (T1)	9686	2000	1.78E+008	0.000
2	Expansion (T2)	7279	1000	5.09E+010	0.000
3	Expansion (T3)	5625	10000	1E+011	0.000
4	Expansion (T1-T2)	16794	1000	2.78E+005	0.004
5	Expansion (T1-T3)	15177	2000	5.04E+005	0.004
6	Expansion (T2-T3)	1654	1000	1E+011	0.000
7				Total	0.008

Summary:

Since the total Cumulative Damage factor is less than 1.0, it implies that

a) Fatigue failure of this system will not occur as per Miner's Rule, and

b) No further node-by-node Fatigue Evaluation needs to be carried out for this stress layout.