Tutorial for Fatigue Evaluation of Piping Systems

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 fluctuation - whether due to changes in temperature, pressure, or mechanical/flow-induced vibrations - can lead to the initiation of microscopic cracks to start with, followed by propagation of those 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, petrochemical, chemical etc.

Starting Version 13.00, CAEPIPE (included in CAEPIPE 3D+) simplifies the fatigue analysis process by automatically checking against design codes and providing fatigue life estimates based on the cyclic loads experienced by the piping system. ASME Section VIII Division 2 provides guidelines for applying fatigue evaluation rules to piping and other pressure-retaining equipment. Where 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 by CAEPIPE.

Detailed Fatigue Evaluation

Detailed Fatigue Evaluation is performed as per **Miner's Rule** which is based on Cumulative Damage Theory. This theory states that fatigue damage accumulates over time and failure occurs when the accumulated damage reaches a critical value, typically set to 1. The rule is mathematically expressed as:

$$D = \sum \frac{n_i}{N_i}$$

where, D = Total cumulative damage, n_i= Actual number of cycles at alternating 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 the fatigue evaluation is considered to have failed."

The number of cycles to failure (N_i) is found using the S-N curves (Wöhler Curves), which are either input by the user (or) imported from ASME Section VIII, Division 2 (2021). The stress amplitudes (or alternating stress) are computed as one-half of total stress range (SE/2) at each node. This alternating stress is then used to find the corresponding number of cycles to failure (Ni) from the S-N curves.

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 also add their own Fatigue curves and import them into CAEPIPE. Please refer to CAEPIPE User's Manual for further information.

Note:

> *Starting Version 13.10, CAEPIPE performs detailed fatigue analysis node-by-node to check the cumulative damage due to various expansion load cases at each node. When the Cumulative Damage is less than 1.0, the stress layout is considered to be safe. On the other hand, when the Cumulative Damage exceeds 1.0, the user needs to make appropriate changes to the piping layout including support scheme in order to meet the above Fatigue requirement.*

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.

$$N = N_E + \sum(q_i^x . N_i) \;\; for\; i = 1,2,\ldots,n$$

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.

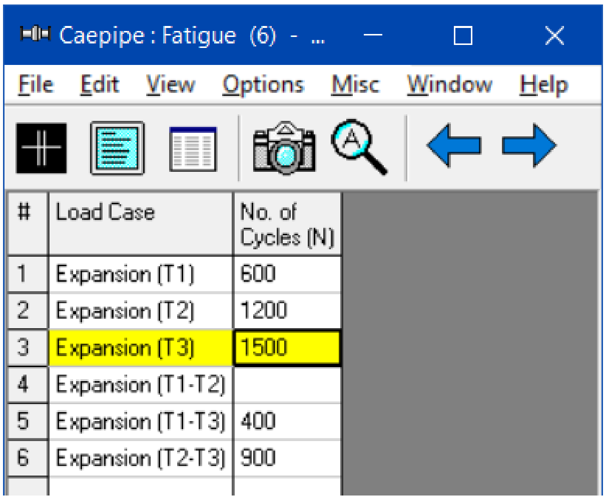
S_i = maximum computed stress range for the i^{th} displacement stress range.

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.

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

In CAEPIPE, the actual number of cycles associated with each selected thermal 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.



When the Detailed Fatigue Analysis is turned ON, CAEPIPE uses the “Fatigue Cycles” input by the user through Layout Window > Misc > Fatigue Cycles to compute the “Cumulative Damage (D)” as outlined above under ‘Detailed Fatigue Evaluation’.

Similarly, when Simplified Fatigue Analysis is turned ON, CAEPIPE uses the “Fatigue 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 for inputting 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.

10000 cycles of $T_1 = Expansion\ (T_1) = T_1 - T_{ref} = 400^0F - 70^0F = 330^0F$

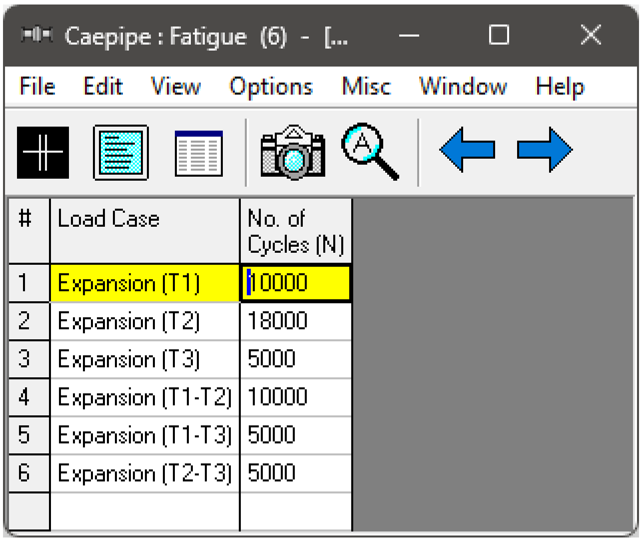
18000 cycles of $T_2 = Expansion\ (T_2) = T_2 - T_{ref} = -250^0F - 70^0F = -320^0F$

5000 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=10000
- For Expansion (T_2), the number of cycles=18000
- For Expansion (T_3), the number of cycles=5000
- For Expansion $(T_1 - T_2)$, the number of cycles = Min(T_1, T_2) = Min (10000,18000) = 10000
- For Expansion $(T_1 - T_3)$, the number of cycles = Min(T_1, T_3) = Min (10000,5000) =5000
- For Expansion $(T_2 - T_3)$, the number of cycles = Min(T_2, T_3) = Min (18000,5000) = 5000

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



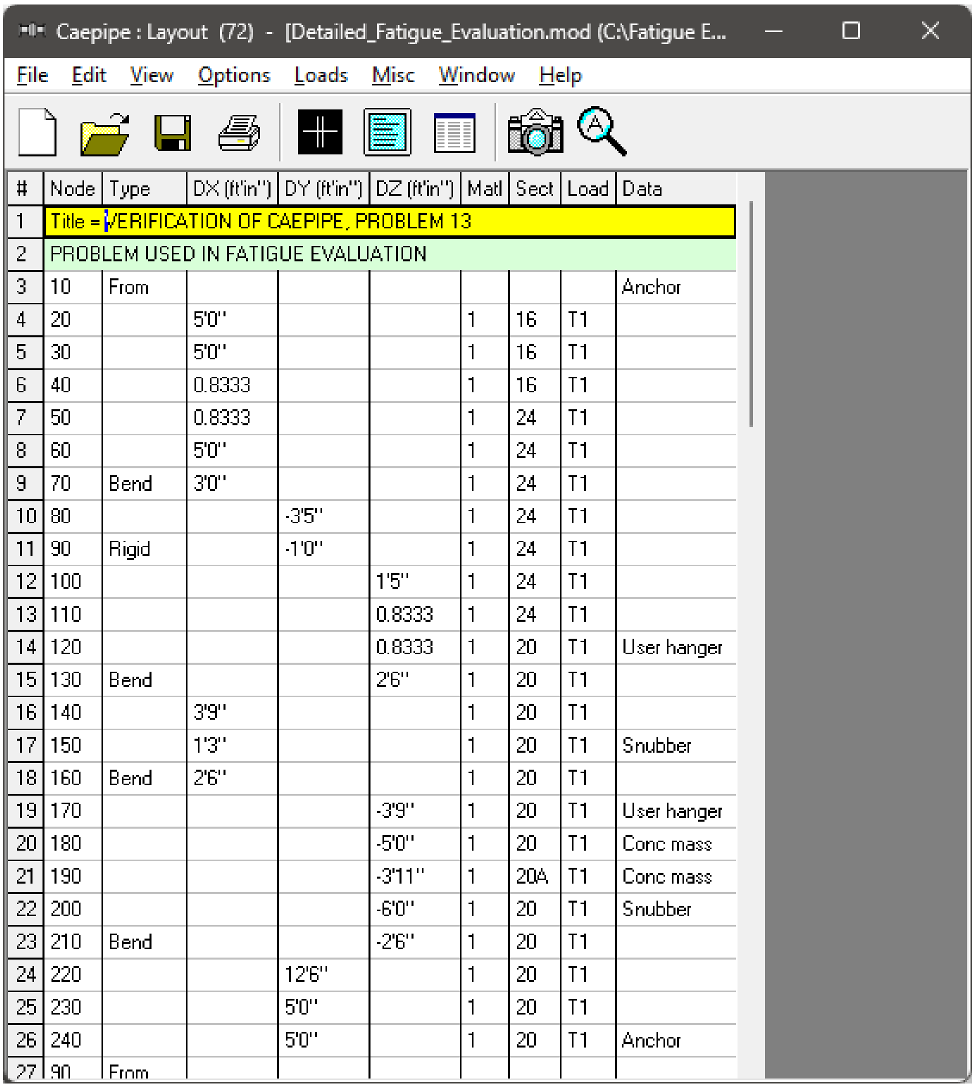
#	Load Case	No. of Cycles (N)
1	Expansion (T1)	10000
2	Expansion (T2)	18000
3	Expansion (T3)	5000
4	Expansion (T1-T2)	10000
5	Expansion (T1-T3)	5000
6	Expansion (T2-T3)	5000

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., [53000 = 10000+18000+5000+10000+5000+5000] > [33000 = 10000+18000+5000]). **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).**

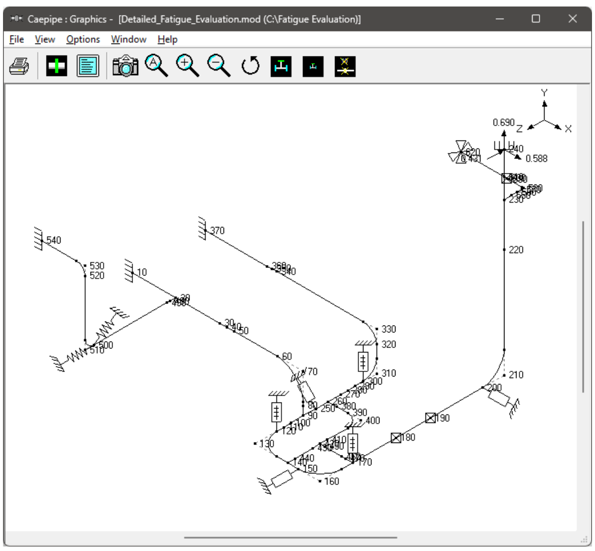
Tutorial:

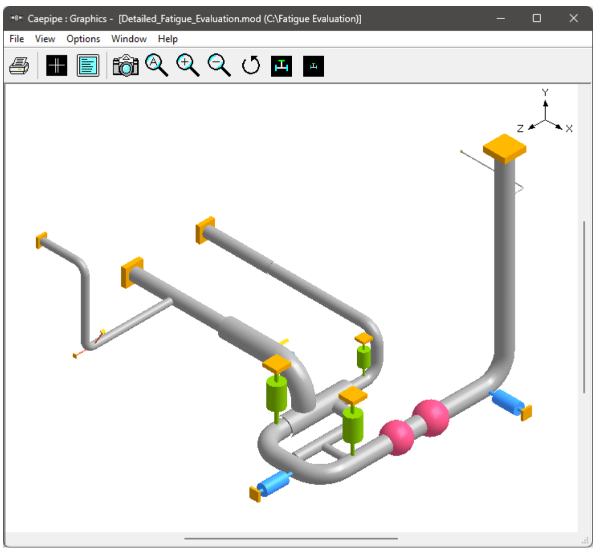
Step 1:

Snapshots shown below are from a sample CAEPIPE Stress layout that is used for Detailed and Simplified Fatigue Evaluation (see the “Detailed_Fatigue_Evaluation.mod” file). The piping code selected for this analysis is ASME B31.1 (2024).



#	Node	Type	DX (ft'in")	DY (ft'in")	DZ (ft'in")	Matl	Sect	Load	Data
1	Title = VERIFICATION OF CAEPIPE, PROBLEM 13								
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
27	90	From							

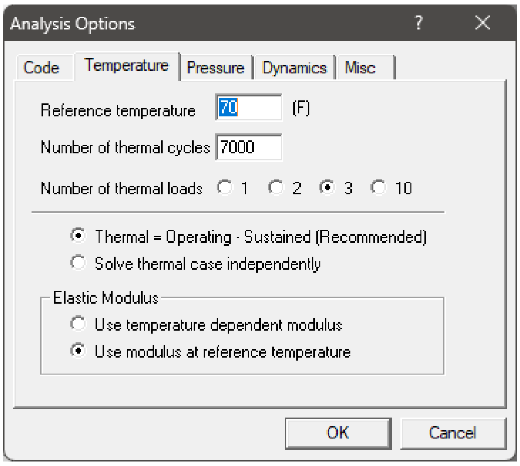




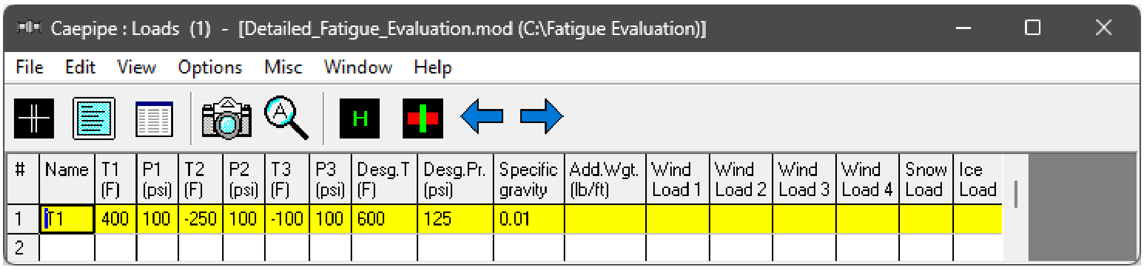
Step 2:

As explained above, this stress layout is assumed to be operating at three different temperature levels T1, T2 and T3 as 400 deg.F, -250 deg.F and -100 deg.F respectively with the reference temperature as $70^0 F$ and 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.



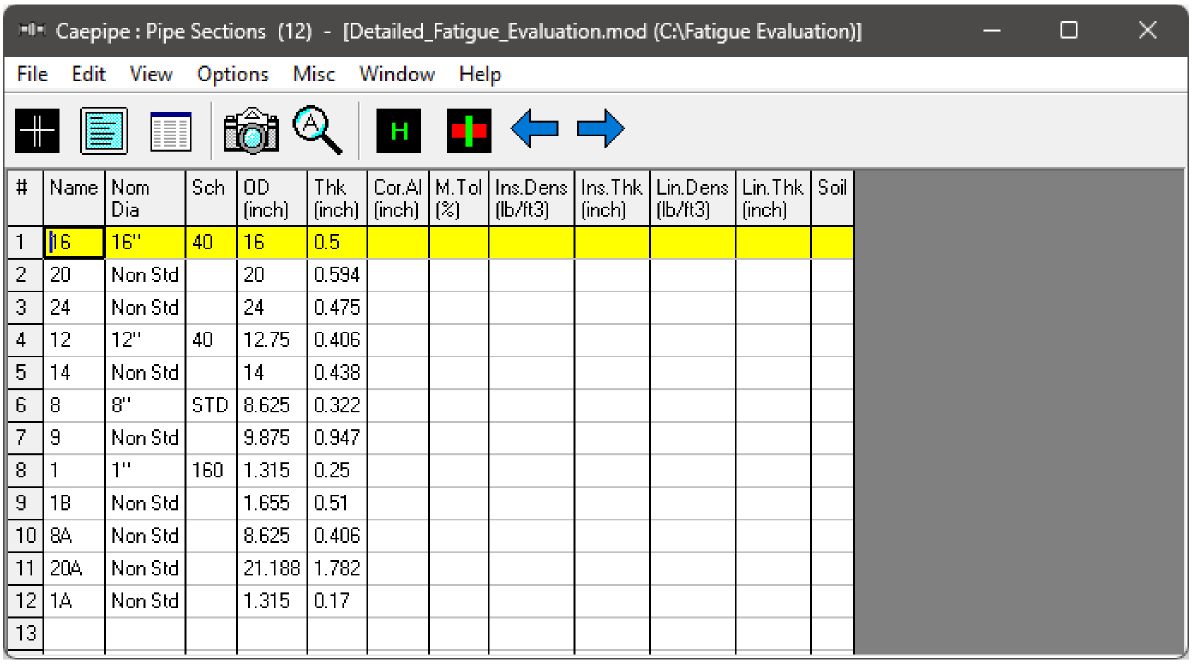
- Input the Temperatures and Pressures for Operating and Design load cases as given below through Layout Window > Misc > Loads.



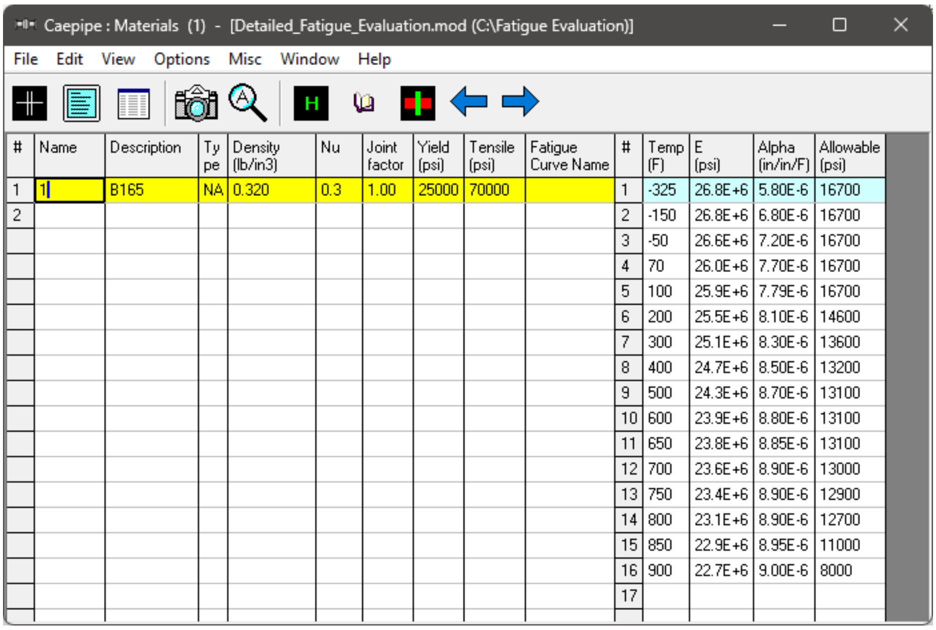
#	Name	T1 (F)	P1 (psi)	T2 (F)	P2 (psi)	T3 (F)	P3 (psi)	Desg.T (F)	Desg.Pr. (psi)	Specific gravity	Add.Wgt. (lb/ft)	Wind Load 1	Wind Load 2	Wind Load 3	Wind Load 4	Snow Load	Ice Load
1	T1	400	100	-250	100	-100	100	600	125	0.01							
2																	

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												

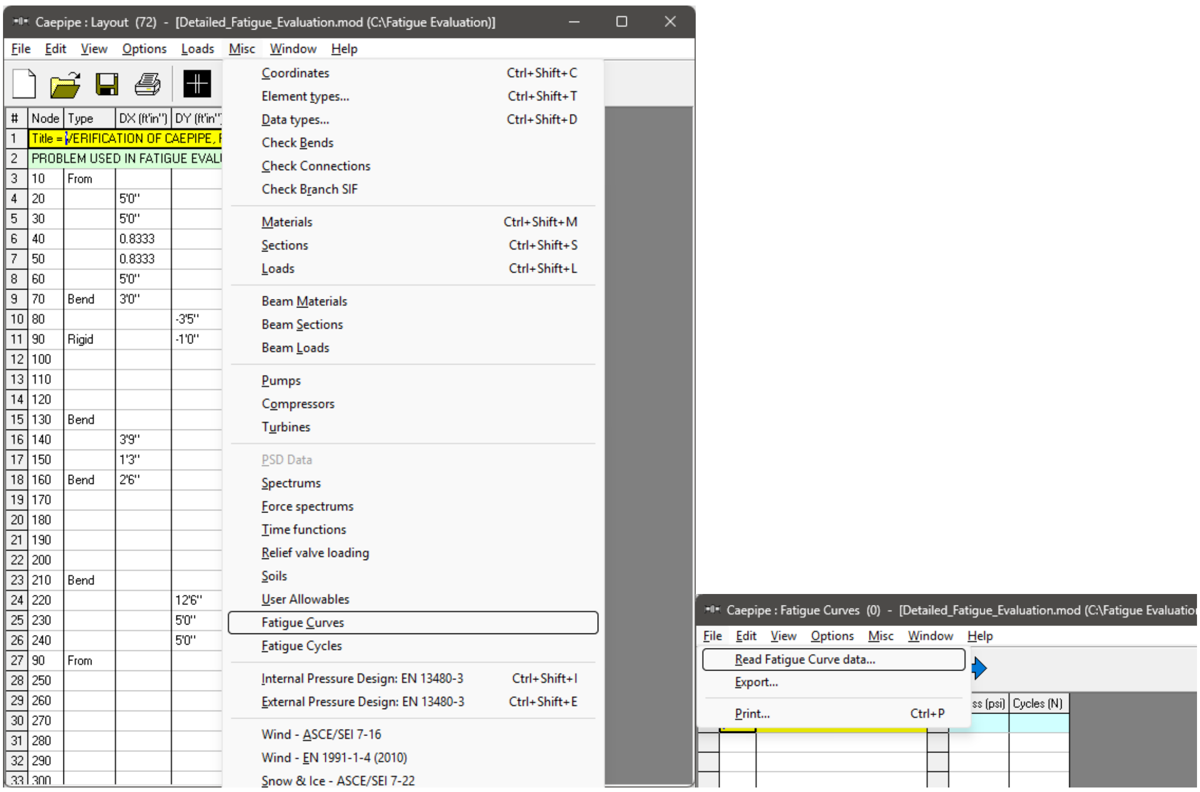


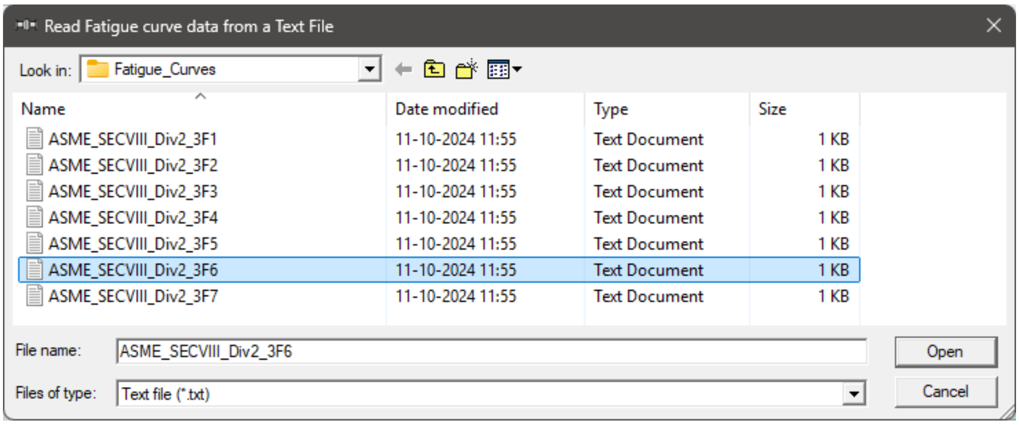
Step 4:

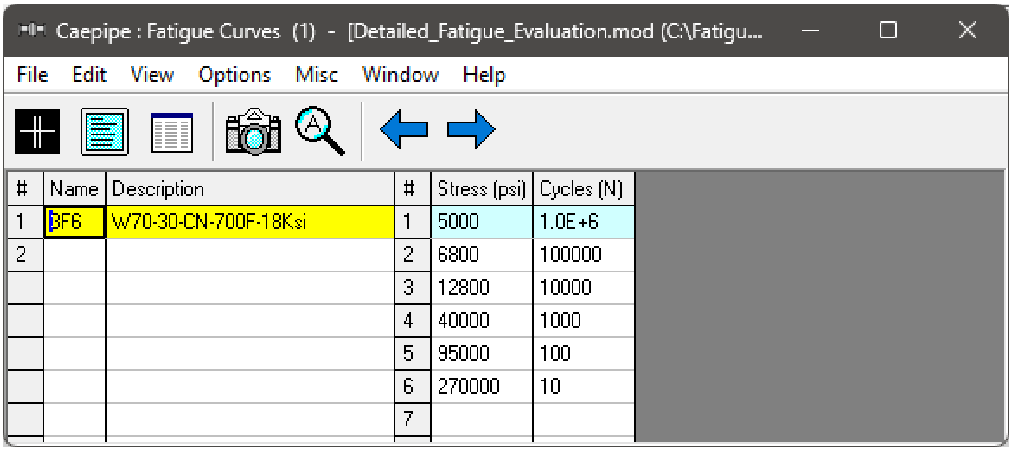
Import / Read the Fatigue Curve into CAEPIPE for Fatigue Evaluation.

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.

Fatigue curve corresponding to ‘Fatigue Curve for Wrought 70–30 Copper–Nickel for Temperatures not Exceeding 700°F—σys = 45 ksi’ *from* ASME Section VIII, Division 2 (2021)’ supplied with CAEPIPE is used for the present Fatigue Evaluation. This fatigue curve is imported into CAEPIPE by selecting the file ‘ASME_SECVIII_DIV2_3F6’ available in Fatigue Curves folder through “Layout Window > Misc > Fatigue Curves > File Menu > Read Fatigue curve data” as shown in the snapshots below.

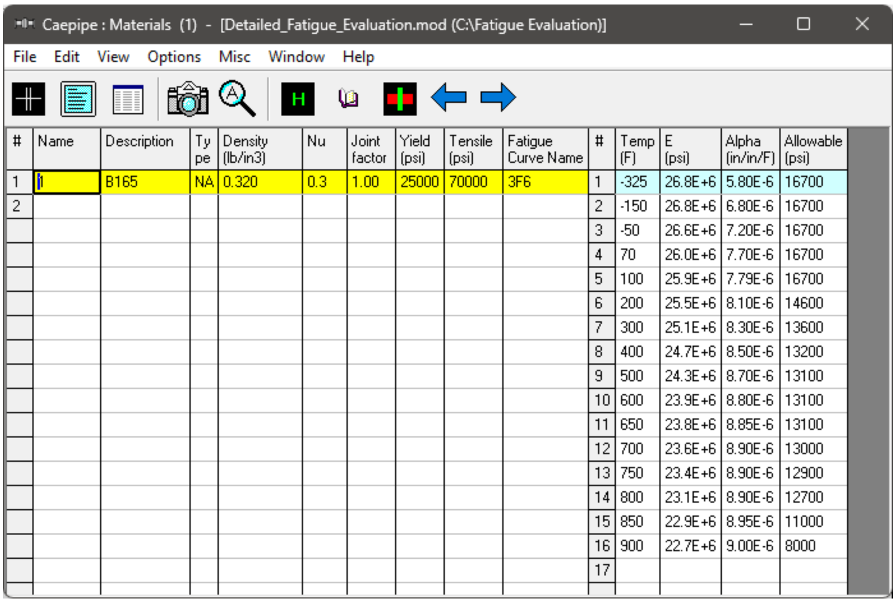






#	Name	Description	#	Stress (psi)	Cycles (N)
1	3F6	W70-30-CN-700F-18Ksi	1	5000	1.0E+6
2			2	6800	100000
			3	12800	10000
			4	40000	1000
			5	95000	100
			6	270000	10
			7		

Step 5:
Assign Fatigue Curves to the Materials 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
1	I	B165	NA	0.320	0.3	1.00	25000	70000	3F6
2									

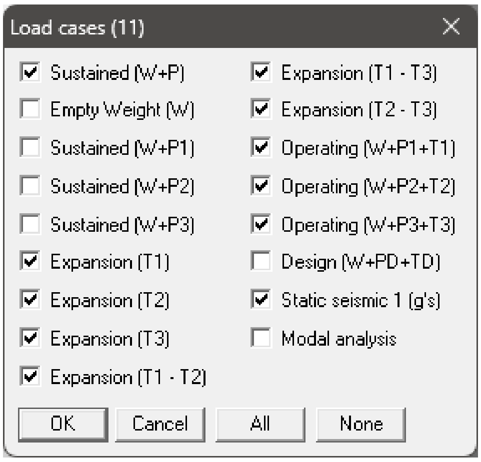
#	Temp (F)	E (psi)	Alpha (in/in/F)	Allowable (psi)
1	-325	26.8E+6	5.80E-6	16700
2	-150	26.8E+6	6.80E-6	16700
3	-50	26.6E+6	7.20E-6	16700
4	70	26.0E+6	7.70E-6	16700
5	100	25.9E+6	7.79E-6	16700
6	200	25.5E+6	8.10E-6	14600
7	300	25.1E+6	8.30E-6	13600
8	400	24.7E+6	8.50E-6	13200
9	500	24.3E+6	8.70E-6	13100
10	600	23.9E+6	8.80E-6	13100
11	650	23.8E+6	8.85E-6	13100
12	700	23.6E+6	8.90E-6	13000
13	750	23.4E+6	8.90E-6	12900
14	800	23.1E+6	8.90E-6	12700
15	850	22.9E+6	8.95E-6	11000
16	900	22.7E+6	9.00E-6	8000
17				

Note:

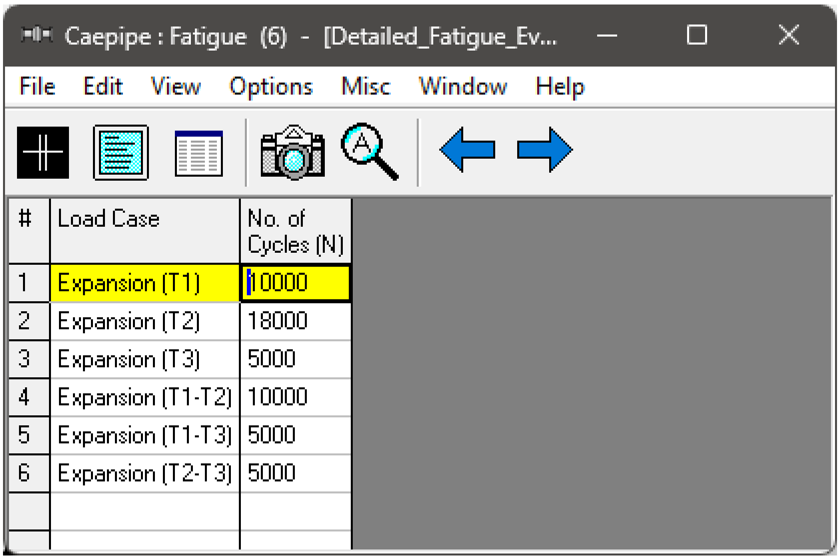
To exclude a section of the layout from fatigue analysis, the user should either create a new material or copy an existing one and leave the fatigue curve section blank. This material, with no assigned fatigue curve, can then be applied to all sections intended to be excluded from fatigue evaluation.

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.



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.

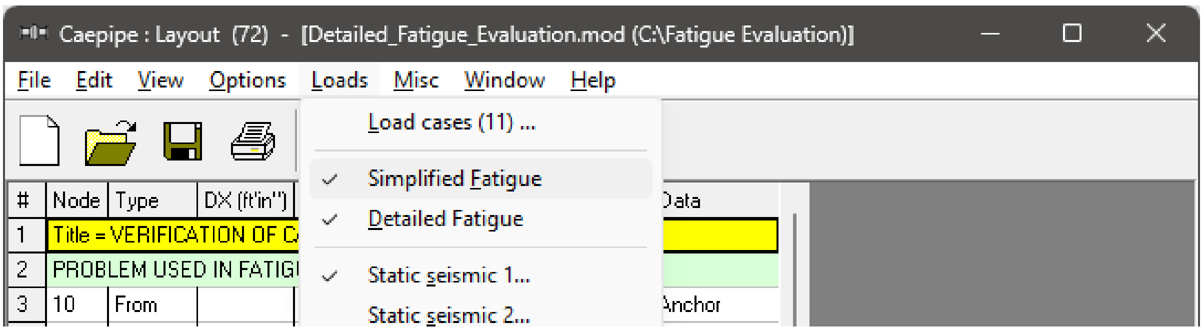


Note:

To exclude any load cases from fatigue analysis, the user should leave the "Number of Cycles (N)" section blank in the corresponding table.

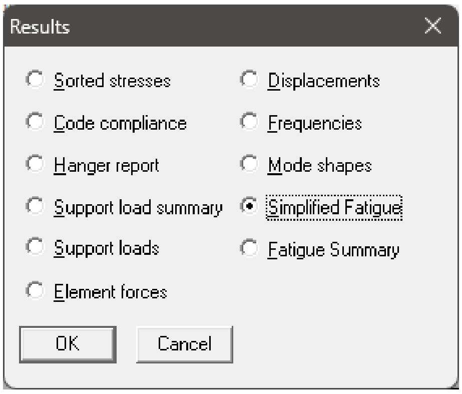
Step 7:

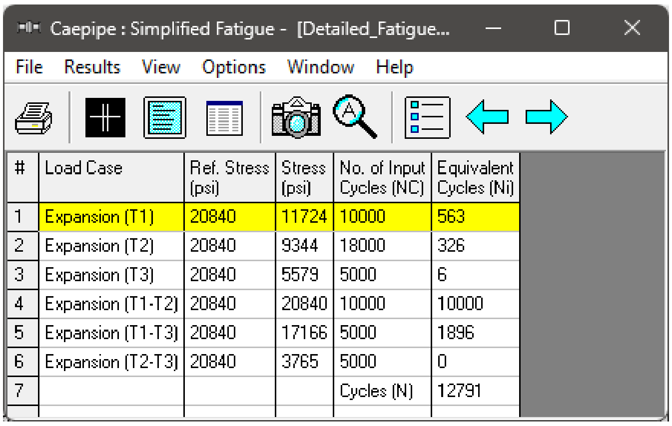
Turn ON (tick) the Simplified and Detailed Fatigue load cases through Layout Window > Loads.



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".

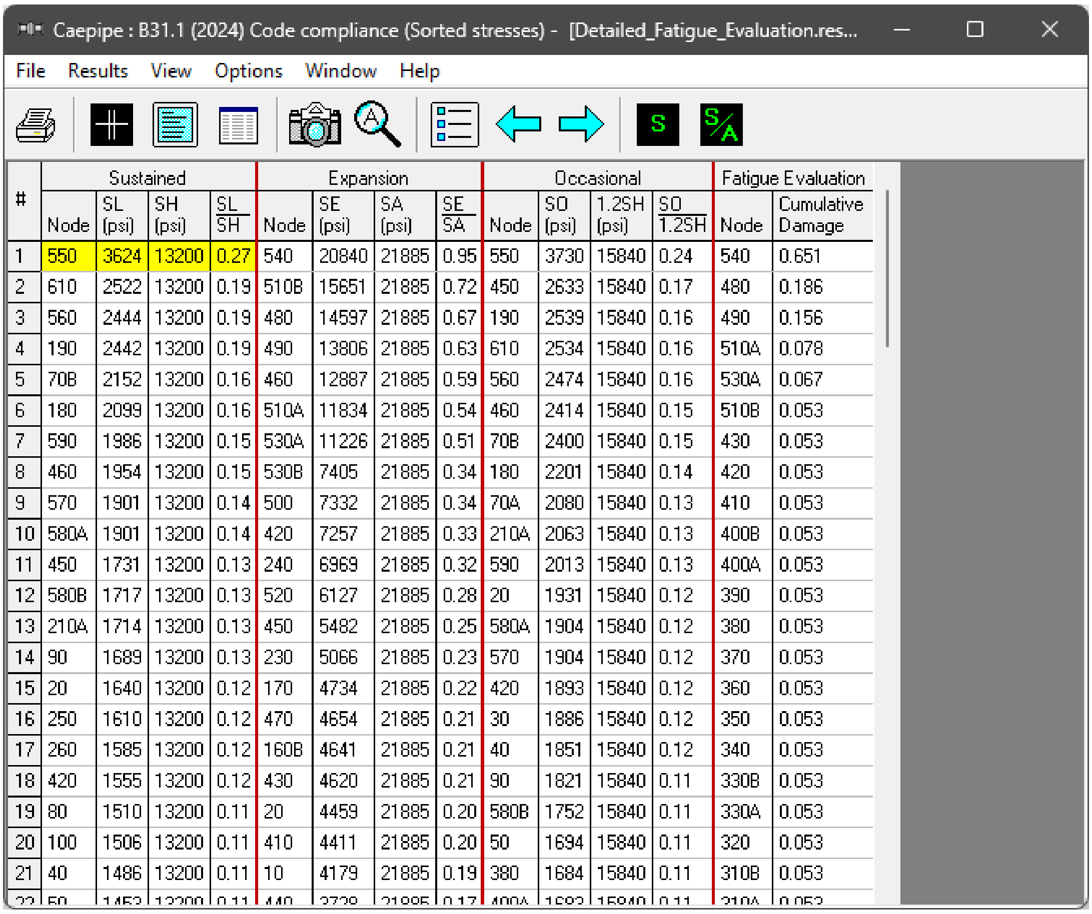




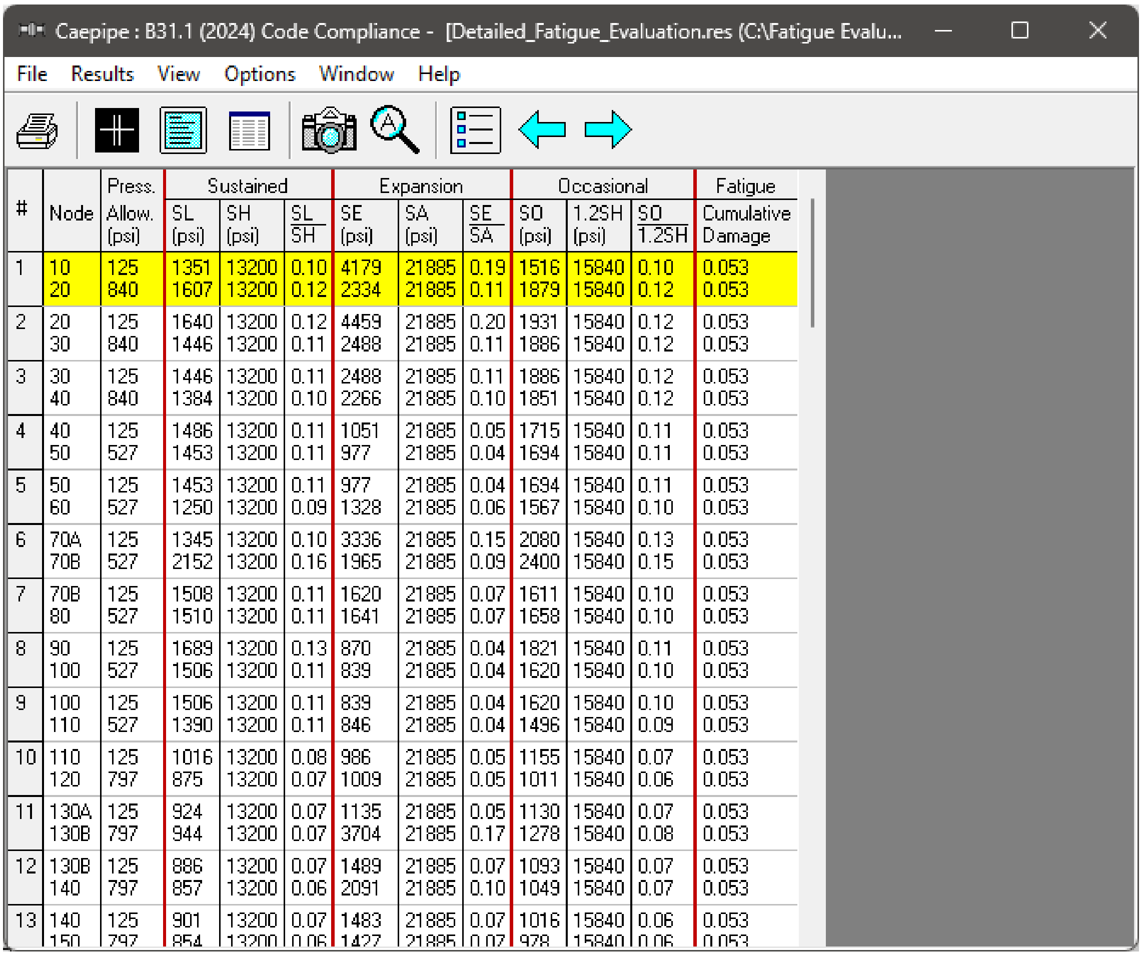
#	Load Case	Ref. Stress (psi)	Stress (psi)	No. of Input Cycles (NC)	Equivalent Cycles (Ni)
1	Expansion (T1)	20840	11724	10000	563
2	Expansion (T2)	20840	9344	18000	326
3	Expansion (T3)	20840	5579	5000	6
4	Expansion (T1-T2)	20840	20840	10000	10000
5	Expansion (T1-T3)	20840	17166	5000	1896
6	Expansion (T2-T3)	20840	3765	5000	0
7				Cycles (N)	12791

CAEPIPE uses the above computed equivalent number of full displacement cycles (N_i = 12791) to determine the Stress Range Reduction Factor (f), which is then used in computing the Expansion Allowable Stress (SA) shown under Sorted Stresses and Code Compliance results of CAEPIPE corresponding to the piping code ASME B31.1 (2024) selected for analysis.

Step 10:
Review the Detailed Fatigue Evaluation Results by selecting "Sorted stresses", "Code compliance", "Elemental Forces", or "Fatigue Summary" through "Results Window > Results" as shown below.

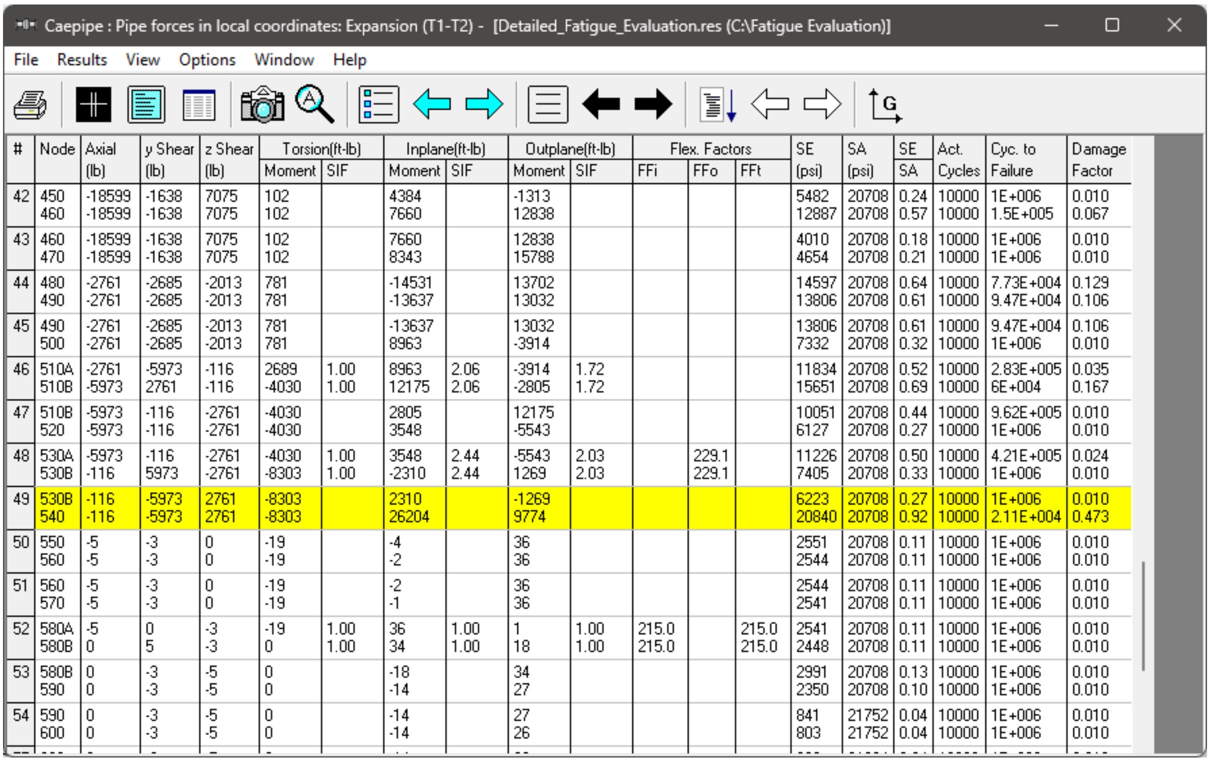


#	Sustained				Expansion				Occasional				Fatigue Evaluation	
	Node	SL (psi)	SH (psi)	SL/SH	Node	SE (psi)	SA (psi)	SE/SA	Node	SO (psi)	1.2SH (psi)	SO/1.2SH	Node	Cumulative Damage
1	550	3624	13200	0.27	540	20840	21885	0.95	550	3730	15840	0.24	540	0.651
2	610	2522	13200	0.19	510B	15651	21885	0.72	450	2633	15840	0.17	480	0.186
3	560	2444	13200	0.19	480	14597	21885	0.67	190	2539	15840	0.16	490	0.156
4	190	2442	13200	0.19	490	13806	21885	0.63	610	2534	15840	0.16	510A	0.078
5	70B	2152	13200	0.16	460	12887	21885	0.59	560	2474	15840	0.16	530A	0.067
6	180	2099	13200	0.16	510A	11834	21885	0.54	460	2414	15840	0.15	510B	0.053
7	590	1986	13200	0.15	530A	11226	21885	0.51	70B	2400	15840	0.15	430	0.053
8	460	1954	13200	0.15	530B	7405	21885	0.34	180	2201	15840	0.14	420	0.053
9	570	1901	13200	0.14	500	7332	21885	0.34	70A	2080	15840	0.13	410	0.053
10	580A	1901	13200	0.14	420	7257	21885	0.33	210A	2063	15840	0.13	400B	0.053
11	450	1731	13200	0.13	240	6969	21885	0.32	590	2013	15840	0.13	400A	0.053
12	580B	1717	13200	0.13	520	6127	21885	0.28	20	1931	15840	0.12	390	0.053
13	210A	1714	13200	0.13	450	5482	21885	0.25	580A	1904	15840	0.12	380	0.053
14	90	1689	13200	0.13	230	5066	21885	0.23	570	1904	15840	0.12	370	0.053
15	20	1640	13200	0.12	170	4734	21885	0.22	420	1893	15840	0.12	360	0.053
16	250	1610	13200	0.12	470	4654	21885	0.21	30	1886	15840	0.12	350	0.053
17	260	1585	13200	0.12	160B	4641	21885	0.21	40	1851	15840	0.12	340	0.053
18	420	1555	13200	0.12	430	4620	21885	0.21	90	1821	15840	0.11	330B	0.053
19	80	1510	13200	0.11	20	4459	21885	0.20	580B	1752	15840	0.11	330A	0.053
20	100	1506	13200	0.11	410	4411	21885	0.20	50	1694	15840	0.11	320	0.053
21	40	1486	13200	0.11	10	4179	21885	0.19	380	1684	15840	0.11	310B	0.053



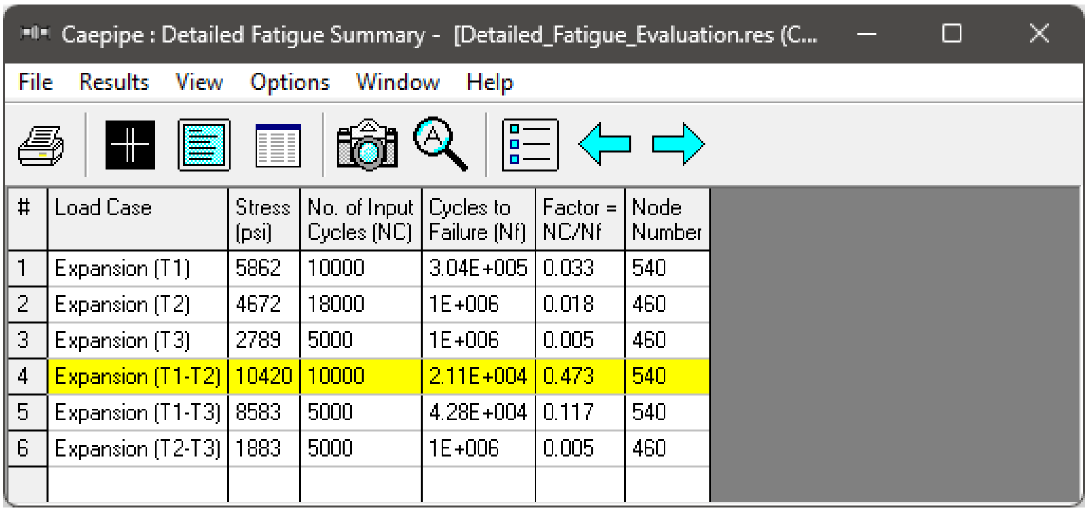
Caepipe : B31.1 (2024) Code Compliance - [Detailed_Fatigue_Evaluation.res (C:\Fatigue Evalu...

#	Node	Press. Allow. (psi)	Sustained SL (psi)	SH (psi)	SL/SH	Expansion SE (psi)	SA (psi)	SE/SA	Occasional SO (psi)	1.2SH (psi)	SO/1.2SH	Fatigue Cumulative Damage
1	10 20	125 840	1351 1607	13200 13200	0.10 0.12	4179 2334	21885 21885	0.19 0.11	1516 1879	15840 15840	0.10 0.12	0.053 0.053
2	20 30	125 840	1640 1446	13200 13200	0.12 0.11	4459 2488	21885 21885	0.20 0.11	1931 1886	15840 15840	0.12 0.12	0.053 0.053
3	30 40	125 840	1446 1384	13200 13200	0.11 0.10	2488 2266	21885 21885	0.11 0.10	1886 1851	15840 15840	0.12 0.12	0.053 0.053
4	40 50	125 527	1486 1453	13200 13200	0.11 0.11	1051 977	21885 21885	0.05 0.04	1715 1694	15840 15840	0.11 0.11	0.053 0.053
5	50 60	125 527	1453 1250	13200 13200	0.11 0.09	977 1328	21885 21885	0.04 0.06	1694 1567	15840 15840	0.11 0.10	0.053 0.053
6	70A 70B	125 527	1345 2152	13200 13200	0.10 0.16	3336 1965	21885 21885	0.15 0.09	2080 2400	15840 15840	0.13 0.15	0.053 0.053
7	70B 80	125 527	1508 1510	13200 13200	0.11 0.11	1620 1641	21885 21885	0.07 0.07	1611 1658	15840 15840	0.10 0.10	0.053 0.053
8	90 100	125 527	1689 1506	13200 13200	0.13 0.11	870 839	21885 21885	0.04 0.04	1821 1620	15840 15840	0.11 0.10	0.053 0.053
9	100 110	125 527	1506 1390	13200 13200	0.11 0.11	839 846	21885 21885	0.04 0.04	1620 1496	15840 15840	0.10 0.09	0.053 0.053
10	110 120	125 797	1016 875	13200 13200	0.08 0.07	986 1009	21885 21885	0.05 0.05	1155 1011	15840 15840	0.07 0.06	0.053 0.053
11	130A 130B	125 797	924 944	13200 13200	0.07 0.07	1135 3704	21885 21885	0.05 0.17	1130 1278	15840 15840	0.07 0.08	0.053 0.053
12	130B 140	125 797	886 857	13200 13200	0.07 0.06	1489 2091	21885 21885	0.07 0.10	1093 1049	15840 15840	0.07 0.07	0.053 0.053
13	140 150	125 797	901 854	13200 13200	0.07 0.06	1483 1427	21885 21885	0.07 0.07	1016 978	15840 15840	0.06 0.06	0.053 0.053



Caepipe : Pipe forces in local coordinates: Expansion (T1-T2) - [Detailed_Fatigue_Evaluation.res (C:\Fatigue Evaluation)]

#	Node	Axial (lb)	y Shear (lb)	z Shear (lb)	Torsion(ft-lb) Moment	SIF	Inplane(ft-lb) Moment	SIF	Outplane(ft-lb) Moment	SIF	Flex. Factors FFi	FFo	FFt	SE (psi)	SA (psi)	SE/SA	Act. Cycles	Cyc. to Failure	Damage Factor
42	450 460	-18599 -18599	-1638 -1638	7075 7075	102 102		4384 7660		-1313 12838					5482 12887	20708 20708	0.24 0.57	10000 10000	1E+006 1.5E+005	0.010 0.067
43	460 470	-18599 -18599	-1638 -1638	7075 7075	102 102		7660 8343		12838 15788					4010 4654	20708 20708	0.18 0.21	10000 10000	1E+006 1E+006	0.010 0.010
44	480 490	-2761 -2761	-2685 -2685	-2013 -2013	781 781		-14531 -13637		13702 13032					14597 13806	20708 20708	0.64 0.61	10000 10000	7.73E+004 9.47E+004	0.129 0.106
45	490 500	-2761 -2761	-2685 -2685	-2013 -2013	781 781		-13637 8963		13032 -3914					13806 7332	20708 20708	0.61 0.32	10000 10000	9.47E+004 1E+006	0.106 0.010
46	510A 510B	-2761 -5973	-5973 2761	-116 -116	2689 -4030	1.00 1.00	8963 12175	2.06 2.06	-3914 -2805	1.72 1.72				11834 15651	20708 20708	0.52 0.69	10000 10000	2.83E+005 6E+004	0.035 0.167
47	510B 520	-5973 -5973	-116 -116	-2761 -2761	-4030 -4030		2805 3548		12175 -5543					10051 6127	20708 20708	0.44 0.27	10000 10000	9.62E+005 1E+006	0.010 0.010
48	530A 530B	-5973 -116	-116 5973	-2761 -2761	-4030 -8303	1.00 1.00	3548 -2310	2.44 2.44	-5543 1269	2.03 2.03		229.1 229.1		11226 7405	20708 20708	0.50 0.33	10000 10000	4.21E+005 1E+006	0.024 0.010
49	530B 540	-116 -116	-5973 -5973	2761 2761	-8303 -8303		2310 26204		-1269 9774					6223 20840	20708 20708	0.27 0.92	10000 10000	1E+006 2.11E+004	0.010 0.473
50	550 560	-5 -5	-3 -3	0 0	-19 -19		-4 -2		36 36					2551 2544	20708 20708	0.11 0.11	10000 10000	1E+006 1E+006	0.010 0.010
51	560 570	-5 -5	-3 -3	0 0	-19 -19		-2 -1		36 36					2544 2541	20708 20708	0.11 0.11	10000 10000	1E+006 1E+006	0.010 0.010
52	580A 580B	-5 0	0 5	-3 -3	-19 0	1.00 1.00	36 34	1.00 1.00	1 18	1.00 1.00	215.0 215.0		215.0 215.0	2541 2448	20708 20708	0.11 0.11	10000 10000	1E+006 1E+006	0.010 0.010
53	580B 590	0 0	-3 -3	-5 -5	0 0		-18 -14		34 27					2991 2350	20708 20708	0.13 0.10	10000 10000	1E+006 1E+006	0.010 0.010
54	590 600	0 0	-3 -3	-5 -5	0 0		-14 -14		27 26					841 803	21752 21752	0.04 0.04	10000 10000	1E+006 1E+006	0.010 0.010



#	Load Case	Stress (psi)	No. of Input Cycles (NC)	Cycles to Failure (Nf)	Factor = NC/Nf	Node Number
1	Expansion (T1)	5862	10000	3.04E+005	0.033	540
2	Expansion (T2)	4672	18000	1E+006	0.018	460
3	Expansion (T3)	2789	5000	1E+006	0.005	460
4	Expansion (T1-T2)	10420	10000	2.11E+004	0.473	540
5	Expansion (T1-T3)	8583	5000	4.28E+004	0.117	540
6	Expansion (T2-T3)	1883	5000	1E+006	0.005	460

When the Detailed Fatigue Evaluation is enabled in the analysis for applicable piping codes, the following additional results will be added:

- Sorted Stresses: CAEPIPE will display additional columns under the "Fatigue Evaluation".
- Code Compliance: CAEPIPE will display additional column under the "Fatigue" section. This column will show the cumulative damage factor calculated from all the selected expansion load cases at each element, as illustrated above.
- Element Forces: CAEPIPE will display additional columns titled Actual number of cycles (Act. Cycles), Number of cycles to failure (Cyc. to Failure) and Damage Factor related to Fatigue Evaluation as shown above.

Summary:

Since the total *Cumulative Damage factor at each node is less than 1.0, the stress layout is considered safe for the considered thermal cycles and no further modifications for the stress layout is required as per Fatigue Evaluation.*