Threaded and Coupled Connector Analysis Using Abaqus CAXA

Roger Chang

Engineering, Research & Computing

Amrik Nijar

FMC Technologies, Inc.

Abstract: Analysis methodologies developed for evaluating three threaded and coupled connectors quantitatively are presented. Two new non-dimensional parameters for assessing the seal leakage and load shoulder separation are introduced for the purpose. Stress Amplification Factor (SAF), defined in API Specification 16R, is scrutinized for what type of stress is to be used and which reference point the alternating stress is measured from. As a result of it, loading sequence Mean Tension with Two Alternating Moments (MT2AM) is proposed for SAF calculation.

Keywords: Oil and Gas, Riser Connector, Load Capacity, Seal Leakage, Load Shoulder Separation, Fatigue, Stress Concentration Factor, Stress Amplification Factor.

1. Introduction

Threaded and coupled (T&C) connection traditionally is used for down-hole casing, but it is becoming popular in deepwater riser application for three reasons: 1) its short makeup time, relative to the flanged connection, 2) its immunity to the problems associated with weld, and 3) the weight saving because of high strength material being used. But because the thread profile is cut on the riser pipe base metal, the cross section area of the most critical first thread root is smaller than the riser pipe. The connection is hence weaker than the connecting pieces, which violates the first rule in connection design. In conjunction with the stress concentration due to notched geometry (thread), it makes riser designers think twice before selecting T&C connector as the connection.

For the above reasons, a major oil company had funded three vendors to design a fit-for-purpose T&C connector for its completion and work-over riser (Craig, 2007). Comprehensive design verification and testing program was developed by this major oil company for evaluating the connectors. Vendors were to design the connector by analysis; however, both analysis verification and testing were to be done by third party for consistency and objectivity.

Four criteria were set to evaluate the connector; they were strength, seal leakage, load shoulder separation and fatigue performance in term of stress concentration. For the strength requirement, the typical stress linearization and utilization factor procedure was followed. For seal leakage and load shoulder separation, two 'new' non-dimensional parameters were introduced in order to make objective assessments. Stress Amplification Factor (SAF), 'ambiguously' defined in API Spec. 16R was scrutinized for what type of stress should be used and which reference the alternating stress measuring from. As a result of it, Mean Tension with Two Alternating Moments loading sequence was proposed for SAF calculation.

T&C connector is an axisymmetric structure subject to non-axisymmetric bending moment. Even though Abaqus now has cylindrical element (CCL), however, since only the tension side and compression side, corresponding to the 0- and 180-degree nodal planes, are of the main concerns, CAXA element is hence chosen for the analysis. The other reason is author's familiarity (Chang, 1994).

2. STRENGTH CHECK

Figure 1 shows one half of a typical T&C connector with two most critical Stress Classification Lines (SCL's) identified. Stress linearization per ASME Section VIII, Division 2 is performed to calculate the membrane stress (P_m) and bending stress (P_b). Case Factor (k) is assigned to obtain the allowable stress and Utilization Factor (U.F.), which is defined as the linearized stress over the allowable stress. The load capacity chart may then be constructed, as shown in Figure 2 for k=1. Any two of pressure, tension and moment are known, the third may be extracted from the chart.

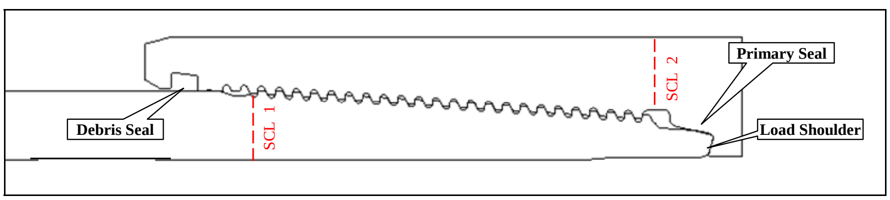

Figure 1. 'Typical' T&C Connector (Half)

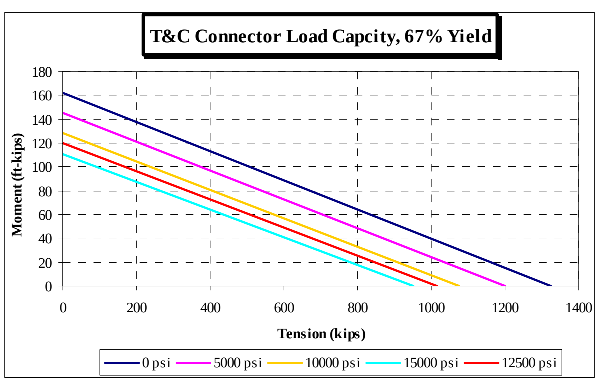

Figure 2. Load Capacity Chart

3. SEAL LEAKAGE

Contact pressure at the seal can be obtained from finite element analysis, as shown in Figure 3. Note the positive X-axis is the seal length on the tension side and the negative X-axis is for the compression side. But there is no well-accepted definite criterion for seal leakage documented in the literature, a non-dimensional parameter (S_L) is proposed for the seal leakage check.

$$S_L = \frac{P_{\max}}{P_{app}} \frac{A}{P_{app} L_o} \frac{l}{L_o} \tag{1}$$

where P_{max} is the maximum contact pressure, P_{app} is the applied internal pressure, A is the area underneath the contact pressure curve, L_o is the seal 'original' length during preload (design seal length), and l is the seal length measured between both ends' contact pressure greater than the applied pressure. It should be noted that the parameter is infinite when the applied pressure is zero, i.e., no applied pressure, the seal is sealed. Also, the term $P_{app}L_o$ is the area of the internal pressure applied uniformly across the design seal length, it may be considered as the 'idealized' seal energy.

The higher the value of S_L is, the better the seal is. The exact value of S_L at which seal leakage occurs is not known at the time of this paper is written; however, it can be determined by testing. This non-dimensional parameter has the potential to be a design specification as the yield strength and CTOD commonly specified in the design requirements.

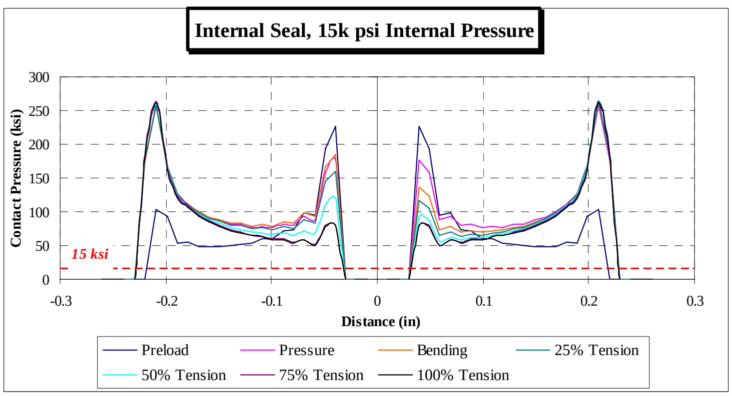

Figure 3. Primary Seal Contact Stress Plot

4. LOAD SHOULDER SEPARATION

If the second term in Equation 1 is 'flipped', then another non-dimensional parameter (S_P) may be defined as:

$$S_P = \frac{P_{\max}}{P_{app}} \frac{P_{app} L_o}{A} \frac{l}{L_o} = \frac{P_{\max} l}{A} \tag{2}$$

Note that the P_{app} and L_o are canceled. Therefore, S_P no longer depends on the applied internal pressure (not for checking leakage). If the shoulder is separated, all three terms in Equation 2 are zero, an undetermined S_p. Otherwise, all three terms should be nonzero. The smaller the value of S_p at preload is, the earlier the separation will occur. Figure 4 shows the contact stress at the load shoulder (identified in Figure 1).

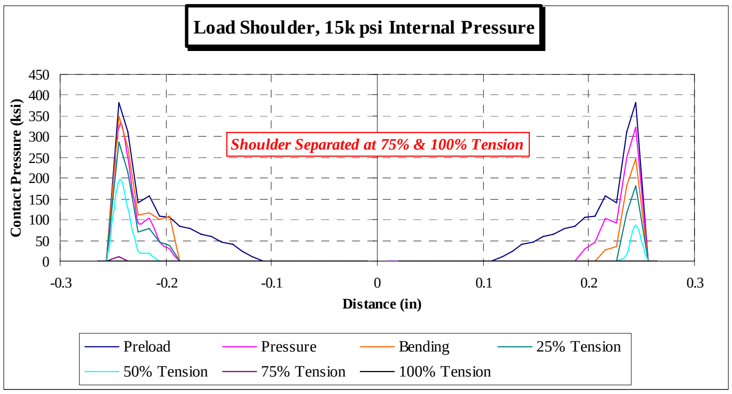

Figure 4. Load Shoulder Contact Stress Plot

5. STRESS AMPLIFICATION FACTOR

In the global riser fatigue analysis, stress histograms are generated by Rainflow counting (RFC) along the full riser length including connectors and/or welds. But, the stresses are calculated based on the riser pipe dimensions. To calculate the fatigue life of a riser connector, either a local fatigue analysis of the connector is to be performed with ***load*** histograms obtained from the global riser analysis as the input or a link between the riser pipe stress and connector peak stress is to be established so that the stress histograms may be multiplied and fatigue analysis is performed at the global level.

Because the local fatigue life analysis is a time-consuming process, the latter approach is generally taken. Stress Amplification Factor (SAF) is the link relates the peak alternating stress obtained from Finite Element Analysis (FEA) of a connector to its connecting pipe's nominal alternating stress. Axisymmetric model for the connector is created and only elastic analysis is performed in the 'traditional' (still commonly practiced) approach. After the preload step, a uniform upward pressure is applied at the top of model (riser pipe) to simulate the tension side connector behavior, and downward pressure for the compression side. Usually, both upward (tension) and downward (compression) pressures are applied in even increments to simulate the nominal alternating stress in pipe. This is so-called the equivalent tension approach, which is an approximation for bending moment. Since the pressures are used to simulate the alternating stress, the same pressure (stress) may also be interpreted as being caused by mean tension. As the result of it, the load sequence is monotonic loading. Figure 5 shows the traditional riser connector analysis flow chart.

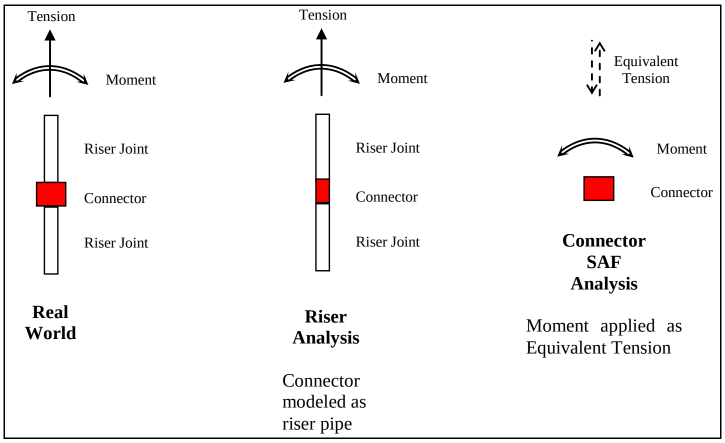

Figure 5. Traditional' Riser Connector Analysis Flow Chart

Even though Stress Concentration Factor (SCF) and Stress Amplification Factor (SAF) have commonly been used interchangeably, however strictly speaking, they are different. SCF used in Peterson and generally practiced for simple geometric singularity, refers to the notch neck section of structural component under study. It is a constant. SAF, defined in API Spec 16R, is to relate the connector local peak stress to its connecting riser pipe. Due to the contact nonlinearity and preload, SAF of a preloaded riser connector will be nonlinear, function of the applied load.

The SAF definition is stated in API Spec. 16R, Section 4.1.3 as:

$$SAF = \frac{\text{Local Peak Alternating Stress}}{\text{Nominal Alternating Stress in THE Pipe}}$$

The definition seems to be simple and straightforward. But, what type of stress should be used has been controversial. Also, the term ‘alternating’ calls for a reference point. Which reference point the alternating stress is measured from leads to different ways calculating SAF. The following two sections discuss these two issues.

5.1 What type of stress should be used?

Three types of stresses are used in practice: 1) Maximum principle stress (absolute value) is documented in most regulatory standards, 2) Axial stress (with sign) is originated from the tensile test, and 3) Scalar stress, such as von Mises stress or Tresca stress, has been suggested in the ‘multi-axial stresses’ fatigue analysis (Fuchs, Stephens, 1980 and Bishop, Sherratt, 2000).

To make the matter worse, FEA calculates the stress at the integration point first, then extrapolates the stress to nodes, and finally averages the nodal stresses. Each program has its extrapolation scheme. Also, each program reports different levels of stress detail; some only allow users to extract the averaged nodal stress, others output the stresses at the three steps of nodal stress calculation.

Finite element analysts have been utilizing 'skin' element to get the surface stress (Bishop, Sherratt, 2000) and finite element programs, such as Abaqus, have surface membrane elements available for the purpose. The idea is quite simple but creative; this skin element in essence is a strain gauge. For a 3D solid element model, membrane element is laying on the surface of area of interest. For axisymmetric model, ultra-thin shell element (0.00001" thick) is historically used even though Abaqus does have axisymmetric membrane element.

Since the stress concentration factor (SCF) of a tension bar of circular section with a U-shape groove is documented in Chart 2.19 of Peterson, finite element analyses were performed for it. The analysis results were then benchmarked against with Peterson to determine what stress to be used, at which location, and whether the strain gauge element is needed.

The test model is shown in Figure 6, the strain gauge elements are shown in Red. The shaft diameter (D) is 6", the groove 'neck' diameter (d) is 5" and the groove radius (r) is 0.5". The bottom end (right end in the graph) was fixed and pressure of 1000 psi was applied at top end. For the dimensions chosen for the test model, Chart 2.19 of Peterson shows that SCF is 2.34 (D/d=1.2, r/d=0.1). It should be noted the σ_{nom} in Peterson is at the neck, if calculated based on the shaft diameter, SAF should be 3.37 (=2.34*1.2^2, where 1.2 is D/d).

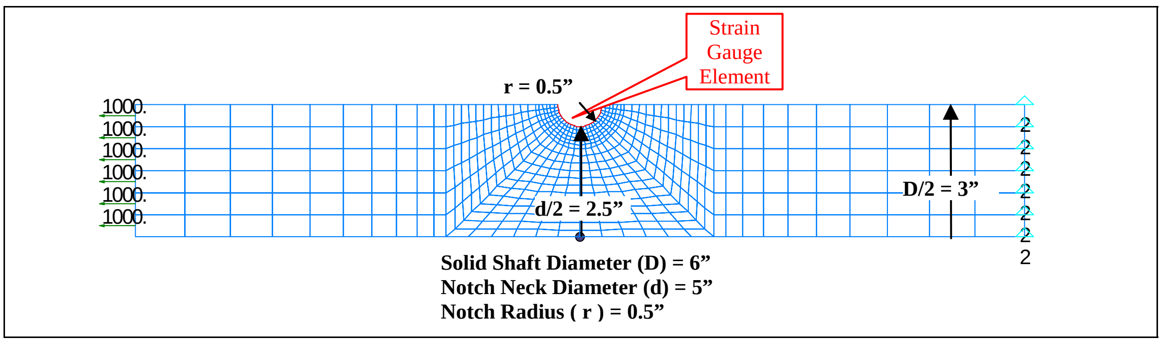

Figure 6. Test Grooved Shaft Model

Ten test runs were performed and the results are summarized in Table 1. Linear and quadratic elements with reduced and full integration were studied in combination with and without strain gauge element. The last two were the CAXA elements. For each run, stress at integration point, extrapolated nodal stress, and averaged nodal stress are requested. Several observations and conclusions are made based on the test results:

1. SAF's by the quadratic elements are closer to the targeted value than those by the linear element and the full integration has 'better' SAF than the reduced integration. These are expected knowing the basic finite element formulation. If no contact nonlinearity exists, higher order elements with full integration should be used for the stress concentration calculation. But, it is also known that higher order contact element has the 'inherited'

stress pattern at mid-node problem; hence, as a general guideline, linear element has been the choice for the analyses with contact.

2. Either axial or principle stress at the integration point of strain gauge element has the most 'consistent' SAF's. Also, strain gauge element on the linear element has the same stress regardless the location (integration point, nodes, averaged at node); another reason for using linear element with strain gauge.
3. Since the applied pressure (dominator of SAF definition) is in essence of axial stress, the axial stress or surface stress should also be used in the numerator to be consistent.

Table 1. Test Runs' Results

Test Case	Element Type	Integration Points			Nodes			Averaged at Node		
		Axial	Principle	VMS	Axial	Principle	VMS	Axial	Principle	VMS
1	CAX4R	2.837	2.845	2.439	2.837	2.845	2.439	2.837	2.837	2.426
	SAX1	3.315	3.315	2.992	3.315	3.315	2.992	3.315	3.315	2.992
2	CAX4	2.943	2.945	2.606	3.026	3.026	2.740	3.026	3.026	2.740
	SAX1	3.293	3.293	2.973	3.293	3.293	2.973	3.293	3.293	2.973
3	CAX4R	2.837	2.845	2.439	2.837	2.845	2.439	2.837	2.837	2.426
4	CAX4	2.943	2.945	2.606	3.026	3.026	2.740	3.026	3.026	2.740
5	CAX8R	3.091	3.092	2.718	3.299	3.299	2.960	3.298	3.298	2.960
	SAX2	3.315	3.315	2.993	3.308	3.308	2.987	3.307	3.307	2.985
6	CAX8	3.225	3.226	2.843	3.392	3.392	2.994	**3.391**	**3.391**	2.993
	SAX2	3.315	3.315	2.993	3.308	3.308	2.987	3.307	3.307	2.985
7	CAX8R	3.090	3.092	2.718	3.298	3.298	2.960	3.298	3.298	2.960
8	CAX8	3.225	3.226	2.843	3.391	3.391	2.993	3.391	3.391	2.993
9	CAXA4R1	2.830	2.838	2.435	2.830	2.838	2.435	2.830	2.830	2.422
	SAXA11	3.312	3.312	2.990	3.312	3.312	2.990	3.312	3.312	2.990
10	CAXA8R1	3.091	3.092	2.718	3.299	3.299	2.960	3.298	3.298	2.960
	SAXA21	3.315	3.315	2.993	3.308	3.308	2.987	3.307	3.307	2.985

5.2 Which Reference Point the Alternating Stress Is Measured From?

Fatigue damage of 5 ksi alternating stress with 20 ksi mean stress will be different than the same 5 ksi alternating stress with 30 ksi mean stress. Therefore, to cover all possible stress states, the SAF calculation should be done for numerous mean stresses (datum point the alternating stress is measured from). Mathematically, it is expressed as:

$$SAF_i^{\,j} = \frac{\sigma_i - \overline{\sigma}^{\,j}}{S_i - \overline{S}^{\,j}} \tag{3}$$

where S is the nominal stress in pipe and $\overline{S}$ is the pipe mean stress. σ is the peak stress in the connector and $\overline{\sigma}$ is the connector peak stress corresponding to $\overline{S}$. The subscript i is the number of alternating stresses and the superscript j is the number of mean stresses.

However, the analyses required to provide this most comprehensive SAF data set are tremendous and the SAF data will be overwhelming. Hence, the SAF calculation is simplified into three ways. The first one is so-called ‘instantaneous slope’ method. The second one is just referring to the preload only. The third one is the proposed One Mean Tension followed by Two Alternating Moments (MT2AM). Mathematically, they may be expressed in Equations 4 and 6, respectively. Figure 7 shows the magnitude of the most comprehensive SAF calculation and the ‘relative position’ of the three SAF simplifications with respect to it.

$$SAF_i = \frac{\sigma_{i+1} - \sigma_i}{S_{i+1} - S_i} \tag{4}$$

$$SAF_i = \frac{\sigma_i - \sigma_o}{S_i} \tag{5}$$

$$SAF_{i=1}^j = 0.5 * \left(\frac{\sigma_{+i}^j - \overline{\sigma}^j}{S_{+i}^j - \overline{S}^j} + \frac{\sigma_{-i}^j - \overline{\sigma}^j}{S_{-i}^j - \overline{S}^j} \right) \tag{6}$$

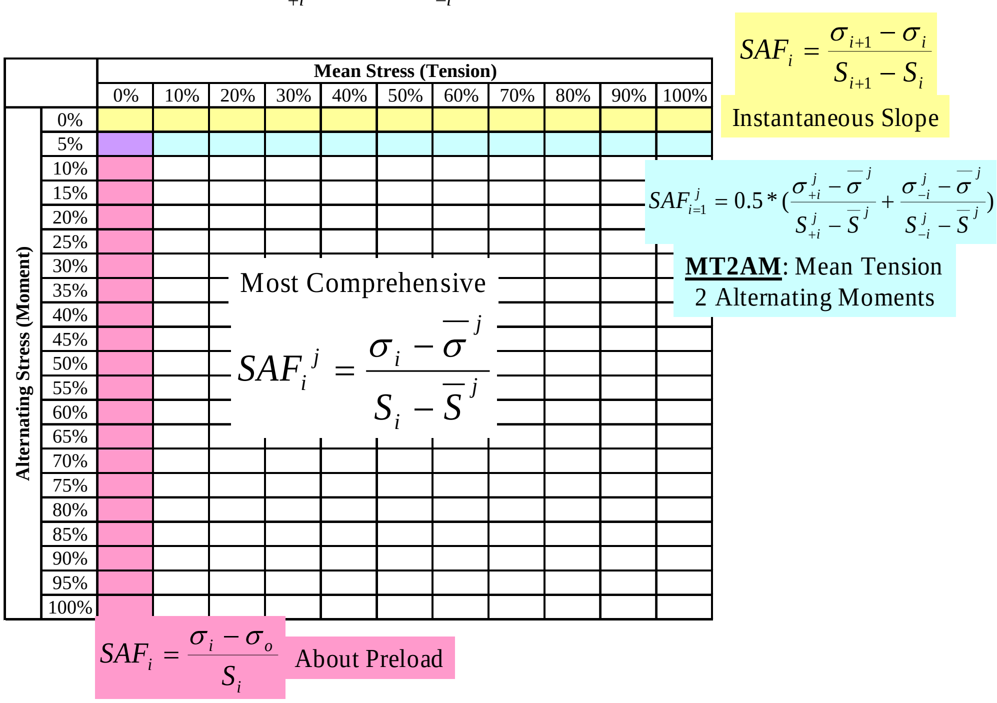

Figure 7. SAF Definitions

The instantaneous slope method, Equation 4, implies that the SAF’s calculated by it will be of the same nominal alternating pipe stress ΔS ($=S_{i+1} - S_i$), if the same load increment is used in the connector analysis. In Equation 5, σ_o is the connector preload stress. Note S_o is zero in Equation 5, hence it is not in the denominator. It shall be noted that neither equation defines the SAF at the preload. Also, a monotonically increasing load sequence is to be used in both methods.

The MT2AM SAF calculation, Equation 6, only one alternating stress (due to moment) is chosen to calculate the SAF, hence *i=1* in comparing with Equation 3. The following two moments, one positive and one negative, are applied after the mean stress (due to tension). Table 2 shows the load sequence in MT2AM method, where the mean tension is increased by 10% of Pipe Body Yield Strength (PBYS, 95 ksi was assumed) and the alternating moment is chosen to be 5% of PBYS. The SAF at the mean stress is the average of two SAF's calculated by alternating stress with respect to the mean stress. Note that the SAF at the preload can now be defined by MT2AM method.

Table 2. Load Sequence in MT2AM Method

Load Step	Applied Load %PBYS		Applied Load (stress ksi)		
	Cmpr. Side	Tens. Side	Cmpr. Side	Tens. Side	
1	0%	0%	0.000	0.000	Preload
2	-5%	5%	-4.750	4.750	Positive Moment
3	5%	-5%	4.750	-4.750	Negative Moment
4	10%	10%	9.500	9.500	10% Tension
5	5%	15%	4.750	14.250	10% Tension with Positive Moment
6	15%	5%	14.250	4.750	10% Tension with Negative Moment
7	20%	20%	19.000	19.000	20% Tension
8	15%	25%	14.250	23.750	20% Tension with Positive Moment
9	25%	15%	23.750	14.250	20% Tension with Negative Moment
10	30%	30%	28.500	28.500	30% Tension
11	25%	35%	23.750	33.250	30% Tension with Positive Moment
12	35%	25%	33.250	23.750	30% Tension with Negative Moment
13	40%	40%	38.000	38.000	40% Tension
14	35%	45%	33.250	42.750	40% Tension with Positive Moment
15	45%	35%	42.750	33.250	40% Tension with Negative Moment
16	50%	50%	47.500	47.500	50% Tension
17	45%	55%	42.750	52.250	50% Tension with Positive Moment
18	55%	45%	52.250	42.750	50% Tension with Negative Moment
19	60%	60%	57.000	57.000	60% Tension
20	55%	65%	52.250	61.750	60% Tension with Positive Moment
21	65%	55%	61.750	52.250	60% Tension with Negative Moment
22	70%	70%	66.500	66.500	70% Tension
23	65%	75%	61.750	71.250	70% Tension with Positive Moment
24	75%	65%	71.250	61.750	70% Tension with Negative Moment
25	80%	80%	76.000	76.000	80% Tension
26	75%	85%	71.250	80.750	80% Tension with Positive Moment
27	85%	75%	80.750	71.250	80% Tension with Negative Moment
28	90%	90%	85.500	85.500	90% Tension
29	85%	95%	80.750	90.250	90% Tension with Positive Moment
30	95%	85%	90.250	80.750	90% Tension with Negative Moment
31	100%	100%	95.000	95.000	100% Tension
32	95%	105%	90.250	99.750	100% Tension with Positive Moment
33	105%	95%	99.750	90.250	100% Tension with Negative Moment

It should be noted that the Instantaneous Slope calculation actually can be derived from MT2AM method. For 20% PBYS mean stress and 5% PBYS alternating stress,

$$SAF_{+5\%}^{20\%} = \frac{\sigma_{25\%} - \overline{\sigma}^{20\%}}{S_{25\%} - \overline{S}^{20\%}} = \frac{\sigma_{25\%} - \overline{\sigma}^{20\%}}{\Delta S_{5\%}}$$

$$SAF_{-5\%}^{20\%} = \frac{\sigma_{15\%} - \overline{\sigma}^{20\%}}{S_{15\%} - \overline{S}^{20\%}} = \frac{\sigma_{15\%} - \overline{\sigma}^{20\%}}{-\Delta S_{5\%}}$$

$$SAF_{5\%}^{20\%} = 0.5*\left(\frac{\sigma_{25\%} - \overline{\sigma}^{20\%}}{S_{25\%} - \overline{S}^{20\%}} + \frac{\sigma_{15\%} - \overline{\sigma}^{20\%}}{S_{15\%} - \overline{S}^{20\%}}\right) = 0.5*\left(\frac{\sigma_{25\%} - \sigma_{15\%}}{\Delta S_{5\%}}\right)$$

It equals to $\frac{\sigma_{25\%} - \sigma_{15\%}}{\Delta S_{10\%}}$, which can be interpreted as $\frac{\sigma_{25\%} - \sigma_{15\%}}{S_{25\%} - S_{15\%}}$, instantaneous slope SCF with load increment of 10% of PBYS ($\Delta S_{10\%}$).

5.2.1 MT2AM Method Illustration

Five cases are examined to evaluate 1) which simplified SAF method provides better link between the connector peak stress and pipe nominal stress, 2) whether plasticity has any effect on SAF, and 3) whether the magnitude of alternating moment matters.

1. Elastic Solution, Low Preload Stress
2. Plastic Solution, Low Preload Stress
3. Elastic Solution, High Preload Stress
4. Plastic Solution, High Preload Stress
5. Parametric Study of Alternating Moment Magnitude

Due to the number of pages limitation, only the low preload stress cases will be presented in this paper. To further illustrate how MT2AM works, Table 3 and Figure 8 are used to show the 'internal screening' process of the method.

There are three sub-tables in Table 3. The upper-left sub-table is the elastic solution and the plastic results are in the upper-right sub-table. The first three columns are at the compression side and the next three columns are at the tension side. Each side has the applied stress, axial stress and SAF values; the applied stresses correspond to the last two columns of Table 2, the axial stresses are extracted from analysis, and the SAF are calculated per Equation 6, i.e., the positive moment step is based on the first term of the equation and the second term is for the negative moment step, the SAF at the mean tension step is the average of the two.

To show the alternating moment stress at the preload, only the tension side's data are graphically shown in Figure 8, it also has three graphs. The upper-left graph is the axial stress vs. applied stress plot of each load step. The alternating moment with respect to the mean tension is well observed, particularly for the plastic solution. The upper right graph is the SAF vs. applied stress plot of each load step; it is quite 'confusing'. The bottom graph corresponds to the bottom table of Table 3, in which the 'intermediate' alternating moment steps are omitted per Equation 6. The axial stress is on the primary Y-axis and SAF on the secondary Y-axis. It is observed that hardly any major SAF difference between the elastic solution and plastic solution. Note that the same observation is not true at the compression side, nor the other two SAF calculations exhibit the same SAF pattern. Both will be shown in the latter graphs.

Table 3. MT2AM Method Illustration

Elastic Solution, Low Preload Stress, MT2AM Load Sequence

Compression Side			Tension Side		
Applied	Axial	SAF	Applied	Axial	SAF
0.00	2.92	**4.950**	0.00	2.92	**4.889**
-4.75	-19.98	4.822	4.75	26.89	5.046
4.75	27.05	5.079	-4.75	-19.56	4.733
9.50	51.66	**4.764**	9.50	51.67	**4.749**
4.75	29.07	4.756	14.25	74.41	4.788
14.25	74.32	4.772	4.75	29.29	4.711
19.00	99.52	**4.637**	19.00	99.53	**4.631**
14.25	77.50	4.637	23.75	121.60	4.647
23.75	121.55	4.637	14.25	77.61	4.615
28.50	141.35	**3.684**	28.50	141.42	**3.707**
23.75	123.71	3.714	33.25	158.72	3.642
33.25	158.71	3.655	23.75	123.50	3.773
38.00	178.88	**3.657**	38.00	178.94	**3.714**
33.25	161.36	3.688	42.75	195.87	3.564
42.75	196.10	3.625	33.25	160.59	3.863
47.50	216.45	**3.615**	47.50	216.50	**3.668**
42.75	199.04	3.665	52.25	233.10	3.495
52.25	233.38	3.564	42.75	198.25	3.842
57.00	254.32	**3.542**	57.00	254.35	**3.592**
52.25	237.23	3.598	61.75	270.46	3.392
61.75	270.88	3.486	52.25	236.34	3.792
66.50	292.19	**3.453**	66.50	292.17	**3.505**
61.75	275.52	3.509	71.25	307.86	3.303
71.25	308.32	3.396	61.75	274.56	3.707
76.00	330.06	**3.361**	76.00	330.02	**3.412**
71.25	313.83	3.417	80.75	345.21	3.198
80.75	345.76	3.305	71.25	312.80	3.625
85.50	367.81	**3.268**	85.50	367.76	**3.319**
80.75	352.03	3.322	90.25	382.51	3.105
90.25	383.08	3.215	80.75	350.98	3.533

Plastic Solution, Low Preload Stress, MT2AM Load Sequence

Compression Side			Tension Side		
Applied	Axial	SAF	Applied	Axial	SAF
0.00	0.83	**4.818**	0.00	0.83	**4.765**
-4.75	-20.26	4.439	4.75	25.27	5.145
4.75	25.51	5.197	-4.75	-20.01	4.385
9.50	49.11	**4.571**	9.50	49.08	**4.607**
4.75	27.24	4.604	14.25	70.55	4.521
14.25	70.67	4.539	4.75	26.79	4.693
19.00	93.19	**3.611**	19.00	93.15	**4.266**
14.25	71.91	4.481	23.75	106.23	2.755
23.75	106.21	2.740	14.25	65.70	5.777
28.50	106.81	**1.939**	28.50	106.81	**3.686**
23.75	89.15	3.718	33.25	107.54	0.154
33.25	107.57	0.160	23.75	72.52	7.219
38.00	108.08	**1.933**	38.00	108.09	**3.662**
33.25	90.22	3.760	42.75	108.56	0.099
42.75	108.58	0.105	33.25	73.77	7.225
47.50	108.97	**1.951**	47.50	108.97	**3.668**
42.75	90.79	3.828	52.25	109.32	0.074
52.25	109.32	0.074	42.75	74.47	7.263
57.00	109.62	**1.911**	57.00	109.62	**3.604**
52.25	91.68	3.776	61.75	109.83	0.044
61.75	109.84	0.046	52.25	75.60	7.163
66.50	110.05	**1.964**	66.50	110.06	**3.607**
61.75	91.58	3.889	71.25	110.25	0.040
71.25	110.24	0.040	61.75	75.98	7.175
76.00	110.50	**2.061**	76.00	110.50	**3.643**
71.25	91.09	4.087	80.75	110.69	0.040
80.75	110.67	0.036	71.25	76.08	7.246
85.50	111.02	**2.257**	85.50	111.02	**3.746**
80.75	89.76	4.477	90.25	111.22	0.042
90.25	111.20	0.038	80.75	75.63	7.451

Low Preload Stress, Condensed MT2AM Load Sequence

Elastic Solution, Tension Side			Plastic Solution, Tension Side		
Applied	Axial	SAF	Applied	Axial	SAF
0.0	2.92	4.889	0.0	0.83	4.765
9.5	51.67	4.749	9.5	49.08	4.607
19.0	99.53	4.631	19.0	93.15	4.266
28.5	141.42	3.707	28.5	106.81	3.686
38.0	178.94	3.714	38.0	108.09	3.662
47.5	216.50	3.668	47.5	108.97	3.668
57.0	254.35	3.592	57.0	109.62	3.604
66.5	292.17	3.505	66.5	110.06	3.607
76.0	330.02	3.412	76.0	110.50	3.643
85.5	367.76	3.319	85.5	111.02	3.746

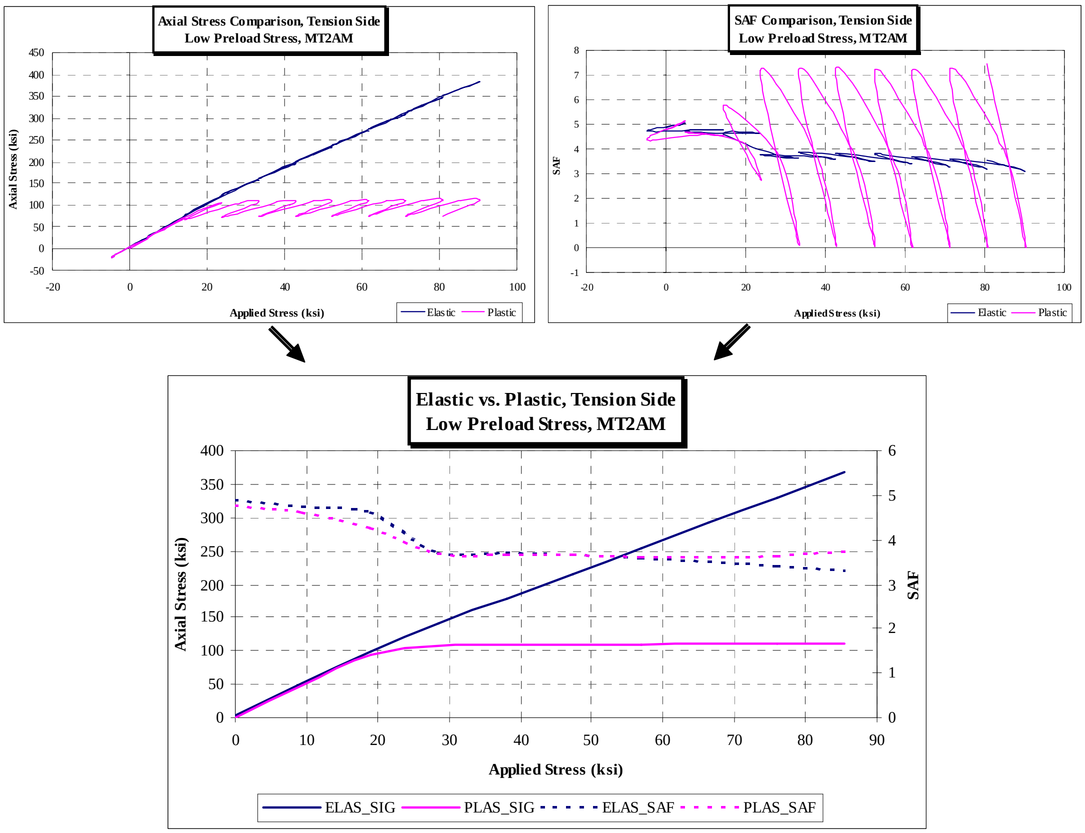

Figure 8. MT2AM Method Illustration

5.2.2 Parametric Study of Alternating Moment Magnitude

The alternating moment was selected to be 5% PBYS in the above MT2AM illustration. It was chosen so that with 10% PBYS mean tension, the overall 'resolution' would be 5% PBYS as the increment used in the current SAF practice by Instantaneous Slope. However, this means that the bending stress range will be 10% PBYS, which is way too high for any well-designed real riser. Therefore, analysis using only 1% PBYS was performed to investigate whether 5% PBYS was too big an increment. It should be noted that only the plastic solution was presented even though the elastic solution was also executed.

Figure 9 is the comparison plot of 1% PBYS alternating moment vs. 5%. The tension side data are on the positive X-axis and the compression side on the negative X-axis. The axial stress is on the primary Y-axis and SAF on the secondary Y-axis. It shall be noted the 'condensed' data is used. It is observed that the 1% PBYS has better 'resolution' near the yield (95 ksi axial stress, 20 ksi applied stress), but almost identical everywhere lese. Most importantly, the maximum SAF is the same. Therefore, it is concluded 5% PBYS alternating moment is acceptable.

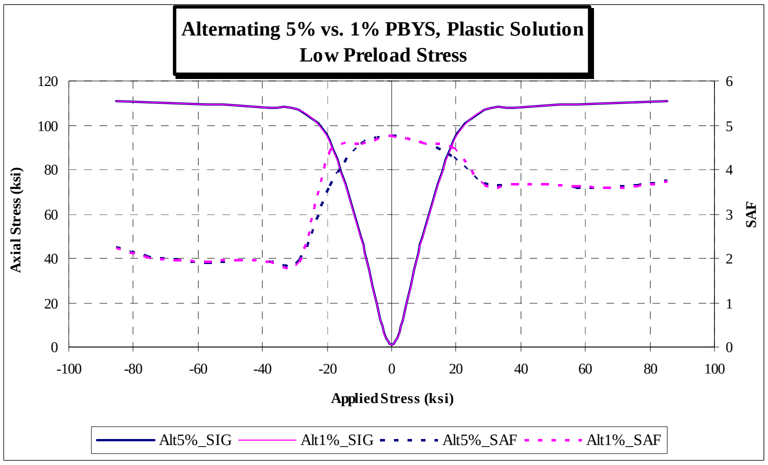

Figure 9. Parametric Study of Alternating Moment Magnitude

5.2.3 Comparison between Three SAF Calculations

Figure 10 is the comparison plot between three SAF calculation methods. It has three graphs: the upper-left graph is the elastic solution and the upper-right graph is the plastic solution. Both have the tension side data to be on the positive X-axis and the compression side on the negative X-axis; the primary Y-axis for the axial stress and the secondary Y-axis for SAF. It shall be noted the axial stresses on the compression side by the monotonic increasing load are negative but they are positive by MT2AM. This is because the load applications of the two approaches are different.

For the upper two graphs, the three SAF results are presented in dashed lines: SAF_I.S is by the Instantaneous Slope (Equation 4), SAF_Prld is calculated with respect to preload (Equation 5), and SAF_MT2AM is the proposed SAF calculation method per Equation 6. The bottom graph is the comparison plot of all six SAF data sets, the combination of three SAF calculations and two solutions.

For the time being, let's concentrate on the tension side (+X axis) of the bottom graph. The major flaw of the instantaneous slope method, Zero Plas_I.S. after yield due to the same peak stresses in the numerator, is quickly revealed. Also observed is that the SAF differences between the elastic solution and the plastic solution of MT2AM are much less than those by the other two methods. As a matter of fact that Plas_MT2AM is about the same as Elas_MT2AM. This makes sense because stress 'concentration' is mainly geometry dependent regardless whether the stress is beyond yield or not.

Now let's shift our attention to the compression side (-X axis). Besides the zero Plas_I.S., two observations are made: 1) the almost 'perfect' symmetry of Elas_Prld and Plas_Prld, and 2) the same Elas_MT2AM on the compression side as on the tension side but lesser Plas_MT2AM on the compression side than the tension side. The first observation is because both Elas_Prld and Plas_Prld are calculated with respect to the preload. As for the second observation regarding the SAF by MT2AM, it is believed that the Bauschinger effect has something to do with it.

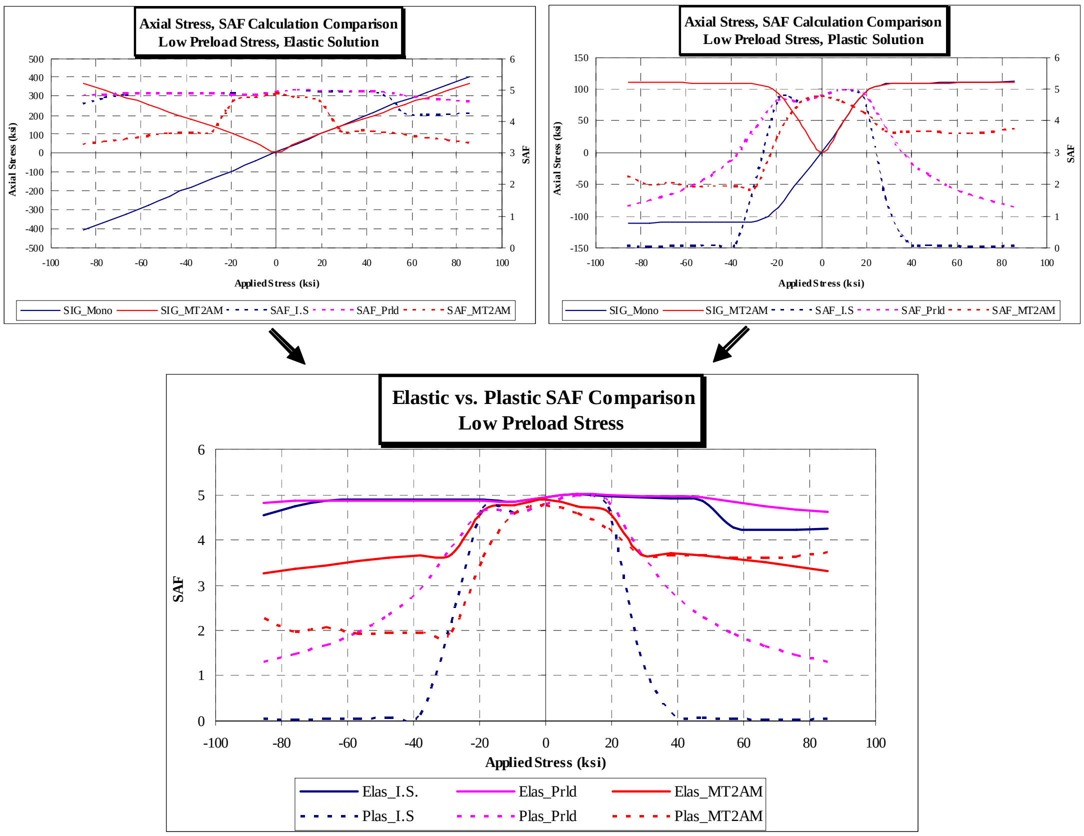

Figure 10. Comparison between SAF Methods and Plastic vs. Elastic Solution

6. CONCLUSIONS AND WISH LISTS

The analysis methodologies developed for evaluating three T&C connectors from the viewpoints of strength, seal leakage, load shoulder separation, and stress 'concentration' in terms of SAF are explained in this paper. Objective and quantitative comparisons between three connectors were made. Even though the comparisons could not be revealed due to the confidentiality agreement, the following technical conclusions may be made:

1. For most of axisymmetric structure subject to non-axisymmetric load, the structural behaviors on the tension (0-degree nodal plane) and compression side (180-degree) are

the main concerns. Abaqus CAXA element is perfectly suited for it. Even though the cylindrical element (CCL) has the advantage of more robust contact formulation, it will be difficult to extract the contact stress right on the two nodal planes of interest.

2. The two 'new' non-dimensional parameters S_L and S_P relate the contact stress, contact length and contact energy area to assess the seal leakage and load shoulder separation quantitatively. Particularly S_L has the potential to become a seal leakage measuring standard.

3. The difference between SCF and SAF is clarified.

4. The 'axial' stress at the integration point of strain gauge element, either by surface membrane element or ultra-thin shell element for axisymmetric structure, has been proven to be the most consistent way to obtain the surface stress concentration regardless element type (linear or quadratic) and location (integration point, nodes, or averaged at nodes).

5. SAF is mean stress dependent. The most comprehensive SAF calculation should be based on Equation 3. Multiple sets of SAF/Mean Stress should be provided. However, the analyses required to provide the data set are tremendous and the data set could be way too overwhelming for riser analyst.

6. Among the three simplified SAF calculation methods, the proposed MT2AM simulates the real riser loading condition, mean tension with oscillating moment due to wave, much closely than the monotonic increasing load (either equivalent tension or true bending moment) used in the current practice. It also solves the difficulty in defining the SAF at preload, which has been bothering the industry for years.

7. MT2AM also resolves the zero Plastic SAF predicted by Instantaneous Slope, a major flaw of the method. Also, based on MT2AM results, plasticity has much less effect on SAF than other two methods, particularly on the tension side.

8. For the two cases studied, 5% and 1% PBYS, the magnitude of the alternating moment does not have major impact on the SAF calculation. As a matter of fact, MT2AM is the 'true' instantaneous slope if one selects 0.1% PBYS or even lesser alternating moment.

9. Judging by the fact that the elastic SAF calculation with respect to preload (2^{nd} method, Equation 5) is almost constant, Elas_Prld in Figure 10, it will be a big surprise that the most comprehensive SAF's are too different from those predicated by MT2AM.

Even though they are not desperately needed because the work around have been developed, three wish lists from authors to Abaqus:

1. CAXA element has been available for years, but there is still no mechanism in Abaqus to apply the bending moment.

2. Surface membrane element compatible with CAXA element, MAXA or SFMAXA, is needed.

3. Output S_L and S_P to .dat, .fil and .odb files.

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8. ACKNOWLEDGMENT

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