Proceedings of the ASME 2024
Pressure Vessels & Piping Conference
PVP2024
July 29-August 2, 2024, Bellevue, Washington

PVP2024-123441

STRUCTURAL CAPACITY ESTIMATION OF SUBSEA FLANGES USING VARIOUS CODES AND STANDARDS

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ABSTRACT

High-pressure flanges of varying sizes, starting from 1/2" are used in subsea oil and gas production equipment such as trees, manifolds, risers, valves, etc. These flanges are designed up to 20 ksi operating pressure with a test pressure of 30 ksi. Additionally, flanges used in subsea applications are exposed to high bending, shear, and torsional loads. API 6A flanges with BX gaskets are commonly used in subsea and surface oil and gas production equipment. API TR 6AF1 and API TR 6AF2 technical reports provide the pressure, bending, and tension capacity of these flanges. The flange capacity is presented as capacity charts. It should be noted that the API flanges are designed to the criteria of API 6A. Along with standard API flanges, subsea equipment also uses non-standard flanges, also known as Other-End Connections (OEC).

In this paper, a subsea API 7 1/16"-15K standard flange design and analysis is presented. This flange is analyzed to design criteria from various codes and standards used in the oil and gas industry such as API 6A, API 6X, API 17D, API17G, API 16A, ASME VIII-2, ASME VIII-3, and NORSOK U-001. These codes and standards allow elastic, elastic perfectly plastic (limit load), and elastic-plastic finite element analysis to estimate the flange capacity. The flange design capacity estimated based on these codes and standards is presented and compared against the existing API 6AF flange capacity. The flange capacity includes functional capacity (leakage and hub separation) and structural capacity (bolt capacity and flange capacity). This paper also discusses the conservatism and limitations in each of these codes and standards for the flange design. The analysis procedures presented in this paper can be used for designing OECs.

Keywords: ASME, API, Subsea, Flange, Plastic Collapse, structural capacity.

NOMENCLATURE

API	*American Petroleum Institute*
EP	*Elastic-Plastic*
EPP	*Elastic Perfectly Plastic*
FEA	*Finite Element Analysis*
FPC	*Factored Plastic Collapse*
ID	*Internal Diameter*
LE	*Linear Elastic*
OD	*Outer Diameter*
Pl	*Bending stress intensity*
PSL	*Product Specification Level*
OEC	*Other End Connection*
QTC	*Qualification Test Coupon*
RWP	*Rated working pressure*
SH	*Strain Hardening*
Su	*Tensile strength*
Sy	*Yield Strength*
w/o	*Without*
w/	*with*
YT	*Yield strength to tensile strength ratio*

1. INTRODUCTION

Subsea oil and gas production equipment are pressure vessels that operate at high pressure, with an operating pressure of up to 20 ksi (hydrostatic test pressure is 30 ksi) and operating temperature of up to 400°F. Flange connections are common in production equipment, which are permanent connections. These production equipment along with flanges are required to operate for 25-30 years at a water depth of 10,000 ft. These flanges are exposed to severe environments such as production fluid (hydrogen sulfide), seawater, various injected chemicals, corrosion inhibitors, brine, etc.

High-pressure flanges of varying sizes, starting from 1/2" (up to 21" in some applications) are used in subsea oil and gas production equipment such as trees, manifolds, risers, valves, etc. Additionally, flanges used in subsea applications are exposed to high bending, shear, and torsional loads, along with high pressure.

API 6A flanges with BX gaskets are commonly used in subsea and surface oil and gas production equipment. API TR 6AF1 and API TR 6AF2 technical reports (TR) provide the pressure, bending and tension capacity of these flanges. The flange capacity is presented as capacity charts in these documents. It should be noted that the API flanges are designed to the criteria of API 6A using elastic analysis. Along with standard API flanges, subsea production equipment also uses non-standard flanges, also known as Other-End Connections (OEC).

In this paper, a subsea API 7 1/16"-15K standard flanged connection analysis is presented. This flange is analyzed to design criteria from various codes and standards used in the oil and gas industry such as API 6X, API 6A, API 17D, API17G, API 16A, ASME VIII-2, ASME VIII-3, and NORSOK U-001. These codes and standards allow elastic, elastic perfectly plastic (limit load), and elastic-plastic finite element analysis to estimate the flanged connection capacity. The analysis methods assume ductile materials with through-thickness mechanical properties. Comparison of material and fatigue requirements are outside the scope of this paper. The flanged connection design capacity estimated based on these codes and standards (design by analysis approach) is presented in this paper and compared against the existing API 6AF flange capacity (Figure 2). The flange capacity includes functional capacity (leakage and hub separation) and structural capacity (bolt capacity and flange capacity). This paper also discusses the conservatism and limitations in each of these codes and standards for the flange design. The analysis procedures and methodology presented in this paper can be used for designing OECs.

2. API, ASME, and NORSOK Standards

The design criteria from all the codes and standards considered in this study are discussed in this Section.

2.1 API standards

2.1.1 API 6X, 2nd Edition [1]

API 6X provides design analysis methodology for pressure containing equipment in oil and gas industry [1]. This document provides elastic and non-linear (limit load) analysis methodologies for analyzing pressure vessels including the flanges. <u>It should be noted that, API 6X refers to API product specifications such as API 6A, API 17D, and API 6A for bolt allowable stress.</u>

API 6X Linear Elastic (LE) analysis

In the LE analysis, membrane and bending stresses are extracted using "linearization" and are compared to allowable for each stress category. The design stress intensity for operating condition S_m = 2/3 yield stress and maximum allowable general primary membrane stress intensity at hydrostatic shell test S_t = 0.9 yield stress.

API 6X Nonlinear analysis – Limit Analysis

Minimum specified values (yield stress) shall be used along with the von Mises yield criteria and associated flow rule in the limit load FEA [1]. The stress-strain curve used in FEA is a bilinear curve with a tangent modulus of approximately zero. The load factor for the normal operating conditions capacity is 1.5. The small-displacement theory (nonlinear geometry off) is required in the FEA. It should be noted that in some cases, the small deformation theory can result in non-conservative results [13]. Large deformation theory results in conservative results and is incorporated in API 17G limit analysis.

API 6X Nonlinear analysis – Plastic Analysis

API 6X refers to API 17TR8 for elastic-plastic analysis methods. The methods in API 17TR8 are identical to elastic-plastic analysis methods in ASME VIII-2 and ASME VIII-3 for normal operating conditions.

2.1.2 API 6A, 21st Edition [2]

API 6A type 6BX bolted-flange connections are mechanical devices used to connect two adjacent components to create a structural joint that resists applied loads and prevents leakage. The design basis for API 6A type 6BX 10 ksi and 15 ksi flanges is given by Eichenberg [11, 12]. Eichenberg [12] found that the ASME VIII-1 code based design method resulted in large flanges and bolts for high pressure applications. The allowable flange stress was the tensile strength divided by 4.0 and the allowable bolt stress was the tensile strength divided by 4.0 of the respective components. Furthermore, the "m" (factor for the gasket operating condition) was not suitable for high pressure design. This problem was solved by:

1) designing the self-energized and pressure-energized soft metal BX-type gaskets;
2) designing the flanges for face-to-face make-up, i.e. any bolt overload will not overload the flange or BX gasket;
3) increasing the allowable bolt and flange membrane stresses to 50 % of the specified minimum yield strength of the respective materials for design pressure. The yield strength of bolting was 105 ksi (725 MPa) and the yield strength for 15K flanges was 75 ksi (517 MPa).

Exaggerated deflections of API 6A type 6BX flanges and load transfer in operation (service) are shown in FIGURE 1. Note that face-to-face contact means contact at the outside diameter of the raised face and not at the bore. There will always be a gap between the gasket and the flange bore, i.e. the gasket will be directly exposed to internal fluids. It should be noted that 20 ksi flanges and 5 1/8-15 ksi flanged connections were introduced later in API 6A.

The following is stated in API 6A [2]:

1) Section 8.1.1. *The maximum tensile stress for closure bolting shall be determined considering initial bolt-up, rated operating conditions, and hydrostatic shell test pressure. Bolting stresses, based on the minimum cross-sectional area of the bolting, shall not exceed 83 % of bolting material SMYS.*
2) Section 14.1.2.3: *Type 6BX flanges are of the ring-joint type and are designed with a raised face. Depending on tolerances, the connection make-up bolting force can react on the raised face of the flange when the gasket has been properly seated. This support prevents damage to the flange or gasket from excessive bolt torque.*

3) Section 14.1.2.3: *Face-to-face contact is not necessary for the proper functioning of Type 6BX flanges.*
4) Nominal bolt preload tables in Annex H API 6A indicate a target bolt stress equal to 50 % of bolt material yield strength for both 80 ksi and 105 ksi bolting.

API 6AF1 [14] and 6AF2 [15] provide API flange capacity based on leakage and hub stress criteria. Leakage capacity is the limiting case in most cases and is used as the flange capacity in design. It should be noted that API 6A 83% of yield stress bolt allowable is for membrane stress only. API flange bolts experience low bending stress and seldom dictate the flange capacity. The design calculations for all API 6A equipment shall conform to the design methodology of API 6X (Section 5.1.3.2).

2.1.3 API 17D, 3rd Edition [4]

API 17D applies specifically to subsea production equipment. The following is stated in API 17D for type 6BX flanges as defined in API 6A:

1) Section 5.1.3.5.1: *The manufacturer shall specify the bolting preload for RWP and normal operating loads.*
2) Section 5.1.3.5.1: *API flange bolting* ***shall be made up for face-to-face*** *flange contact and bolting shall have a minimum preload stress of 50 % of bolting SMYS after flange make-up. Additional bolt preload stress may be applied to assure face-to-face flange contact and should not exceed 67 % of bolting SMYS.*
3) Section 7.1.2.1: *All flanges used on subsea completion equipment shall be of the ring-joint type designed for face-to-face make-up. The connection make-up force and external loads shall react primarily on the raised face of the flange. Therefore, at least one of the flanges in a connection shall have a raised face.*
4) API 17D Table F.1 gives flange bolt torque for 67 % yield strength tension for both 80 ksi and 105 ksi bolting.

As stated above, API 17D requires face-to-face flange contact. This requirement defines the functional capacity along with gasket contact pressure and hub separation. In this paper, 67% of bolt yield stress (105 ksi) is used as the preload. It should be noted that the preload is calculated based on the tensile area of the bolt and bolt stress for verification is calculated based on the root area of the bolt. API 17D also states that the pressure-containing and controlling components shall be designed in accordance with API 6A (Section 5.1.3.3 and 5.1.3.4), which in turn refers to API 6X.

2.1.4 API 16A, 4th Edition [3]

This specification defines the requirements for drill-through equipment used for drilling for oil and gas [3]. API 16A, Section 4.3.1 provides requirements for the API flanges. API 16A equipment requires design methodology (Section 4.4.2.2) described in API 6X. This specification provides bolt allowable stress for both membrane and membrane + bending stress.

Membrane stress <= 0.83 yield stress
Membrane + Bending stress <= 1.0 yield stress

Bolt stress shall include initial bolt-up, operating condition (including thermal stress), and hydrostatic test pressure.

2.1.5 API 17G, 3rd Edition [5]

API 17G is primarily used for the design and manufacture of subsea well intervention equipment. According to API 17G Sec 5.6.1.5, the structural capacity of all bolted flanges shall be in accordance with API 6A. Unlike other API standards, API 17G explicitly requires structural and functional capacity evaluation, similar to connectors.

2.2 ASME Standards

2.2.1 ASME VIII-2, 2021st Edition [8]

ASME VIII-2 provides Design by rule (Part-4) and Design by analysis (Part-5) criteria for designing pressure containing and supporting equipment. In this paper, only Design by analysis approach is used for the flange analysis.

ASME VIII-2 Part 5 Design by analysis requirements:

This part includes design requirements for the application of design-by-analysis to evaluate components for plastic collapse and other critical failure modes. For plastic collapse estimation, elastic, limit-load, and elastic-plastic analysis methods may be used.

ASME VIII-2 Elastic analysis:

The linear elastic material model is used with the small displacement theory. Allowable stress is the minimum (yield/1.5, tensile/2.4). This method is not commonly used in the oil and gas industry and thus is not considered.

ASME VIII-2 Limit-load analysis:

This method is similar to the API 6X limit analysis, with small displacement theory, except the yield strength defining the plastic limit shall equal 1.5S, where S=min (yield/1.5, tensile/2.4).

ASME VIII-2 Elastic-plastic analysis:

This method uses stress-strain curves with strain hardening and large displacement theory. The allowable pressure is the collapse pressure divided by 2.4 (Class-2 Vessel). Only this method is used in this paper.

2.2.2 ASME VIII-3, 2021st Edition [7]

ASME VIII-3 provides design criteria for designing high pressure vessels (typically pressure greater than 10 ksi). This code provides design criteria to address plastic collapse, ratcheting, fatigue, etc., failure modes. Elastic plastic method is typically used in designing high pressure vessels. ASME VIII-3 KD-231 states: "Elastic-plastic stress analysis closely approximates *the actual structural behavior by considering the redistribution of stress that occurs as a result of inelastic deformation (plasticity) and deformation characteristics of the component"*. This method is identical to ASME VIII-2 EP analysis, with a load factor of 1.8 instead of 2.4 as required by ASME VIII-2.

ASME VIII-3, KD-621 provides design requirements for threaded fasteners for EP basis. This section refers to KD-231 rules, KD-231.2 acceptance criteria and Table KD-230.4 load factors. This table provides load factors for different load combinations. Typically, flange bolts in FEA are modelled as a cylinder without threads as it is not practical to model threads. If this is the case, there should be additional requirements to limit the average membrane and bending stress on the cylindrical bolts, so that the threads are not overloaded. The plastic collapse study or any criteria in Table KD-230.4 do not address this.

API Standards addresses this by limiting the membrane stress to 83% of yield stress (based on root area). This ensures that the threads are not overloaded at any point. ASME VIII-3 design requirements does not limit the average stress on the bolt (if threads are not modelled) and requires only to meet the load factors in KD-230.4. This can lead to non-conservative assessment of bolts and therefore, a limitation of the ASME VIII-3. This needs to be addressed by ASME VIII-3 Subgroup.

2.3 NORSOK U-001 [9]

NORSOK U-001 is a Norwegian standard and provides requirements and recommendations for the development of subsea production systems within the Norwegian continental shelf (NCS). NORSOK U-001 requires the use of DNV-RP-0034 steel forging class 2 for low alloy steel forgings to ensure thorough thickness mechanical properties and ductile material behavior.

NORSOK U-001 uses the same design margin for the flange and the bolting. The design margin for design pressure (RWP) is 3 for both bolts and flanges. For normal operating conditions, i.e. design pressure combined with bending moment, the design margin is 1.5. This means that the connection allows for significant bending moments which are typical for bolted flange connections in a riser system. Bolts are preloaded to a minimum of 67 % of bolt material yield strength which ensures flange face contact for normal (design) operating conditions. Flange face contact during normal operating conditions improves fatigue performance (bolting) and reduces the risk of leakage due to fretting between the gasket and seat. Normal operating conditions include design pressure in combination with bending moment and axial tension.

U-001Annex B provides structural design and qualification of subsea components including flange connections. U-001 Annex C provides guidelines for the determination of structural and functional capabilities of API Spec 6A type BX bolted flange connections as a replacement to API TR 6AF.

U-001, Annex B includes the following methods:

1) Elastic analysis – limited to preliminary design
2) Elastic-plastic analysis

a) Limit load method with nonlinear geometry, which is identical to API 17G EP without strain hardening.
b) Factored plastic collapse method including nonlinear geometry and strain hardening. This is identical to ASME VIII-3 and API 17G EP with strain hardening with an increase in the 1.2 factor for materials with tensile to yield strength ratio greater than 1.2.

For bolts, Static structural yielding capacity = External load corresponding to through cross section yielding of any bolt.

Static functional capacity shall be based on the hub separation, seal/gasket leakage, galling, loss of functionality, excessive deformation, etc. Hub face separation is the load limit that defines the maximum load the connector can sustain before hub face separation occurs [9]. Seal/gasket leakage acceptance criteria shall be specified by the manufacturer and shall be based on analysis that has been validated by testing [9].

3. SUMMARY OF DESIGN CODES

Pressure-containing products and equipment in the oil and gas industry are predominately designed in accordance with the codes listed in TABLE 1. TABLE 2 gives an overview of the analysis methods used by the referred codes. API 6A, 16A and 17D refer to API 6X for design calculations of pressure-containing equipment. API 6X includes elastic, limit-load and elastic-plastic analysis for protection against plastic collapse. API 6X refers to API 17TR8 for elastic-plastic analysis.

API 6X refers to product specifications with respect to bolting. API 6A, 16A and 17D states that bolting shall be modelled as elastic and provide allowable bolt tensile stresses. This bolt stress requirement is not stated in ASME VIII-2 and ASME VIII-3.

Note that the design factor for pressure design in API 17G is 0.6 and 0.67 bending moment. Test pressure is not governing design pressure in API 17G.

Allowable bolt stress per API 6A is 0.83 times the bolt material yield strength. The plastic collapse load for bolting corresponds to bolt stress equal to 100 % of yield strength.

The bolted flange connection design load is the minimum of the design load for the flange and the bolt.

The design pressure, P_D, and design bending moment, M_D, and the design tension T_D, for the design of bolted flange connections against plastic collapse for internal pressure only, bending moment only and tension only are given by the following equations.

$$P_D \leq= \frac{\text{Plastic collapse pressure capacity}}{\text{Design margin}_{P_D}} \tag{1}$$

$$M_D \leq= \frac{\text{Plastic collapse moment capacity}}{\text{Design margin}_{M_D}} \tag{2}$$

$$T_D \leq= \frac{\text{Plastic collapse tension capacity}}{\text{Design margin}_{T_D}} \tag{3}$$

TABLE 3 and TABLE 4 provide the summary of the design margin for design pressure and moment/tension at room temperature for bolted flanges for all the standards considered in this paper. Both flange and bolt design margin are provided in these tables.

4. MATERIALS AND METHODS

In this study, API 6A 75K standard material is used with yield and tensile strength of 75 ksi and 95 ksi, for the flange body. The gasket is solution annealed Alloy 625 with yield and tensile of 60 ksi and 120 ksi. Bolts are 105 ksi yield and 125 ksi tensile ASTM A320 Grade L7. API 6A 7"-15K flange uses 16 x 1.5" diameter bolts. All these materials have good ductility and toughness properties. These three materials have a minimum elongation and reduction in the area of 17% and 35% respectively.

Table 5 shows the summary of the mechanical properties of the flange assembly materials used in this study.

FIGURE 3 shows the F22, Alloy 625 and Grade L7 Elastic perfectly plastic stress-strain curves and true stress-strain curves. True stress-True strain curves are generated using ASME VIII-3, KM-6 procedure.

5. ANALYSIS

In this study, API 6A 7"-15K standard flange is considered which is used in many subsea production/ completion equipment. API 6AF 1 and API 6AF2 documents provide the flange capacity (pressure, tension and bending) using capacity charts. These capacities are conservative in many cases and were developed using API 6A design criteria. The FEA model used in these two documents are simplified model (LE analysis without gasket) and thus resulted in conservative results (structural capacity).

In this paper, flange functional and structural capacity based on API 6X, ASME VIII-2, -3, API 17G and Norsok U-001 design criteria is estimated. The procedures developed in this section can be used for non-standard flanges (OECs).

5.1 FINITE ELEMENT ANALYSIS

Figure 4 shows the ANSYS FE model of the API 6A 7"-15K flange. The model used in the analysis is a half-symmetry model. The top end of the flange model is closed so that the pressure end load (end cap) effects are modeled by just applying the pressure on the ends. Bolts are modeled as solid cylinders (without threads) and the preload is applied on them. The gasket is modeled just touching the gasket grooves. Preload per bolt is calculated as follows:

Preload = 0.67 x 105 ksi (yield) x 1.492 in^2 (bolt tensile area)
= 105 kips.

In the first FEA load step, preload is applied on the bolts which simulates the flange crushing the gasket. Note, unlike some ASME flanges, only a fraction of the preload is utilized in crushing the gasket, remining preload acts on the flange raised face.

The following assumptions are considered in the FEA:

1) through-thickness mechanical properties without detrimental defects.
2) plastic collapse occurs before local failure and brittle fracture.

For quenched and tempered low alloy steels this means that the selected materials must have sufficient hardenability, ductility and toughness to meet the assumptions made by the analysis.

Several FEA load cases were carried out for API 7"-15K flange assembly. Table 6 shows the summary of all the load cases: pressure to failure, tension to failure, and bending to failure with EP and EPP material models. Additionally, linear elastic analysis was carried out with unit load for each of the load cases. Six additional FEA cases with flange bodies alone (EP and EPP) were also carried out. These cases were run to identify the structural capacity of the flange body. This is because, in the flange assembly analysis, when the bolts failed, the analysis stopped prematurely and failed to provide the flange structural capacity. Table 7 shows the summary of the results.

5.2 Results

Three FEA analysis cases were carried out to estimate the flange capacity with EP, EPP, and LE material models. These three cases are: pressure to failure, tension to failure and bending to failure. For LE cases, only unit load is applied and the results were extrapolated.

Figure 5 shows the elastic plastic FEA, pressure to failure analysis results. The von Mises stress plot at 15 ksi pressure and collapse pressure of 40 ksi is presented. The bolts failed (stress reached tensile strength) at 40 ksi internal pressure before the flange failed. Additional flange body only analysis was carried out where the flange body collapse pressure is 43 ksi. Figure 6 shows the membrane and membrane+bending stress plots for all eight bolts. Membrane and Mem+Bend stress allowable stress are 87.2 ksi and 105 ksi respectively. The bending stress is significantly small compared to the membrane stress. This is typical for API flanges and is a sign of good rigid flange design. The hub separation plot shows the gap between the two flanges behind the gasket OD. Hub separation is one way of defining the functional capacity or the leakage criteria. Flange capacity based on hub separation of 0.004" (0.1mm) and 0.008" (0.2mm) are 20 ksi and 24 ksi respectively. If hub separation is used as the functional capacity, then these values have to be qualified based on API 6A/17D requirements. The Flange force diagram plot is also shown in Figure 6. The total bolt load, flange raised face load and the gasket crush load are three curves. API 17G / NORSOK U-001 defines flange raised face force as the functional capacity. This force becomes zero at 23 ksi pressure, which is the functional capacity.

A similar study was carried out for tensile-to-failure and bending-to-failure cases. Figure 7 shows the tensile to failure case. The bolts and flange collapsed at 2,900 kips and 5,000 kips respectively. Figure 8 shows the bolt stress, hub separation and force diagram. The hub separation force is 1,400 kips and 1,750 kips for 0.1 mm and 0.2 mm respectively. The raised face remains in contact up to 1,550 kips tension load. Figure 9 shows bending to failure results. The collapse bending moment for bolts and flange are 1,100 ft-kips and 1,250 ft-kips. Figure 10 shows the bolt stress, hub separation and force diagram.

Table 7 presents the summary of all the capacity results. Case-8 is the API 6A 7"-15K flange capacity based on the API TR6AF2. In all cases, the flange structural capacity is larger than the API capacity. The functional capacity depends on the criteria (hub separation or the raised face separation) selected and qualified. ASME VIII-2 based flange structural capacity is conservative in all cases. API 6X capacity is similar to other API codes and can be used in the flange design.

6. Conclusion

The functional and structural capacity of API 6A 7"-15K flange is calculated using design criteria from API 6X, API6A, API 17D, API 17G, ASME VIII-2, and -3 and NORSOK U-001 codes. These codes are used extensively in the design of various subsea equipment. These codes allow elastic, limit analysis, and elastic-plastic FEA for estimating the capacity. It is critical to understand the conservatism and limitations in some of these codes.

Table 7 shows the summary of the API 7"-15K flange capacity along with the API 6AF2 capacity. The flange capacity estimated using design criteria from these codes resulted in higher capacity. The flange analysis methodology presented in this paper can be applied in analyzing non-standard flanges (OECs). This study helps to understand the procedure and limitations of different codes and standards used in subsea oil and gas equipment.

ACKNOWLEDGEMENTS

TechnipFMC, Structural Integrity Associates Inc., and Equinor are acknowledged for providing the opportunity to work with this and publish this paper.

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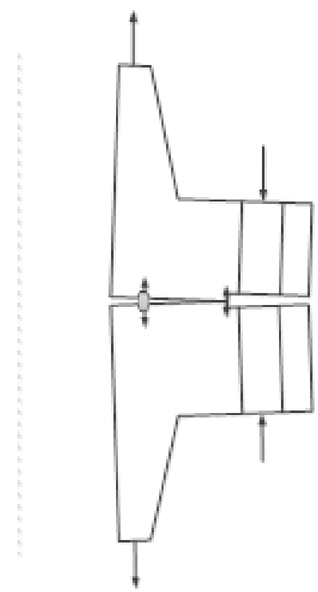

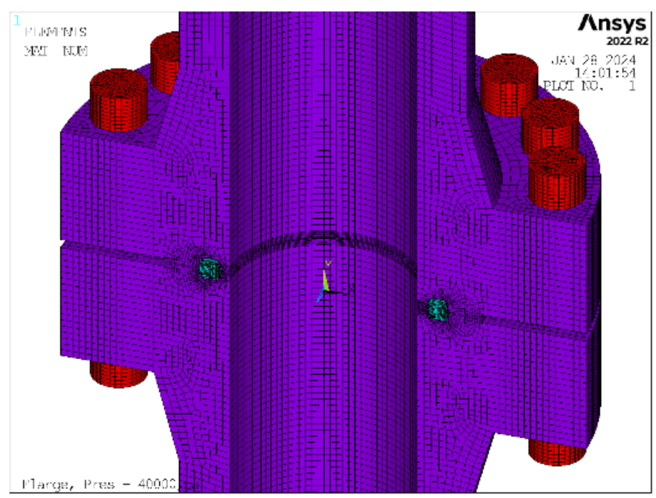

FIGURE 1: API 6A 7"-15K TYPE BX FLANGE

TABLE 1: DESIGN CODES

Design code	Applications	Design pressure limit
API 6A	Surface wellhead and tree equipment	≤ 138.0 MPa (20 ksi)
API 16A	Surface and submerged drill through equipment	≤ 206.8 MPa (30 ksi)
API 17D	Subsea wellhead and tree equipment	≤ 103.5 MPa [1] (15 ksi)
API 17G	Subsea well intervention equipment	≤ 103.5 MPa (15 ksi)
API 17TR8	HPHT [2] subsea equipment (API 17D and API 17G)	> 103.5 MPa (15 ksi)
ASME VIII-2	Pressure vessels	[3]
ASME VIII-3	High pressure vessels	No limit
NORSOK U-001 Annex B	Subsea wellhead and tree equipment + Completion and workover risers	≤ 103.5 MPa [4] (15 ksi)

1) API 17D includes informative Annex D applicable for HPHT equipment for design pressure > 103.5 MPa (15 ksi).

2) HPHT is defined as design pressure above 103.5 MPa (15 ksi) and/or design temperature above 177 ℃ (350 °F)

3) No maximum pressure is given; however, reference is made to ASME VIII-3 for pressures exceeding 69 MPa (10 ksi).

4) Plastic collapse design method has no pressure limit.

TABLE 2: ANALYSIS METHODS FOR BOLTED FLANGES

Code	Plastic collapse analysis methods		
	Elastic	Limit-load [1]	Elastic-plastic
API 6A API 16A API 17D API 17G API 6X	✓	✓	✓ [2]
API 17TR8	✓	✗	✓
ASME VIII-2	(✓)	(✓)	✓
ASME VIII-3	(✓)	(✓) [5]	✓
NORSOK U-001	✗ [3]	✗	✓ [4]

1) Limit-load includes elastic-perfectly plastic material model and small deformations.

2) API 6X refers to API 17TR8 for elastic-plastic analysis.

3) Elastic analysis is limited to the preliminary design of components.

4) The elastic-plastic analysis includes two options, a) non-strain hardening material (limit-load method) and b) strain hardening material (factored plastic collapse method).

5) Limit load analysis can be used, but the load factor remains the same as the EP analysis

TABLE 3: DESIGN MARGINS FOR DESIGN PRESSURE AT ROOM TEMPERATURE FOR BOLTED FLANGES

Code	Analysis method	Flange	Bolt
API 6X API 6A API 16A API 17D API 17G	Elastic	1.67 [1]	1.81 [2]
	Limit-load SD	1.67 [1]	1.81 [2]
	Elastic-plastic – VIII-2	2.4	1.81 [2]
	Elastic-plastic – VIII-3	1.8	1.81 [2]
API 17TR8	Elastic	1.58 [3]	1.81 [2]
	Elastic-plastic – VIII-2	2.4	1.81 [2]
	Elastic-plastic – VIII-3	1.8	1.81 [2]
ASME VIII-2	Elastic	$1/S$ [4]	3.0
	Limit-load SD	$1/S$ [4]	$1/S$ [4]
	Elastic-plastic	2.4	2.4
ASME VIII-3	Elastic	$1.5/k_{c1}$ [5]	1.8
	Elastic-plastic	1.8	1.8
U-001	Limit-load LD	1.67 [6]	1.67 [6]
	Elastic-plastic	1.67β [7]	1.67β [7]

1) Hydrostatic test pressure is $p_t = 1.5P_D$. Design margin for design pressure then becomes: $1/\min(2/3\,;(0.90/1.5)) = 1.67$.

2) Hydrostatic test pressure is $p_t = 1.5P_D$. Elastic bolting with design margin for design pressure becomes: $1/(0.83/1.5) = 1.81$.

3) Pressure testing is governing, p_t=1.5P_D, see API 17D D.8.2.2. Design margin for design pressure then becomes: $1/\min(2/3\,;(0.95/1.5)) = 1.58$.

4) Allowable stress, $S = 1/\min\left(\frac{2\sigma_y}{3};\frac{\sigma_u}{2.4}\right)$.

5) The design correction factor k_{c1} is given by Eq. 9-210.1 Appendix 9 ASME VIII.3.

6) The design factor is 0.6, hence design margin is 1/0.6=1.67.

7) Material strain hardening factor, $\beta = \max(1.2;\sigma_u/\sigma_y)$.

TABLE 4: DESIGN MARGINS FOR DESIGN MOMENT/ TENSION AT ROOM TEMPERATURE FOR BOLTED FLANGES

Code	Analysis method	Flange	Bolt
API 6X API 6A API 16A API 17D API 17G	Elastic	1.5[1)]	1.2[2)]
	Limit-load SD	1.5[1)]	1.2[2)]
	Elastic-plastic – VIII-2	2.4	1.2[2)]
	Elastic-plastic – VIII-3	1.8	1.2[2)]
API 17TR8	Elastic	1.5[1)]	1.2[2)]
	Elastic-plastic – VIII-2	2.4	1.2[2)]
	Elastic-plastic – VIII-3	1.8	1.2[2)]
ASME VIII-2	Elastic	$1/S$[3)]	3.0
	Limit-load SD	$1/S$[3)]	$1/S$[3)]
	Elastic-plastic	2.4	2.4
ASME VIII-3	Elastic	$1.5/k_{c1}$[4)]	1.8
	Elastic-plastic	1.8	1.8
U-001	Limit-load LD	1.5	1.5[5)]
	Elastic-plastic	1.67β[6)]	1.67β[6)]

1) Design margin for design pressure then becomes: 1/(2/3)=1.5.
2) Elastic bolting with design margin for design pressure becomes 1/0.83=1.2.
3) Allowable stress, $S = \min\left(\frac{2\sigma_y}{3}; \frac{\sigma_u}{2.4}\right)$.
4) The design correction factor k_{c1} is given by Eq. 9-210.1 Appendix 9 ASME VIII.3.
5) The plastic collapse load is through-thickness yielding of one bolt.
6) Material strain hardening factor, $\beta = \max\left(1.2; \sigma_u/\sigma_y\right)$. The plastic collapse load is through-thickness yielding of one bolt.

Table 5 SUMMARY OF THE MECHANICAL PROPERTIES OF THE MATERIAL USED FOR THE FLANGE

Part	Material	Yield stress, ksi	Tensile strength, ksi	Elongation, %	Reduction in area, %
BX gasket	Alloy 625	60	120	18	35
Flange	F22	75	95	18	35
Bolts	ASTM A320 Grade L7	105	125	16	50
Bolts*	ASTM A320 Grade L7M	80	100	18	50

*Grade L7M bolts are given for reference only and is not used in the analysis. These bolts are used when the flanges are insulated and are considered as exposed bolts.

Table 6 SUMMARY OF ALL THE FEA ANALYSIS CASES

Case	Material Model	Pressure	Tension	Bending
1	EP	to fail	NA	NA
2	EP	NA	to fail	NA
3	EP	NA	NA	to fail
4	EPP	to fail	NA	NA
5	EPP	NA	to fail	NA
6	EPP	NA	NA	to fail
7	LE	10 ksi	NA	NA
8	LE	NA	1000 kips	Na
9	LE	NA	NA	100 ft-kips

Table 7 SUMMARY OF THE RESULTS: FUNCTIONAL AND STRUCTURAL CAPACITY OF THE 7"-15K API FLANGE, IN ABSOLUTE VALUES AND NORMALIZED VALUES[3]

				Pressure capacity, ksi					Tension capacity, kips					Bending capacity, ft-kips				
				Functional capacity			Structural capacity[5]		Functional capacity			Structural capacity[5]		Functional capacity			Structural capacity[5]	
Case	Code	Material Model	Description (Analysis and Material model)	0.1 mm H.S.	0.2 mm H.S.	Raised face Sep	Bolt Mem	Plastic collapse, Assembly[4]	0.1 mm H.S.	0.2 mm H.S.	Raised face Sep	Bolt Mem	Plastic collapse, Assembly[4]	0.1 mm H.S.	0.2 mm H.S.	Raised face Sep	Bolt Mem	Plastic collapse, Assembly[4]
1	API 6X[6]	LE	Linear elastic analysis, Stress linearization	16.5	24.0	22.5	24.0	19.9	1,400	1,750	1,600	1,600	2,403	430	570	NA	400	469
2	API 6X[6]	EPP	Limit load analysis	16.5	24.0	22.5	27.0	24.0	1,400	1,750	1,600	1,700	1,600	430	570	NA	425	633
3	ASME VIII-2	EP	Elastic-plastic analysis with strain hardening	16.5	24.0	22.5	NA	16.7 (=40/2.4)	1,400	1,750	1,600	NA	1,208	430	570	NA	458	458
4	ASME VIII-3	EP	Elastic-plastic analysis, with strain hardening	16.5	24.0	22.5	NA	22.2 (=40/1.8)	1,400	1,750	1,600	NA	1,611	430	570	NA	611	611
5	NORSOK U-001	EP	Elastic-plastic true stress-strain curve with strain hardening	16.5	24.0	22.5	22.8[2]	22.3[2]	1,400	1,750	1,600	1,541	1,619	430	570	NA	469	614
6	API TR6AF2	LE	Linear elastic analysis, Stress linearization	18.5[1]	18.5	18.5	NA	19.0	NA	NA	NA	NA	NA	417	417	417	NA	550

				Pressure capacity, ksi					Tension capacity, kips					Bending capacity, ft-kips				
				Functional capacity			Structural capacity		Functional capacity			Structural capacity		Functional capacity			Structural capacity	
Case	Code	Material Model	Description (Analysis and Material model)	0.1 mm H.S.	0.2 mm H.S.	Raised face Sep	Bolt Mem	Flange Plastic collapse	0.1 mm H.S.	0.2 mm H.S.	Raised face Sep	Bolt Mem	Plastic collapse	0.1 mm H.S.	0.2 mm H.S.	Raised face Sep	Bolt Mem	Plastic collapse
1	API 6X	LE	Linear elastic analysis, Stress linearization	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	NA	1.00	1.00
2	API 6X	EPP	Limit load analysis	1.00	1.00	1.00	1.13	1.21	1.00	1.00	1.00	1.06	0.67	1.00	1.00	NA	1.06	1.35
3	ASME VIII-2	EP	Elastic-plastic analysis with strain hardening	1.00	1.00	1.00	NA	0.84	1.00	1.00	1.00	NA	0.50	1.00	1.00	NA	1.15	0.98
4	ASME VIII-3	EP	Elastic-plastic analysis, with strain hardening	1.00	1.00	1.00	NA	1.12	1.00	1.00	1.00	NA	0.67	1.00	1.00	NA	1.53	1.30
5	NORSOK U-001	EP	Elastic-plastic true stress-strain curve with strain hardening	1.00	1.00	1.00	0.95	1.12	1.00	1.00	1.00	1.04	1.48	1.00	1.00	NA	1.17	1.31
6	API TR6AF2	LE	Linear elastic analysis, Stress linearization	1.12	0.77	0.82	NA	0.95	NA	NA	NA	NA	NA	1.03	1.37	NA	NA	1.17

H.S. - Hub separation, Mem - Membrane,

1) In API TR6AF2, gasket is not modelled in the flange FE model and the leakage failure is assumed to occur when the gasket reaction reaches a value of zero. This is the reason the functional capacity is different.

2) Bolt stress reached 105 ksi (yield) at 34 ksi pressure. Thus, structural bolt capacity is 22.8 ksi = 34 ksi*0.67. Structural flange capacity is 22.3 ksi = 40 ksi /1.2*0.67. Same approach applies to tension and bending loads.

3) Normalized to the LE analysis results

4) Plastic collapse of the assembly case considers the collapse of the assembly. Usually, the bolts fail first. The flange alone has higher capacity.

5) For design purpose, the structural capacity should be lowest capacity from bolt stress and plastic collapse of the assembly. Example, Case-2, structural capacity of the flange is min(27,24)ksi = 24 ksi.

6) API 6X results are valid for API 6A, 17D, 16A and 17G.

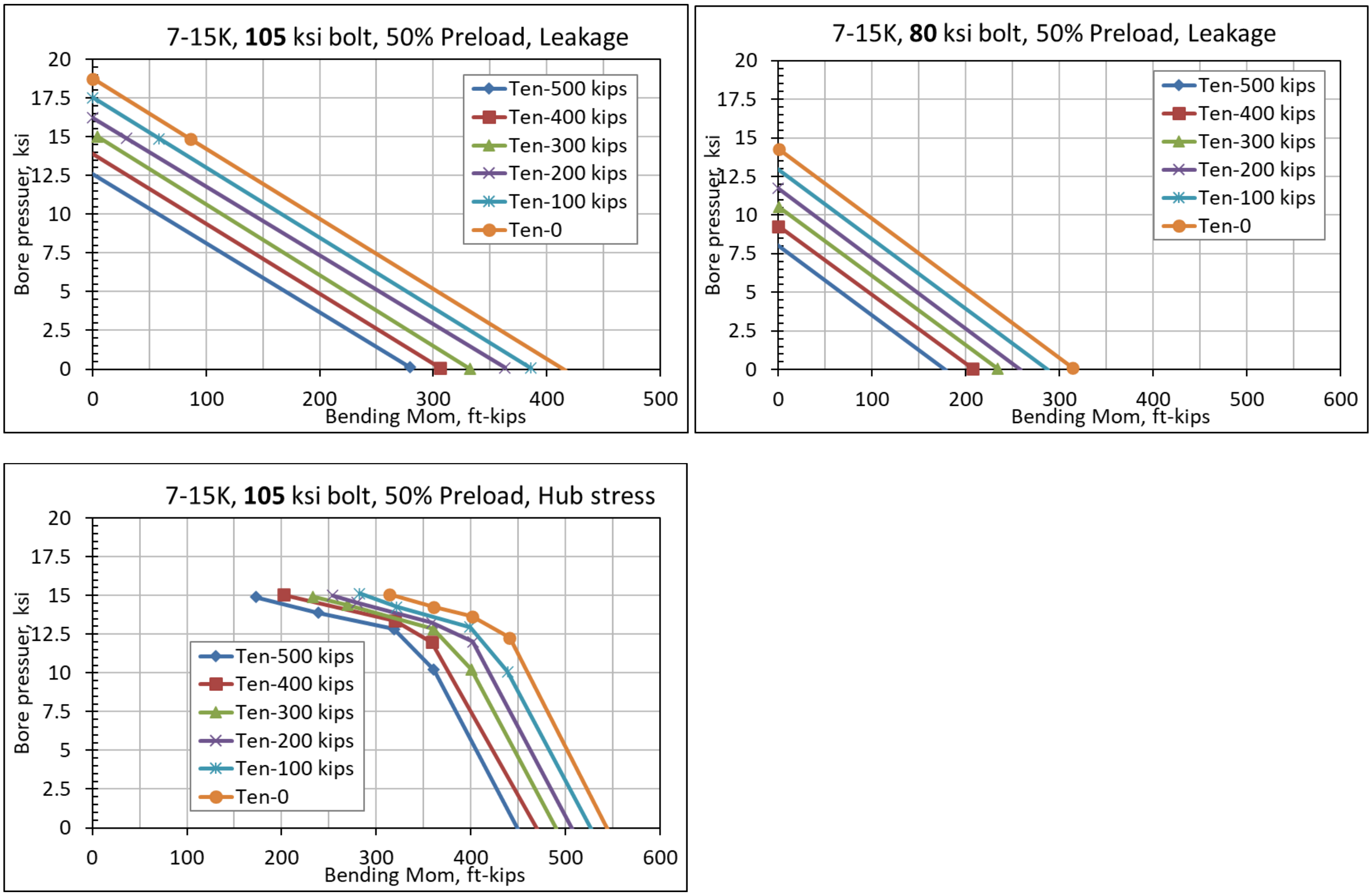

Figure 2: API 6A 7"-15K FLANGE CAPACITY CHART, TOP PLOTS ARE CAPACITY BASED ON THE LEAKAGE CRITERIA AND THE BOTTOM PLOT IS BASED ON THE FLANGE HUB STRESS (API 6AF2)

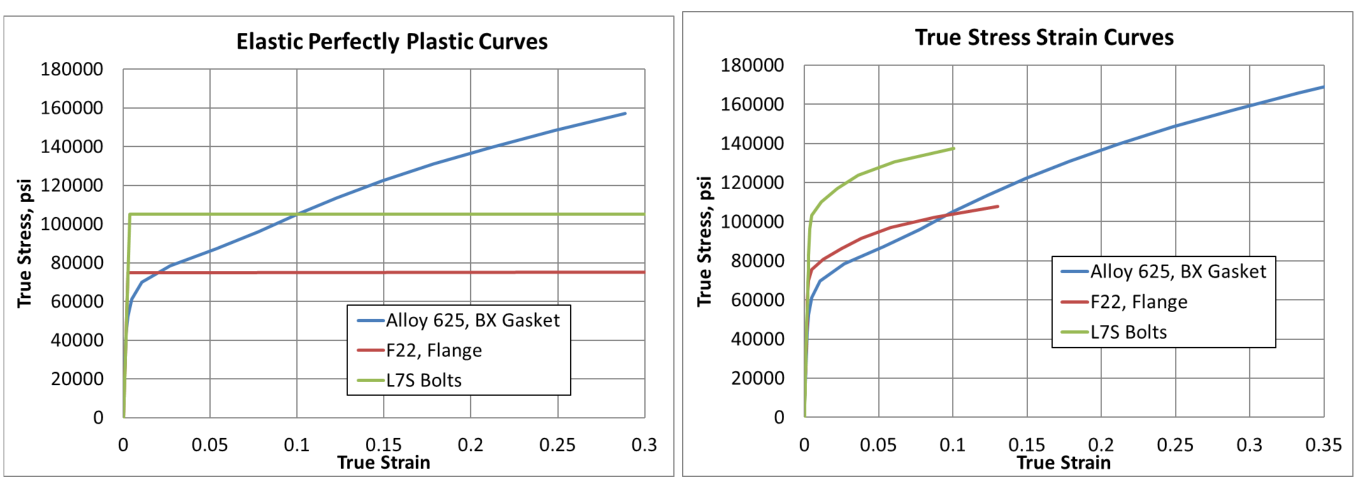

FIGURE 3: API 6A 7"-15K FLANGE MATERIAL STRESS STRAIN CURVES

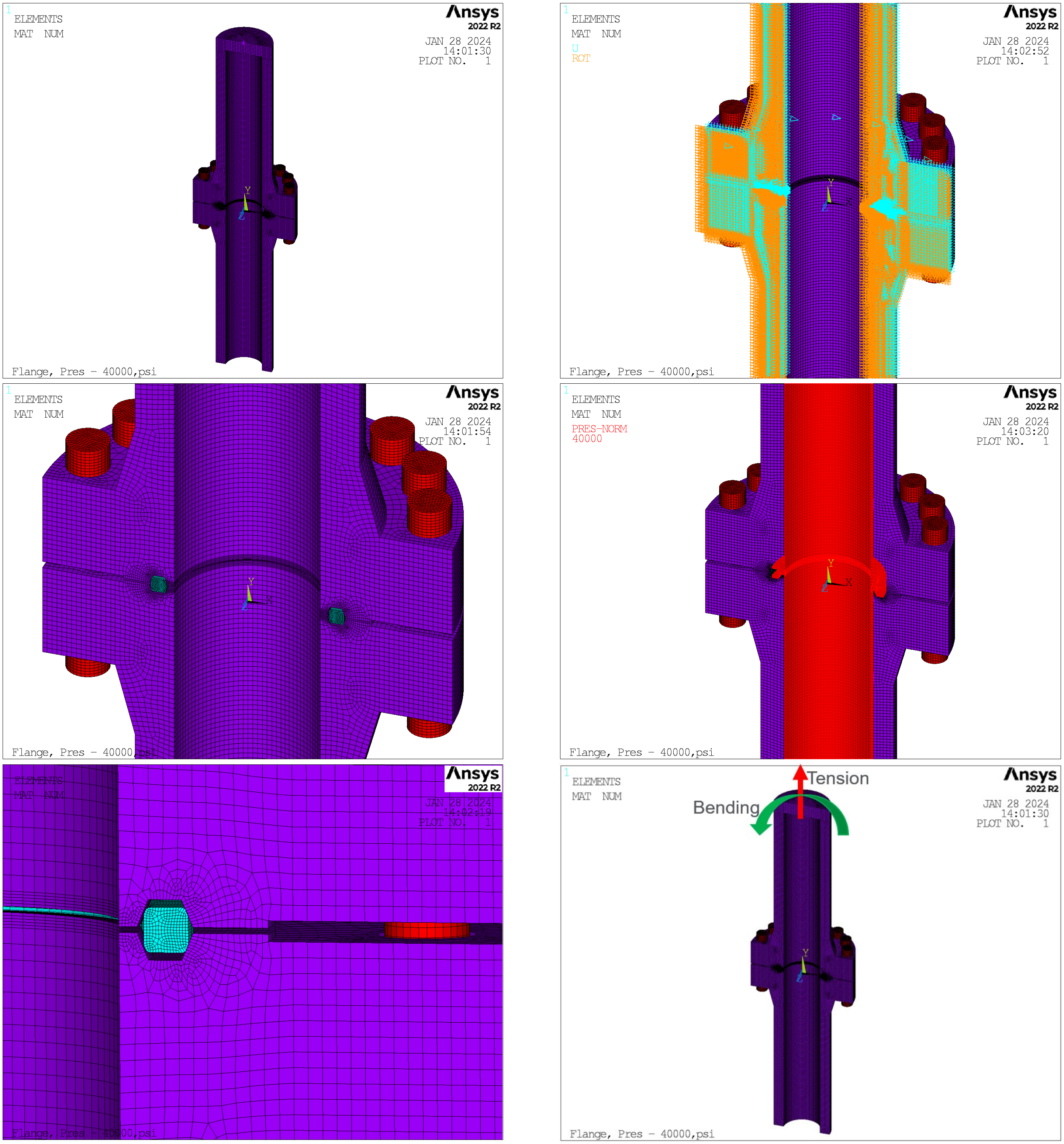

Figure 4: FE model of the 7"-15K flange, boundary condition and loading

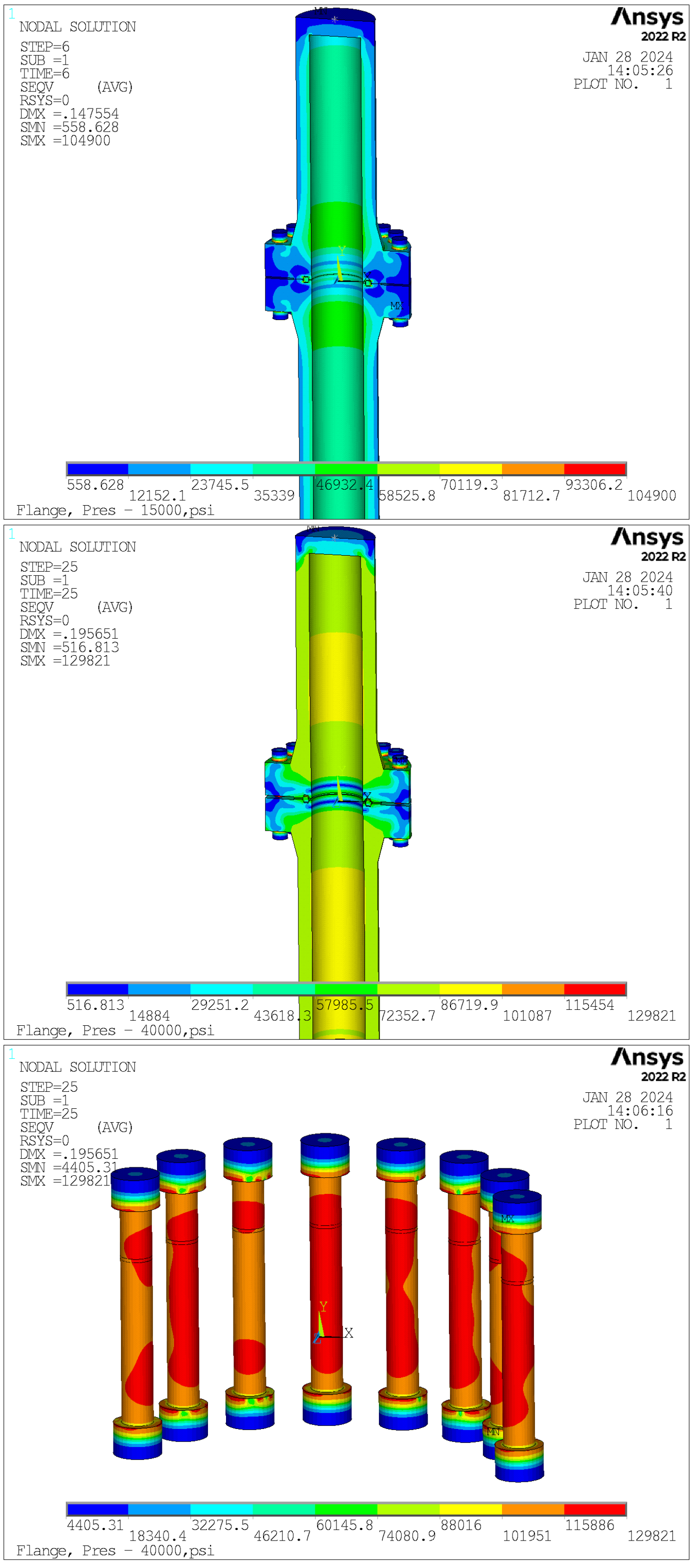

Figure 5: EP FEA, Pressure to failure, von Mises stress plot at 15 ksi, 40 ksi (collapse) and bolt stress

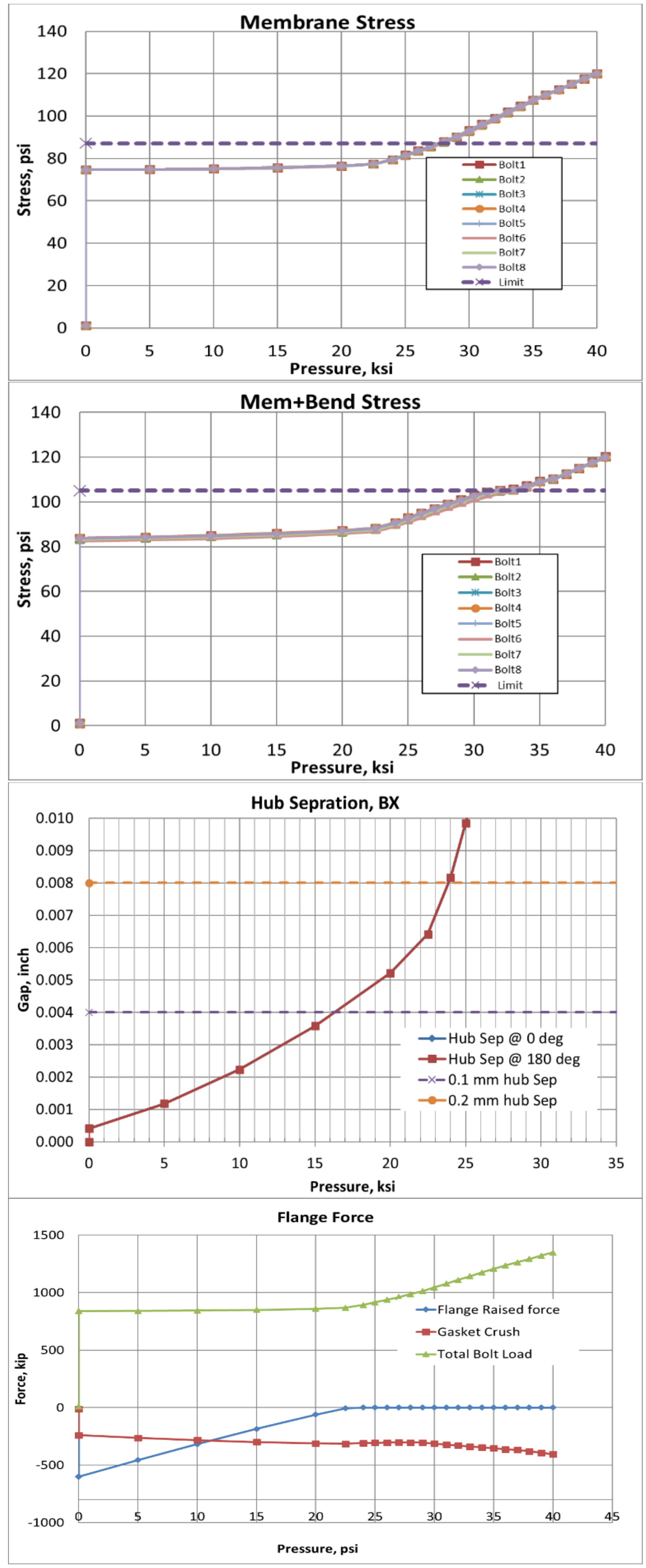

Figure 6: Pressure to failure, Bolt stress, gasket hub separation and raised face force plots

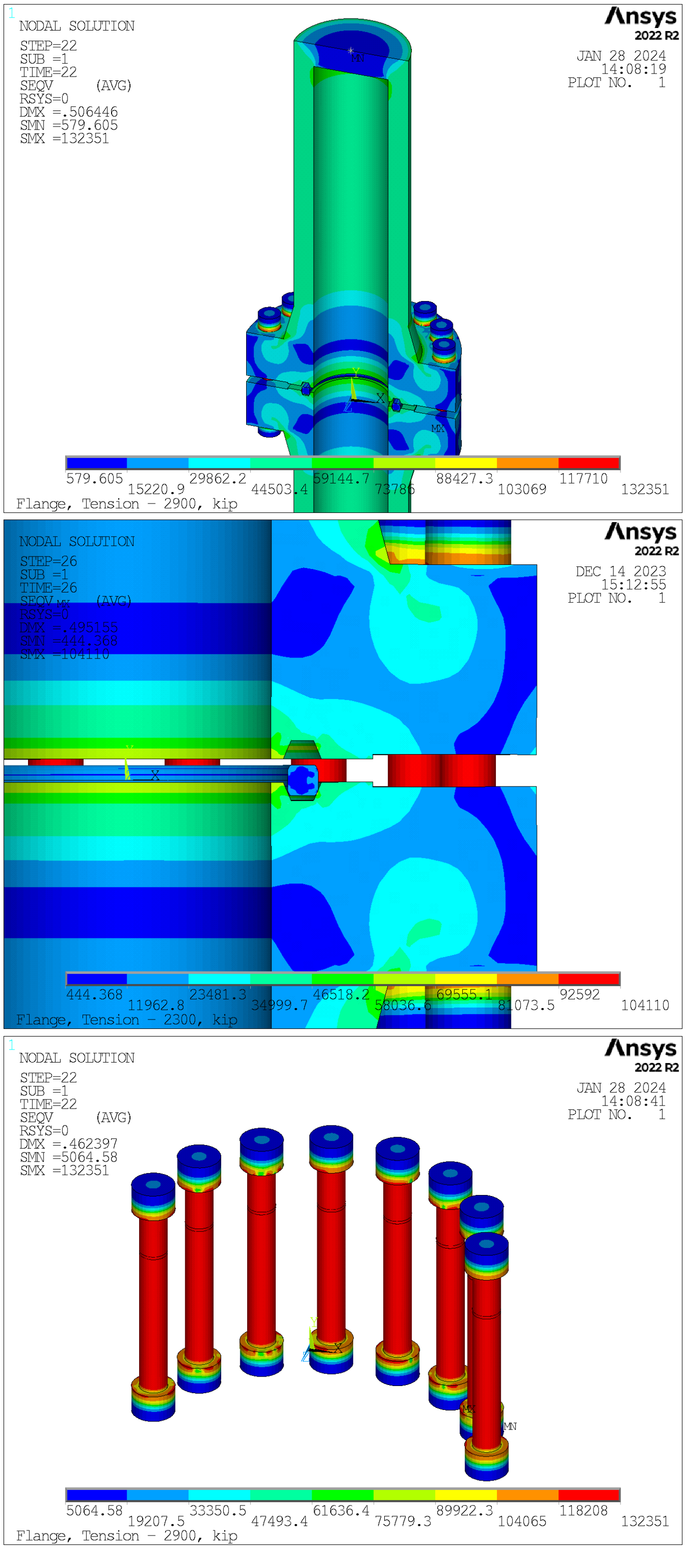

Figure 7: EP FEA, Tension to failure, von Mises stress plot at 2900 kips (collapse) and bolt stress

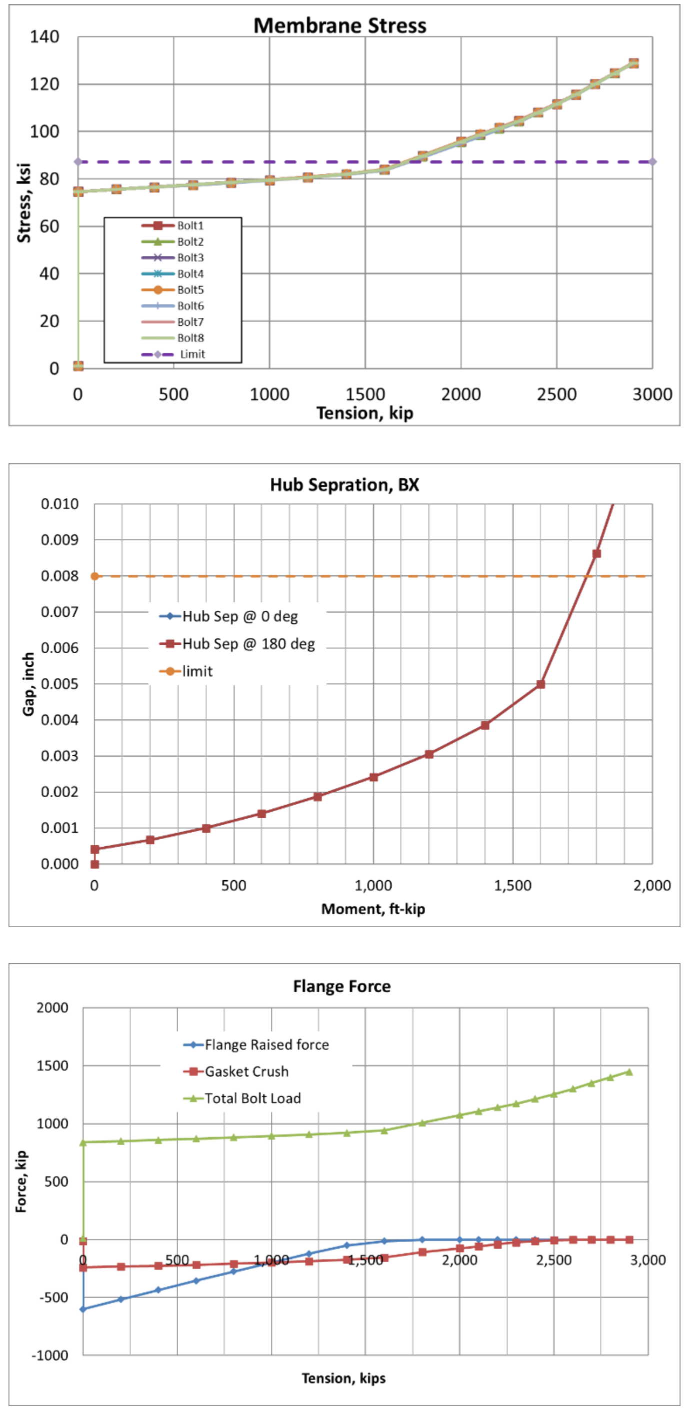

Figure 8: Tension to failure, Bolt stress, gasket hub separation and raised face force plots

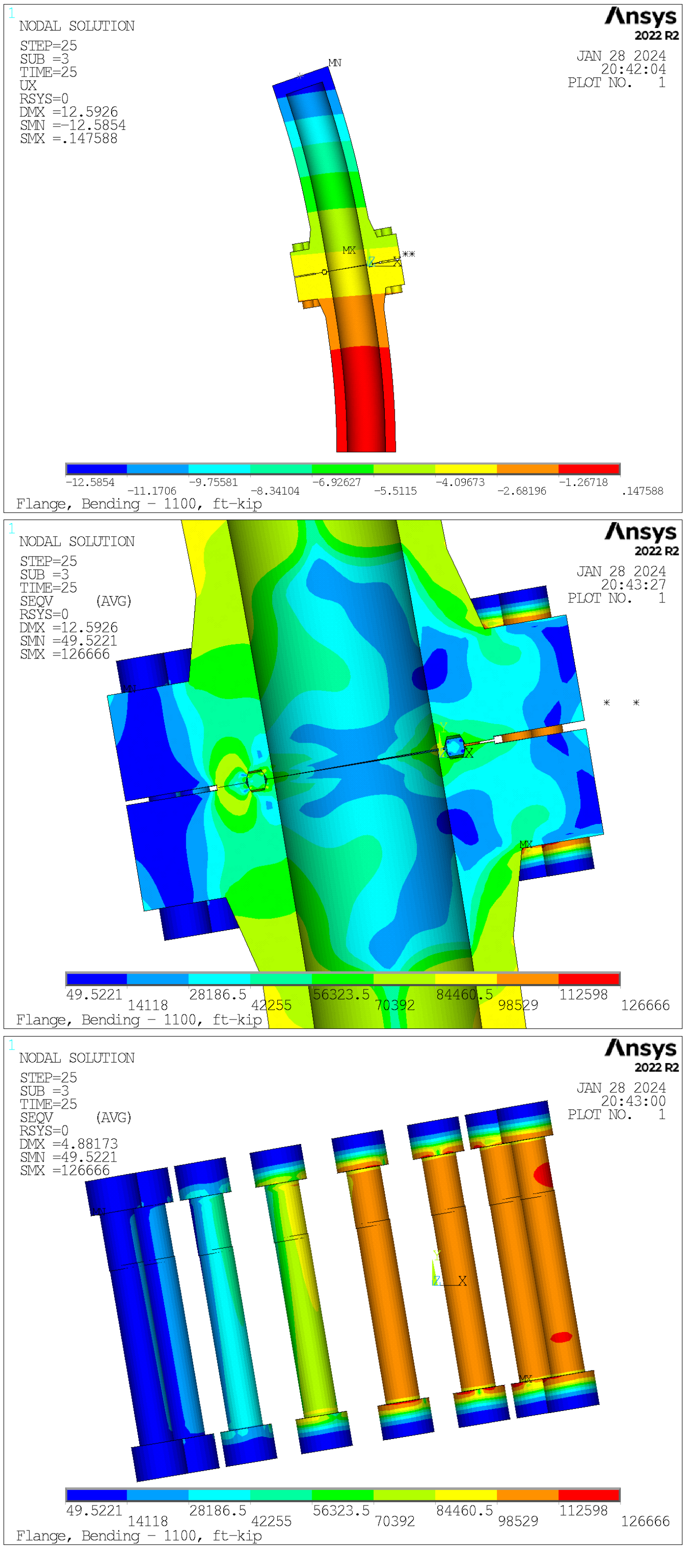

Figure 9: EP FEA, Bending to failure, von Mises stress plot at 1100 ft-kips (collapse) and bolt stress

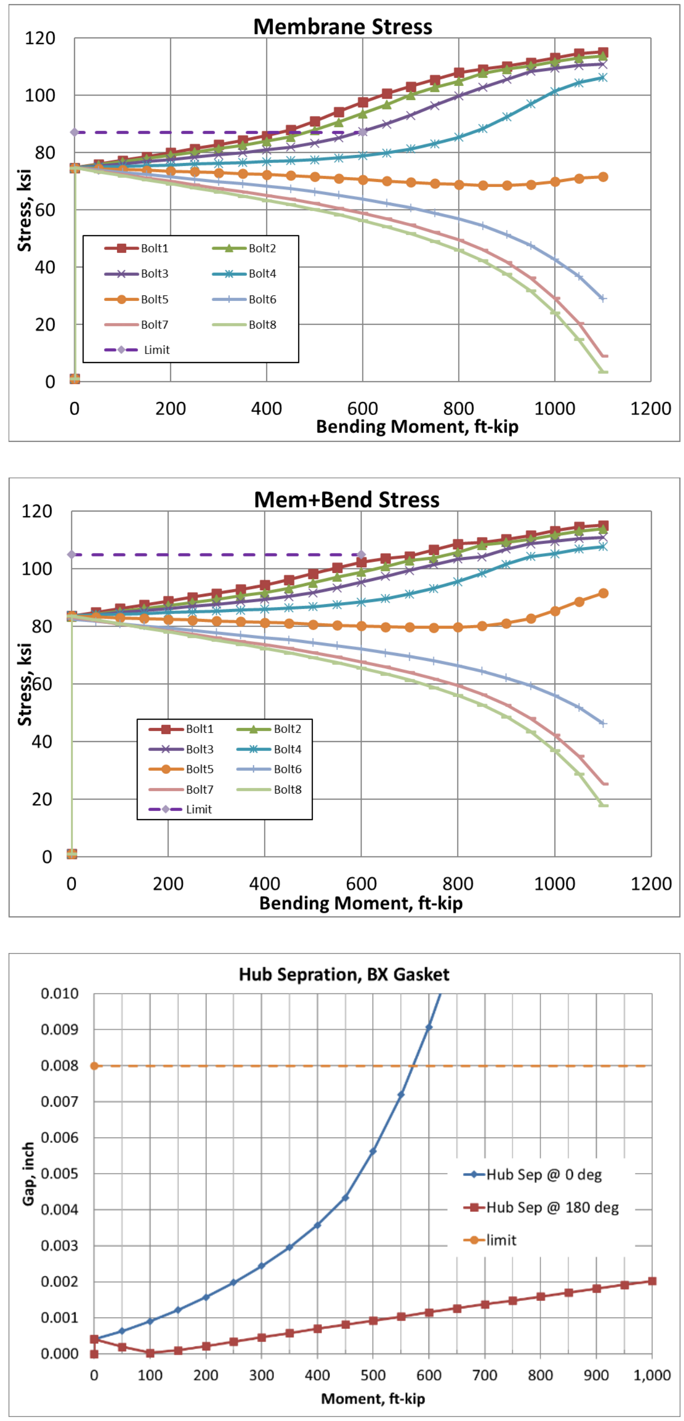

Figure 10: Bending to failure, Bolt stress, gasket hub separation and raised face force plots