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Research Paper

Approaches for assessing exerted piping loads on flanged joints

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ABSTRACT: *This document is intended to provide the engineer involved in the design of piping systems with an overview of assessment methods for flanged joints subject to both internal pressures and imposed external loads. However, although the methods to be considered pursue a common goal of preventing leakage of the flange connection, the differences in the approaches to achieve this goal are significant. The article provides insight into the applied methodologies and shows how they relate to each other. The differences are made clear on the basis of worked examples. This facilitates prudent consideration of which approach is most suitable for the application in question.*

KEYWORDS: *piping systems, imposed external loads, flanged joints, preventing leakage.*

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I. INTRODUCTION

Flange joint sealing integrity is of imminent importance and therefore requires special attention. Recommendations for ensuring sealing integrity of flanged joints are widely scattered throughout design codes, standards and in the literature. It is crucial to realize that each flange connection is prone to leakage and is often the weakest link in a piping system. Emphasis will be paid to the diversity of possible approaches to this topic.

II. FLANGE LEAKAGE CONCERN

The possibility of flange leakage occurring well before the failure of the pipe or the flange is a major concern of piping engineers when the allowable piping expansion stress-range runs well over the yield strength of the piping material. Even with the structural integrity of the flange intact, the system is still not functional if the flange tightness is not maintained. Flange leakage is a very complex problem involving many factors. Inadequate pressure rating, poor gasket selection, insufficient bolt loading, temperature gradient, bolt stress relaxation, piping forces and moments, and so forth, can all cause leakage at a flange. In this paper, we will limit us to the effects of piping forces and moments.

III. APPROACHES

A. Kellogg's Equivalent Pressure Method

The approach [1] assumes that the action of the moment and force is equivalent to the action of the pressure, which produces a gasket stress that is the same as the gasket stress produced by the force and the moment. The equivalence criteria is $S_F + S_M = S_P$, where S_F represent the gasket stress due to force, S_M the maximum gasket stress due to moment, and S_P the gasket stress due to equivalent pressure. Hence the equivalence relation becomes:

$$\frac{F}{\pi\,G\,b} + \frac{4\,M}{\pi\,G^2\,b} = \frac{\pi\,G^2\,P_e}{4\pi\,G\,b} \Rightarrow \text{i.e., } P_e = \frac{4\,F}{\pi\,G^2} + \frac{16\,M}{\pi\,G^3}$$

$$\text{Condition to be met: } P_e + P_d \leq P_r$$

Where: P_e = equivalent pressure (MPa)
P_d = internal design pressure (MPa)
P_r = rated flange pressure according ASME B16.5 [2] or ASME 16.47 [3]
G (mm) and b (mm) as per Appendix 2 of ASME BPVC Section VIII-Division 1 [4]
F = external tensile axial force (N)
M = external bending moment (Nmm)

Note that only tensile axial forces have to be taken into account, as these cause the flange connection to be pulled apart and thus lead to a reduction in the gasket pressure, while in the case of compressive axial forces the opposite is achieved.
Kellogg's equivalent pressure method [1] is a commonly used engineering approach which is referenced in many design codes. This method is very popular among piping engineers.

B. ASME VIII - 1; UG-44 Method
The main advantage of this method is that it is less conservative than Kellogg method. This method is published in paper: "Improved Analysis of External Loads on Flanged Joints" PVP2013-97814 by Dr. Warren Brown, 2013 [5].

$$16M_E + 4F_EG \leq \pi G^3\left((\mathrm{P_R} - \mathrm{P_D}) + \mathrm{F_M}\mathrm{P_R}\right)$$

Was included in Code Case 2901 on December 11, 2017[6], followed by inclusion in Section UG-44 of ASME BPVC Section VIII-Division1 in 2018[4].

$$16M_E + 4F_EG \leq \pi G^3[(P_R - P_D) + F_MP_R]$$

$$\frac{16M_E + 4F_EG}{\pi G^3} + P_D \leq P_R + F_MP_R$$

$$\frac{16M_E}{\pi G^3} + \frac{4F_E}{\pi G^2} + P_D \leq (1 + F_M)P_R$$

Nomenclature of the above expressions are according paragraph UG-44 of [4].

Finally, the expression can be presented as follows:

$$P_{eq} = P + \frac{4F}{\pi G^2} + \frac{16M}{\pi G^3} < (1 + F_M)P_{rating}$$

It applies that only F should be taken into account if this is a tensile force, else F should be set at zero. It is the same as the Kellogg method [1] , but the allowable pressure is increased times $(1+F_M)$, selecting the F_M factor from Table UG-44-1(see Table 1) which is taken from ASME BPVC Section VIII-Division 1[4].

Table 1

Table UG-44-1 Moment Factor, F_M							
		Flange Pressure Rating Class					
Standard	**Size Range**	**150**	**300**	**600**	**900**	**1500**	**2500**
ASME B16.5	≤ NPS 12	1.2	0.5	0.5	0.5	0.5	0.5
	> NPS 12 & ≤ NPS 24	1.2	0.5	0.5	0.3	0.3	-
ASME B16.47							
Series A	All	0.6	0.1	0.1	0.1	-	-
Series B	< NPS 48	[Note (1)]	[Note (1)]	0.13	0.13	-	-
Series B	≥ NPS 48	0.1	[Note (2)]	-	-	-	-

GENERAL NOTES:
(a) The combinations of size ranges and flange pressure classes for which this Table gives no moment factor value are outside the scope of this Table.
(b) The designer should consider reducing the moment factor if the loading is primarily sustained in nature and the bolted flange joint operates at a temperature where gasket creep/relaxation will be significant.

NOTES:
(1) F_M = [0.1 + (48 - NPS)]/56.
(2) F_M = 0.1, except for NPS 60, Class 300, in which case F_M = 0.03.

In general, the contribution of the bending moment to the equivalent pressure is much greater than that of the axial force. The bending moment dominates the equivalent pressure.

C. DNV Method

The idea of DNV method [7] is that the flange allowable pressure in Kellogg's method can be increased to hydrostatic test pressure that is 1.5 times the design pressure. But for safety reasons the factor 1.3 is used instead of 1.5.

$$MAWP = 1.5\ x\ P_R - P_{eq}$$

The equation can be represented in the following form:

$$P_{eq} = P + \frac{4F}{\pi G^2} + \frac{16M}{\pi G^3} < 1.3P_{rating}$$

Again, only tensile axial forces should be considered.

D. 'Koves' Method

For a standard flange conforming ASME B16.5 or ASME B16.47 Series A the following condition should be satisfied:

$$P + \frac{4}{\pi G^2}\left[F + \frac{4\,M}{C\,K_f}\right] \leq P_r$$

The above mentioned expression originates from the well-known M.W. Kellogg equivalent pressure approach [1] which assumes that the action of the moment and forces is equivalent to the action of the pressure. This produces a gasket stress that it the same as the gasket stress produced by the force and moment. However the original expression has been adjusted with the so-called Koves-factor (K_f). The method recognizes the non-uniform load distribution due to bending moments and takes the flange flexibility into account to some extent.For those interested in the Koves - method, I refer to ref. [8] and [9].

Note that in the event case F is compressive, then F should be left out of consideration in the above expression.

$$K_f = 1 + \frac{\{t^2 + [0.5\,(A - B) - d_{hred}]^2\}}{2.6\,t^2}$$

$$d_{hred} = \max\,[d_h\,(1 - B/1000)\,;\,0.5 \times d_h]$$

Nomenclature

A	Outside diameter of the flange (mm)
B	Inside diameter of flange (mm)
C	Bolt pitch circle diameter (mm)
d_h	Diameter of bolt holes (mm)
d_{hred}	Reduced bolt hole diameter (mm)
t	Flange thickness (mm)
F	External force (N)
G	Diameter of gasket load reaction (mm)
K_f	Koves factor (-)
M	External moment (Nmm)
P	Internal pressure (MPa)
P_r	Rated pressure according ASME B16.5 or ASME B16.47 (MPa)

E. ASME B31.8 Method

For some flanged joints, leakage may occur at expansion stresses otherwise permitted herein. The moment to produce leakage of a flanged joint with a gasket having no self-sealing characteristics can be estimated by the following equation:

$$M_L = (C/4)\,(S_b\,A_b - PA_p)$$

Where:

A_b = total area of flange bolts, (mm^2)

A_p= area to outside of gasket contact, (mm^2)

C = bolt circle, (mm)

M_L = moment to produce flange leakage, (Nmm)

P = internal pressure, (MPa)
S_b = bolt stress, (MPa)

This method [10] uses a rigid flange model having the pipe moment resisted by the bolt and gasket combination. By idealizing the bolt force and also the sealing force as distributed line loads located around the bolt circle, the residual sealing force per unit circumference, after subtracting the pressure force, is uniform and equal to: $(S_b A_b - P A_p) / (\pi C)$. With a bending moment applied, the bolt force and thus the sealing force will be linearly redistributed across the diametrical direction. The maximum and minimum forces per unit circumference due to the moment occur at two extreme points and equal to $M_L / (\pi C^2/4)$. The moment will cause the sealing force at one end to increase and at the other end to decrease. The flange is assumed to leak when the sealing force, after subtracting pressure and moment forces, at any point of the circumference is zero. In other words, the flange will leak when:

$$(S_b A_b - P A_p) / (\pi C) - M_L / (\pi C^2/4) = 0$$

Considering M_L as the allowable moment is not correct. The formula is meant to predict the moment to produce leakage. The formula is simple and its intent is clear, but is not very easy to apply. Proper margins has to be included that require a solid substantiation. This method will not be discussed further because its practical application is doubtful.

IV. DISCUSSION

In order to provide more insight into the various methods, an approach has been chosen that is based on a selected standard flange that is loaded by internal pressure and an external bending moment. The axial load is ignored (set to zero) because it is assumed that it is a compressive force. Successively, the methods described in this article are applied to the selected flange. The results will be presented both in tabular form and graphically.

V. ANALYSIS OF SELECTED FLANGE

An NPS 16" (NB 400) Welding Neck Flange in accordance with ASME B16.5 - Class 300 has been selected. Further details are shown in the Table 2. By rearranging the formulas for the various methods, expressions can be derived to determine the maximum allowable bending moment on the flange connection, where the axial force is assumed to be a compressive force and is therefore disregarded. For clarity, the notations for the different parameters are synchronized.These respective formulas are for each method included in Table 3 and it also contains the results of the calculation.

Figure 1. Typical Welding Neck Flange Configuration

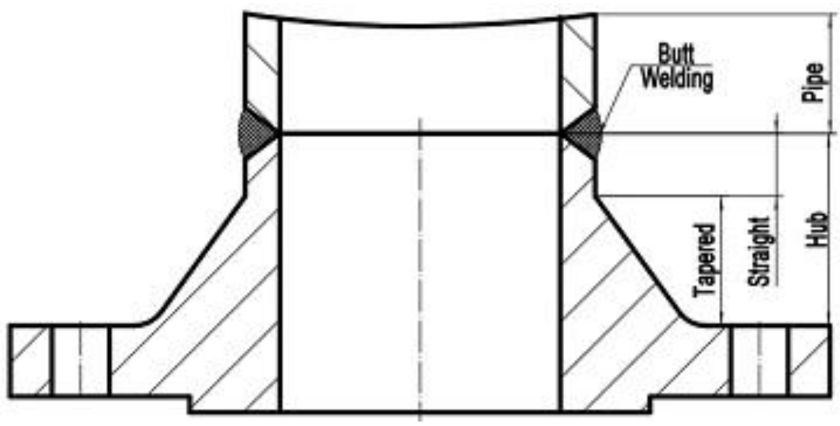


Table 2

Design Condition		Flange Dimensions NPS 16"(NB 400)		Gasket Data Spiral Wound ASME B16.20	
Design Pressure (MPa)	3.5	A = OD of flange (mm)	650	OD Gasket (mm)	463.6
Design Temperature (°C)	150	B = ID of flange (mm)	387.34	ID Gasket (mm)	422.4
Flange Rated Pressure (MPa)	4.51	C = Bolt-circle diameter (mm)	571.5	Effective OD Gasket(mm)	463.6 - 2 x 1.5 = 460.6
Flange Rating Class	300	t = Flange thickness (mm)	55.6	N = Effective gasket width (mm)	19.1

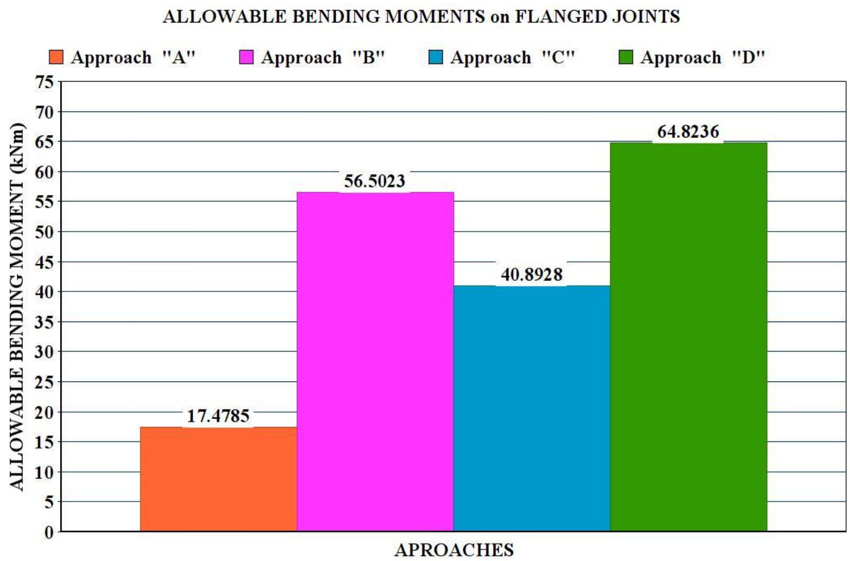
Bolting Data 20 x 1 1/4"- 8 UN bolts		**Auxiliary Data**		b_0 = Basic seating width (mm)	9.55
S_b = Allowable bolt stress at design temperature (MPa)	172	G = Diameter at location of gasket load reaction (mm)	445.025	b = Effective gasket seating width (mm)	2.52√9.55 = 7.7875
A_b = Total cross-sectional area of the bolts (mm^2)	20 x 599 = 11980	A_p = Area to outside of gasket contact, (mm^2)	$\pi/4 \times 460.6^2 =$ 166624		
Factors					
F_M = 0.5 acc. UG-44					
d_h = Diameter of bolt holes (mm)			34.925		
d_{hred} = Reduced bolt hole diameter (mm) $d_{hred} = \max [d_h (1 - B/1000) ; 0.5 \times d_h]$			21.397		
K_f = Koves factor (-) $K_f = 1 + \frac{\{t^2 + [0.5 (A - B) - d_{hred}]^2\}}{2.6 t^2}$			2.888		

Table 3

Approach number	**Formula for the allowable bending moment**	**Allowable bending moment on flanged joint**
A	$M = \frac{\pi G^3 (P_r - P_d)}{16}$	17478513 Nmm **17.4785 kNm**
B	$M = \frac{[(1 + F_M) P_r - P_d] \pi G^3}{16}$	56502323 Nmm **56.5023 kNm**
C	$M = \frac{\pi G^3 (1.3 P_r - P_d)}{16}$	40892799 Nmm **40.8928 kNm**
D	$M = \frac{\pi G^2 C K_f (P_r - P_d)}{16}$	64823654 Nmm **64.8236 kNm**
E	$M = \frac{C}{4} (S_b A_b - P_d A_p)$	211080059 Nmm (*) **211.080 kNm**

(*) Should not be considered an allowable moment, but predicts the moment to produce leakage. See section E for more details. The combined bending stress due to moment and the axial stress due to pressure amounts to approximately 220 MPa, which is quite high.

Graphical representation of allowable bending moments on selected flange connection



From the graph follows the following ranking in terms of conservatism, namely: A - C - B and least conservative approach number D. The related ratios in parentheses are successively: A (0.0973) - C (0.2276) - B (0.3144) and D (0.3607).
The bending stresses in the connecting pipe section (OD 406.4 mm and nominal wall thickness of 9.53 mm) of the flange subjected to the allowable bending moment is displayed in Table 4.

Table 4

Approach number	σ_b = M/Z	Bending stress (MPa)
A	17478513/1151925	15.17
B	56502323/1151925	49.05
C	40892799/1151925	35.50
D	64823654/1151925	56.27

VI. ALTERNATIVE MORE COMPREHENSIVE APPROACH

Where flanges are subject to external loads or moments, these are converted to their pressure equivalents, which are then added to the initial internal design pressure (Pd) to give a substitute design pressure. Subsequently, a traditional flange calculation according to ASME Section VIII-Division 1; Appendix 2 are performed with the substitute pressure (P_s) entered as the design pressure. If it is found that the bolt and flange stresses do not exceed the allowable values, the external flange loads can be considered acceptable. We can also mirror this approach to that used for methods A to E, again assuming that the axial force (F) is a compressive force and that we can calculate the allowable bending moment on the flange connection using the following expression:

$$M = \frac{\pi\, G^3 (\, P_s - P_d\,)}{16}$$

For the flange described in section V, the calculated allowable internal pressure is 5.75 MPa (Determined using a software program from P3 Engineering).
With this approach, the pressure of 5.75 MPa can be considered as the substitute pressure P_s and the calculation of the allowable bending moment yields:

$$M = \frac{\pi\,.\,445.025^3 (5.75-3.5)}{16} = 38937282 \text{ Nmm} = 38.9373 \text{ kNm}$$

The bending stress in the connecting pipe associated with this moment is:

M/Z = 38937282 / 1151925 = 33.80 MPa

VII. CONCLUSIONS

Although the various methods I thru IV have only been applied to an individual case, namely an NPS 16" (NB 400) Class 300 flange connection, it can be said that the "Kellogg" Equivalent Pressure Method is by far the most conservative. The least conservative is the so-called "Koves" method closely followed by the method described in paragraph UG-44 of ASME BPVC Section VIII- Division 1. The result of the alternative approach as elaborated in section VIII is close to approach C according to DNV. Nevertheless, a reasonable indication can be derived from this article with regard to the approach to be applied.

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