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# Comparative study of bolt spacing formulas used in bolted joint designs

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ABSTRACT

Bolted flange joints are the most popular type of connection between pressure vessels and piping equipment. They are very attractive type of connection because they are simple to mount and offer the possibility of disassembly. However, they are very complex structures to design and analyze and often result in leakage failure. One of the raisons is the loss of tightness that results from the uneven distribution of the gasket contact stresses in the radial and circumferential direction. Many factors contribute to such a failure; bolt load non-uniformity, inadequate flange to gasket stiffness, inappropriate bolt spacing requirements or a combinations of some of these.

The variation of the contact stress in the circumferential direction between any two bolts is dictated by bolt spacing. This paper is an extension of the work in which the more accurate analytical solution based on the theory of circular beams resting on a linear elastic foundation is used to validate some existing flange bolt spacing formulas and in particular the TEMA formula, Robert's formula and the one recently developed by Koves. The relationship between bolt spacing and the gasket compression modulus, flange thickness and size is deduced from an analysis that considers a maximum tolerated gasket contact stress difference obtained at the bolt and between two bolts. Comparison between these different methods is also provided.



## 1. Introduction

It is well established that existing flange designs do not provide a rational method for the determination of appropriate bolt spacing. Even though considerable research has already been conducted worldwide, bolted flanged connections are in general still designed based on experience and lessons learned. Because the current ASME flange design procedure [1] is not based on leakage, there is no consensus within the ASME code committee to adopt a more realistic and modern flange design procedure such as that of the European EN1591 standard [2]. Taylor–Bonney Division [3] has developed a rule on bolt spacing which was adopted by TEMA [4] for the design of heat exchangers.

The theory of a circular beam supported on a linear elastic foundation has been the subject of few investigations involving bolted flange joints [5]. Since the mechanical behavior of a gasket is complex, idealized models have been introduced [6]. The simplest approach was to assume that the gasket has a linear elastic behavior making the foundation stiffness constant. Since the early work by Water et al. [7,8] on bolted joints in the late thirties, there has been little research on the effect of bolt spacing on the circumferential distribution of the gasket contact stress and its impact the leakage tightness of bolted flange connections. Other approaches have been applied for joints with metal-to-metal contact [9,10]. Roberts [11] developed a numerical summation approach to achieve maximum bolt spacing by considering the flange to behave as a straight beam on an elastic foundation. In 1975, Kilborn [12] treated the subject of bolt spacing in flanged joints in which formulas are derived for calculating approximate values for maximum bolt spacing in flange and gasket joints. In deriving the Rotscher pressure-cone-envelope theory (Rt) to include bolt clearance, Lehnhoff et al. [9] showed that bolt spacing depends on the pressure at the parting surfaces, which depends on the thickness ratio of the bolted parts and the total grip length.

In 2007, Koves [13] expanded the approach used by Roberts based on the theory of beams on elastic foundation, to develop a closed form analytical solution that does not require a numerical

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**Nomenclature**

| | |
|---|---|
| $\beta$ | bending rotation (rad) |
| $\theta$ | flange twist rotation (rad) |
| $\nu$ | axial flange displacement (mm) |
| $A$ | flange outside diameter (mm) |
| $A_g$ | gasket outside diameter (mm) |
| $b_f$ | flange width equals to (AB)/2 (mm) |
| $b_g$ | gasket contact width (mm) |
| $B$ | flange inside diameter (mm) |
| $C$ | bolt circle (mm) |
| $D_0$ | diameter of flange centroid (mm) |
| $D_g$ | gasket deflection (mm) |
| $d$ | nominal bolt diameter (mm) |
| $E_f$ | Young's modulus of flange (MPa) |
| $E_g$ | compression modulus of gasket (MPa) |
| $g_0$,$g_1$ | hub small and big end thickness (mm) |
| $h$ | hub length (mm) |
| $H$ | bolt spacing (mm) |
| $G$ | gasket reaction diameter (mm) |
| $G_f$ | flange shear modulus (MPa) |
| $I$ | ASME flange equivalent bending stiffness |
| $J$ | flange torsional moment of area (MPa) |
| $K_g$ | gasket stiffness (N/mm) |
| $m$ | gasket maintenance factor |
| $M_f$ | flange twisting moment (N.mm/mm) |
| $M_n$ | ring bending moment (N.mm) |
| $M_t$ | ring twist moment (N.mm) |
| $n$ | bolt number |
| $P_b$ | ring axial force per unit length (N/mm) |
| $R$ | radius of flange centroid equal to $D_0/2$ (mm) |
| $t_f$ | flange thickness(mm) |
| $t_g$ | gasket compressed thickness(mm) |
| $V_b$ | ring axial shear force (N) |

*Acronyms*

| | |
|---|---|
| ASME | American Society of Mechanical Engineers |
| EN | European Normalisation |
| HE | heat exchanger |
| TEMA | Tube Exchanger Manufacturer Association |

summation. Bouzid et al. [14] studied the effect of flange rotation on tightness, and used Dual Kriging interpolation to evaluate the radial distribution of contact stress of a non-linear gasket. Realizing that the circumferential distribution of the gasket contact stress is also a key parameter to estimate the leakage performance of bolted flange joints, Bouzid et al. lunched an investigation to study the effect of bolt spacing by developing two analytical models; the first one is based on the theory of circular beams resting on a linear elastic foundation [15] and the second one is based on the theory of ring on non-linear elastic foundation [16]. Later they used a regression method to obtain a simple bolt spacing formula [17].

## 2. Backround: existing bolt spacing formulae

There are few bolt spacing formulae that have been developed through the years for bolted flanged joints some of which are more popular than others. This paper treats some of them which are to be known as THEMA formula, Robert's formula and Koves' formula.

### 2.1. THEMA formula

For heat exchanger designs, TEMA [4] uses a very simple formula for a maximum spacing between bolt centers when exceeding twice the bolt diameter and the flange thickness $2d_b + t_f$. This is given by the expression:

$$H = 2d + \frac{6t_f}{m + 0.5} \tag{1}$$

This formula does not take into account the relative stiffness between the flange and gasket and does not consider flange size and width.

### 2.2. Robert's formula

In the 50's Roberts [11] provided a more realistic formula of bolt spacing based on beam on elastic foundation shown in Fig. 1 to obtain gasket contact stress between bolts. He superposed the contribution of forces from not less than 15 bolts to obtain a convergence for the gasket stress. The numerical summation led to the following formula of the maximum bolt spacing achieved to obtain not less than 95% contact stress midway between bolts.

$$H = t_f \sqrt[4]{1 + K} \tag{2}$$

where $K$ is flange to gasket stiffness ratio

$$K = \frac{E_f b_f t_g}{E_g b_g t_f} \tag{3}$$

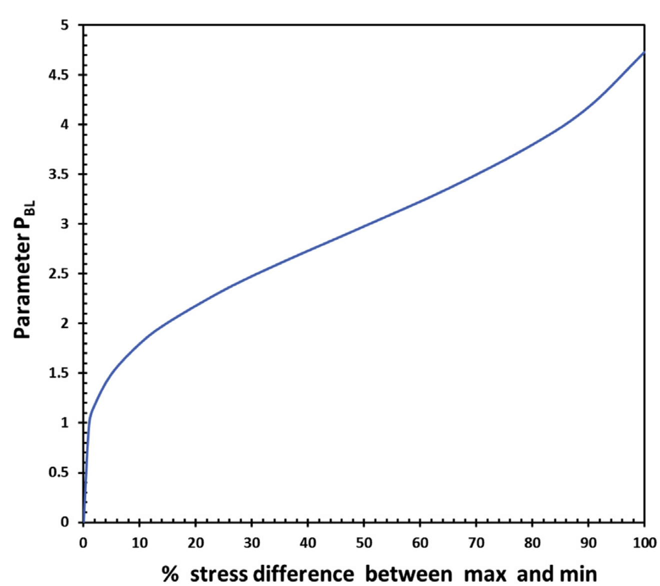


**Fig. 1.** Bolt spacing parameter BL (Kove's method).