

Bolt Prying, A Mechanical Engineers Point of View.

1 Introduction

Prying of a bolted joint is a phenomenon which causes an increased bolt load due to a lever like action exerted on the bolt shank by the clamped components under load. It is affected by the clamped component thickness (stiffness), distance of the bolt centre line to the line of action of the applied load, length of outstand and the bolt preload force. Our learned friends from the structural engineering fraternity have deliberated a multitude of analytical models which apply to various steel sections and in this article I will attempt to compare their methods with the best that the mechanical engineering community has to offer, step forward VDI 2230.

In this article we will consider one application of a single bolted joint with an eccentric application of load, which will enable us to do a direct comparison between the two methods.

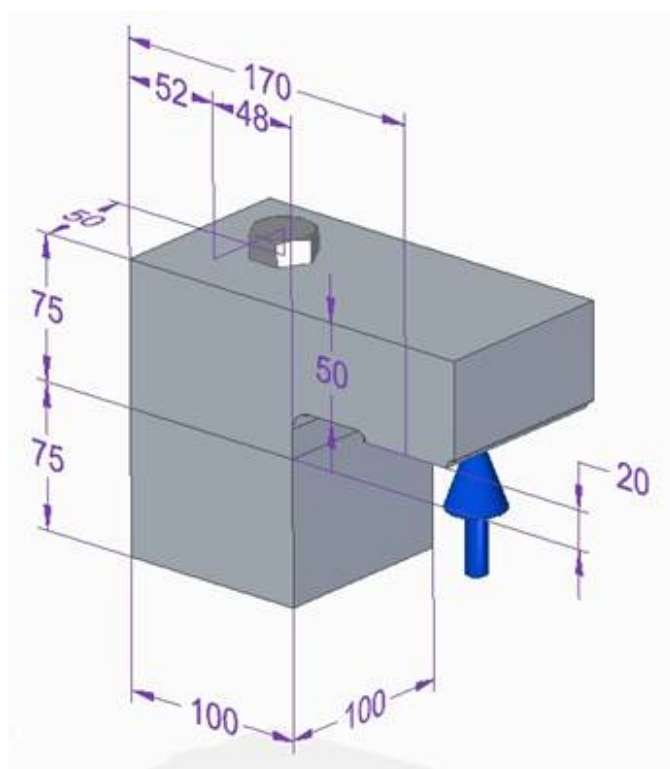


Figure 1 - ISO View of Eccentrically Loaded Single Bolted Joint Examined in this Article

2 The Douty and McGuire Method

When formulating the mathematical models for prying, our structural peers derive a "prying ratio", Q/F [3] [4], where Q is the additional prying force and F is the externally applied force. A high prying ratio would mean a large prying load is generated for a relatively small applied bolt load.

By taking moments, the prying ratio, in its simplest form, can be shown to be: -

$$Q/F = b/a - (1) [3]$$

This is observed from the figure below: -

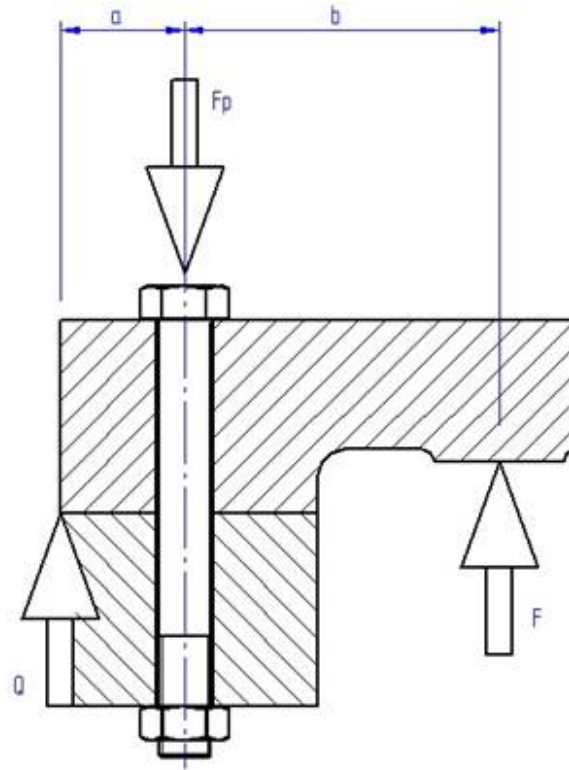


Figure 2 - Section View of Eccentrically Loaded Single Bolted Joint

Douty and McGuire have derived a model which takes account of the bolt pre-load and combines analytical methods with empirical modifications [3][4]. As the bolt pre-load induces a compressive force in the clamped plates, the material under the bolt head is deformed. Subsequently, the plate thickness in this region is reduced. It is postulated that the joint will not separate until the flange thickness is restored in the bolt area by the prying load [3][4].

The reduced form of the Douty and McGuire prying ratio is: -

$$Q/F = 3b/8a \text{ [3][4] - (3)}$$

This can be expressed as: -

$$Q = (3b/8a)F - (4)$$

If we treat the upper clamped component as a free body, then to achieve equilibrium and by resolving in the vertical direction the bolt force must be equal to: -

$$F_p = F + Q - (5)$$

If we let $P = 3b/8a$ then equation 5 can be rewritten as: -

$$F_p = (1 + P)F - (6)$$

At this stage it is probably worthwhile highlighting that although the above equation yields an additional bolt force including prying effects, the actual force which is translated to the bolt is a fraction of this, due to bolt pre-loading. A pre-loaded bolted joint behaves like a set of springs in series and parallel. As the joint is pre-loaded the joint plates are compressed and the bolt is stretched. When an external working load is applied to the bolted joint, the load translated to the bolt is a function of the relative stiffness of the bolt and plate. When an external load is applied, some of the applied load is transferred to the bolt but a much larger component acts to relieve the compression in the clamped plates. This is due to the clamped plates being significantly stiffer than the bolt [1].

From references [1] and [2], the additional bolt force can be shown to be, in its general form: -

$$F_b = n \cdot F_p \cdot K_b / (K_b + K_m) - (7)$$

Where,

K_b = Bolt Stiffness

K_m = Member Stiffness

n = Load introduction factor

If we let $C = nK_b/(K_b + K_m)$ then the total bolt force can be expressed as: -

$$F_b = (1 + P)FC + F_{pl} \text{ - (8)}$$

Where,

F_{pl} = Pre-Load Force

For comparison with VDI 2230 it is necessary to define a term for additional bolt force in terms of the prying factor. The additional bolt load does not include the pre-load force: -

$$F_s = (1 + P)FC \text{ - (9)}$$

We can therefore define the structural engineering prying factor as: -

$$S = (1 + P) \text{ - (10)}$$

Take note of equation 10, we will refer to it later.

3 VDI 2230 in a Nutshell

VDI 2230 first made an appearance in 1986 [2] in Germany and is widely recognized as the all-encompassing standard for calculating bolted joints not only within but also outside the German-speaking area. The aim of the guideline is to provide the design engineer with a systematic procedure for calculating bolted joints in the form of calculated steps and once one is familiar with its structure it is relatively straightforward to implement.

The standard focusses on a single bolt and the clamped material in the surrounding area. Therefore, if one is designing a multi-bolt joint, care must be taken to separate out a single bolt and this is explained in detail within the standard. In this article we will concentrate on a single bolted joint for ease of calculation.

To accurately predict the bolt forces, it is first important to establish the area of influence surrounding the bolt and this part sometimes requires a little artistic license. For a typical bolted joint, the compressed region of the clamped components resemble two frusta mirrored about the transverse center line of the joint, with a cylindrical sleeve sandwiched in the middle [2], see the figure below: -

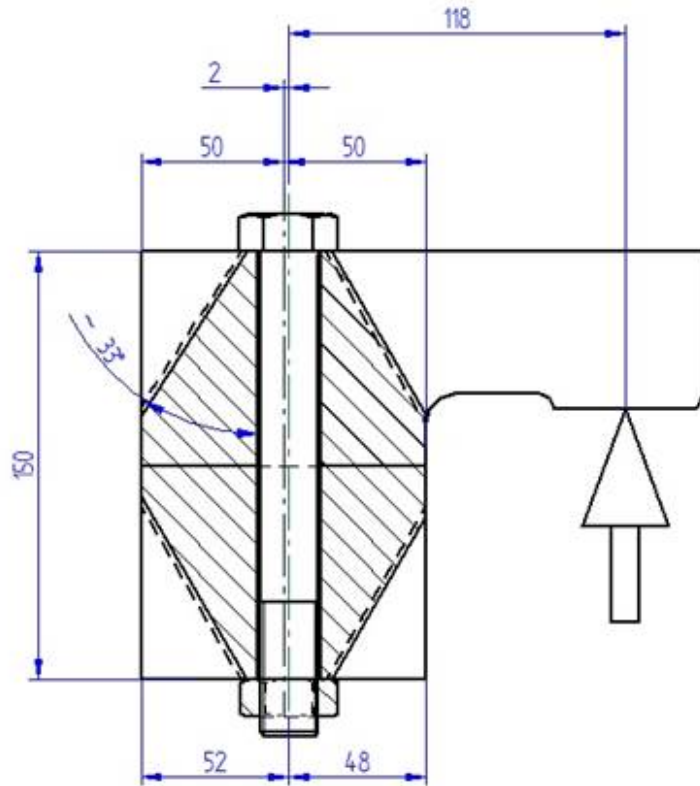


Figure 3 - Section View of Joint Showing the Deformed Solid Region of the Clamped Components

Once this "deformation solid" region has been established, the stiffness requires calculating and VDI details a very structured approach to this. The stiffness of a body of uniform cross-section in tension is EA/L where, E is the Elastic Modulus, A is the cross-sectional area and L is the length then to calculate the stiffness of a frustum one would integrate this expression over the height. VDI 2230 goes one step further and takes account of the bending stiffness of the joint, which is required for an eccentric application of load. If linear stiffness is EA/L then bending stiffness is related to EI/L , where I is the second moment of area. As the second moment of area of the deformation solid changes with respect to its vertical position then the expression for bending stiffness must be integrated over the clamped plate length to get the bending stiffness of the joint [2].

VDI 2230 also takes account of eccentric clamping, which is when bending is introduced into the bolt shank by pre-loading alone. This occurs when the deformation solid cannot be fully formed on all sides as shown in figure 3. If the clamped components are more compliant at the side of the joint tending to open, then the bolt loads will be higher [2].

The combination of eccentric clamping and eccentric loading is the least favorable, however it is the one most commonly occurring in practice. The example that we will use for comparison will be eccentrically clamped and eccentrically loaded.

To make a comparison between the Douy and McGuire method and VDI 2230 we need to first treat the above example as a concentrically clamped and loaded model and then perform an eccentric calculation. The prying factor will be the ratio between the two, which can then be directly compared to the structural method.

In VDI 2230 the equations for bolt load are expressed in terms of the bolt and plate compliance as opposed to the stiffness, remember that compliance is the reciprocal of stiffness. Therefore, in terms of compliance, the VDI2230 prying factor is derived by dividing the eccentric bolt load equation by the concentric equivalent to give: -

$$M = (n_e/n_c) \cdot (d_p^{**}/d_p) \cdot (d_p + d_s)/(d_p^* + d_s) - (12)$$

We are now ready for the mechanical and structural world to cross swords.

4 The Showdown

We will first look at a comparison of the structural and mechanical prying factors as defined in equations 10 and 12 for the geometry shown in figure 3. We will then extend this study by incrementally increasing the moment arm of the applied load and then plot the prying factor against the moment arm. The clamped components and bolt geometry will remain unchanged throughout. The table of calculated values is shown below: -

Calculation Parameters	1	2	3	4
a, mm	122	242	482	962
b, mm	50	50	50	50
S_{sym}	2	2	2	2
Member Stiffness, N/mm	2718156	2718156	2718156	2718156
Bolt Stiffness, N/mm	338089	338089	338089	338089
Member Compliance, δ_p , mm/N	3.67896E-07	3.67896E-07	3.67896E-07	3.67896E-07
Bolt Compliance, δ_s , mm/N	2.9578E-06	2.9578E-06	2.9578E-06	2.9578E-06
Eccentric Clamping & Loading				
I_{Bers}^V , mm ⁴	285539.57	285539.57	285539.57	285539.57
I_{Bers}^{VE} , mm ⁴	316955.49	316955.49	316955.49	316955.49
I_{Bers}^H , mm ⁴	11000000.00	11000000.00	11000000.00	11000000.00
I_{Bers} , mm ⁴	387048.38	387048.38	387048.38	387048.38
δ_p^* , mm/N	3.75458E-07	3.75458E-07	3.75458E-07	3.75458E-07
δ_p^{**} , mm/N	8.29174E-07	1.28289E-06	2.19032E-06	4.00518E-06
a_k/h	0.5	0.5	0.5	0.5
I_A/h	0.99	2.59	5.79	12.19
$n_{concentric}$	0.13	0.13	0.13	0.13
$n_{eccentric}$	0.04	0.04	0.04	0.04
Additional Bolt Load Factor, Concentric	0.014	0.014	0.014	0.014
Additional Bolt Load Factor, Eccentric	0.010	0.015	0.026	0.048
Prying Ratio				
VDI2230	0.692	1.071	1.828	3.342
Douty & McGuire	1.915	2.815	4.615	8.215
	2.768	2.630	2.525	2.458

Table 1 - Calculations of Structural and Mechanical Prying Factors

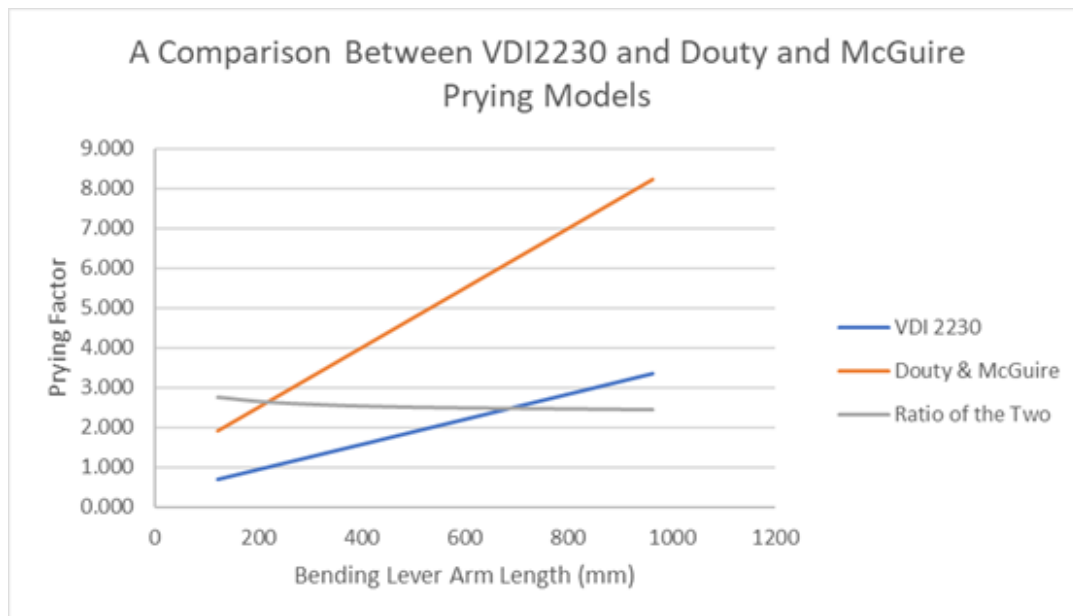


Figure 4 - A Graph Illustrating the Difference between the Structural and Mechanical Prying Factors

5 Conclusion

If one was to draw conclusions based on the results presented in this article, then the Douty and McGuire method gives a prying factor in the order of 2.5 times larger than that of VDI 2230 across a range of prying moment arms. As VDI2230 is a lot more involved and computational heavy, it wouldn't be unreasonable to assume that this standard is more accurate. Although the structural method is much quicker to implement, it is at the expense of being more conservative. You may think that in the structural world, where one structure is likely to have thousands of bolted connections then conservatism is not a good thing. By using the Douty and McGuire method the designer may have to select the next size up bolt than the one required for the job. Although, the cost implication for one bolt would be small, multiplied over thousands of connections in a structure, plus the extra time taken to torque up the larger bolts, it may start to become significant.

However, engineering problems are rarely this straightforward. In order to achieve the calculation accuracy possible with VDI 2230, the interface area of the bolted joint requires tight controls [2]. The limiting value for bolted joints with nuts is the width of the area of the bolt head in contact with the plates plus the thickness of the thinnest plate in the stack [2]. As the bolt in this article is an M20 and the flange under the bolt head is approximated to $1.5 \times \text{Bolt Diameter}$, then this would give a limiting value of: -

$$1.5 * 20 + 75 = 105$$

Our joint is 100 mm wide, so we are only just inside the limiting width and therefore the accuracy of the calculation is high. In mechanical engineering applications we have much more control over this interface and it can be incorporated into the design early on. To guarantee that joints in large structural engineering applications adhere to the same criteria then a significant amount of machining and/or welding would need to take place which would drive huge cost into the project.

A much greater study looking at a wider set of geometrical arrangements would need conducting to ascertain any general trends between the two methods, which could be used to benefit designers. Based on this, very limited, study it would be safe to say that the Douty and McGuire method can be used by mechanical engineers looking to get a conservative idea of the additional forces generated as a result of prying. If greater accuracy and economy is required then it would be prudent to invest some time in the calculation methods detailed in VDI2230, especially for volume manufacture, where real savings can be made. Also, VDI 2230 has a comprehensive section on bolt fatigue, which is beyond the scope of this article.

6 References

- [1] Shigley's Mechanical Engineering Design, Richard G Budynas, Keith J Nesbett
- [2] VDI 2230 - Systematic Calculation of high Duty Bolted Joints, Joints with One Cylindrical Bolt, Various
- [3] Determination of Prying Loads on Bolted Connections, Mert Atasoy

[4] High Strength Bolted Moment Connections, Doudy, R. T., McGuire, W