COMETa 2022
6th INTERNATIONAL SCIENTIFIC CONFERENCE
17th - 19th November 2022
Jahorina, B&H, Republic of Srpska
University of East Sarajevo
Faculty of Mechanical Engineering
Conference on Mechanical Engineering Technologies and Applications

COMPARATIVE ANALYSIS OF LOAD CARRYING CAPACITY OF SHEAR-LOADED BOLTED JOINTS

Pavle Ljubojević[1], Ivan Simonović[2], Tatjana Lazović[3]

Abstract: The function of shear-loaded bolted joints is the prevention of joint members' slip. This can be achieved in two ways, depending on the construction, i.e. relative dimensions of bolts and holes in connected parts. There are two types of shear-loaded bolted joints, clamped (friction) and fitted bolted joints. In both cases, a connection between joint members is shear-loaded, but the bolts have different stress and strain states. In clamped bolted joints the actual load is tensile stress, while fitted bolts are loaded with shear and contact pressure. In this paper, a comparative analysis of the load capacity (safety factors) of clamped and fitted bolts, under the same geometrical and operational conditions was performed. The analysis showed multiple higher load-carrying capacity of fitted bolts that go up to 60 times(!).

Key words: clamped bolted joints, fitted bolted joints

1 INTRODUCTION

A machine system may consist of a greater or lesser number of components with different complexity and composition. The load carrying capacity of parts of different joint types is a crucial aspect of the evolution of machine construction. Bolted joints are one of the most commonly used joints. Due to a number of advantages, such as low manufacturing costs and simple assembly and disassembly, they are widely used in all industries, including the automotive, aerospace, civil, and boating sectors, among others [1]. As evidence of the significance of screw threads, the key element of bolted joints, the very first ISO technical committee was devoted to them. The fundamental classification of bolted joints is determined by the direction of the external load. Bolted joints are, based on that, divided into tensile joints and shear joints. For tensile joints, the load acts in the direction of the bolt's axes, opposite to shear joints,

[1] Assist. Pavle Ljubojević, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia, pljubojevic@mas.bg.ac.rs
[2] Assist. Ivan Simonović, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia, isimonovic@mas.bg.ac.rs
[3] Prof. dr Tatjana Lazović, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia, tlazovic@mas.bg.ac.rs

where the load is perpendicular to the bolt's axis. The distinction between these two groups is substantial and not insignificant. The joint spot, as a discontinuity presents a place for creating high stress that can initiate failure [2]. They differ in how they respond to load, how they fail, how they are assembled and disassembled, as well as how they are calculated and manufactured. Some joints endure both shear and tensile loads, but they are referred to by the name of the prevailing load [3]. Even though bolted joints are simple in design, they must be extremely reliable when they are used. Their failure might result in the breakdown of the entire assembly or machine and result in significant harm. Failure can be caused by volumetric destruction of the threaded part of the screw thread, or by the nut or screw self-loosening. The calculation of bolted joints focuses on the selection of shape, material, dimensions, number of bolts, and their arrangement, which will be operationally reliable [4-6]. The load carrying capacity of shear-loaded bolted joints, as very important elements of complex machine assemblies and systems.

2 SHEAR-LOADED BOLTED JOINTS

The operating load of the shear-loaded bolted joints is perpendicular to the axis of the bolt. The primary objective of shear-loaded bolted joints is to avoid relative movement (sliding) and separation of joint members. The load of group shear loaded bolted joint can be force or torque (Figure1).

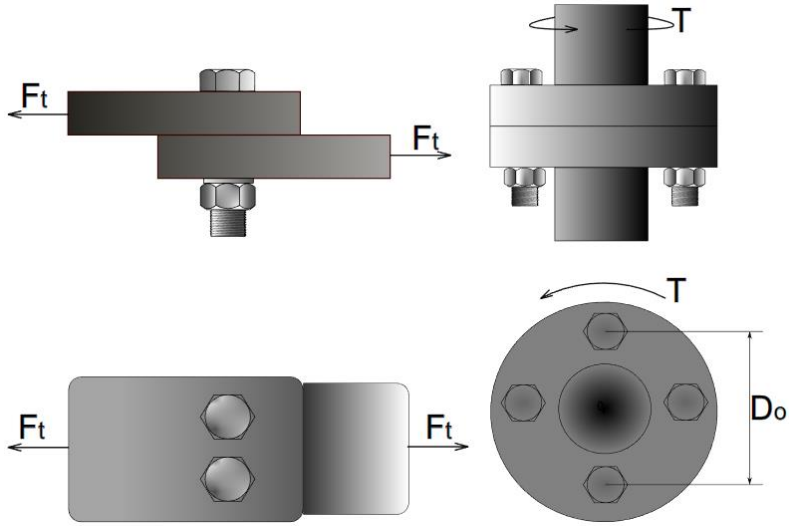

Figure 1. *Shear loaded bolted joints*

Two types of shear-loaded bolted joints exist. The first is a fitted (bearing type) bolted joint, whereas the second is a clamped (friction) bolted joint. With fitted bolted joints, the load is transferred from one area of the connection to another through the unthreaded part of the bolt body [4-6]. This kind of bolt behaves like a pin. In the case of clamped bolted joints, the relative movement of the joined components is prevented by the acting of frictional force of appropriate intensity, which is dependent on the tightening torque.

2.1 Fitted bolted joints

In a fitted bolt, the load, in the form of shear force and contact pressure, is transmitted through the unthreaded part of the bolt body (Figure 2a). To transfer the load straight over the bolt body, a transition fit must be formed. The suggested fits are H7/k6 and H7/n6 [5, 6]. A minor clearance may form between the member joint and the bolt, but the likelihood of this occurring is extremely low. If there is a clearance, the load distribution becomes inequal. This issue can be prevented by incorporating a 0.1 mm tolerance into the non-threaded part of the bolt body. The threaded part of bolt is non-load-carrying and with nut helps to prevent the separation of joint elements.

2.2 Clamped bolt joints

Unlike fitted bolted joints, where preload is not required, clamped bolted joints are provided with strictly calculated tightening torque values. This type of joint is realized with bolts whose nominal (major) thread diameter is smaller than the hole in the joint members (Figure 2b). The reduced accuracy of manufactured hole and bolt reduces the costs of making and assembling and makes this type of joint more economical. By tightening the bolt with precise tightening torque, the slipping resistance of joint members is created. Frictional force occurs between joint members due to clamping force caused by tightening torque. For clamped bolted joints to perform their function successfully, self-loosing must be prevented. In addition, the bolt must have the necessary volumetric strength.

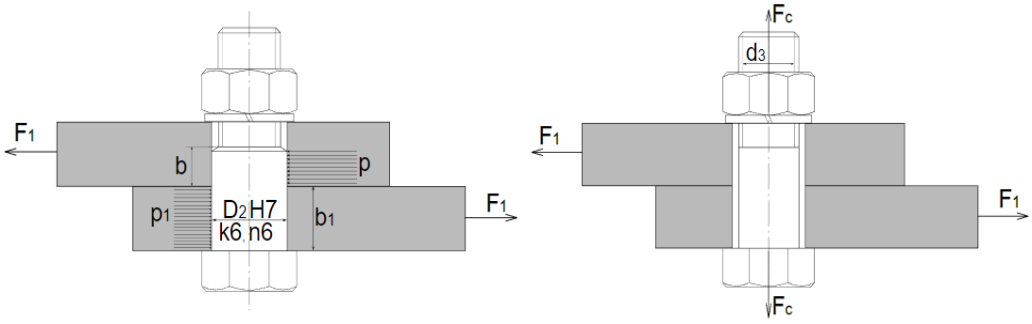

Figure 2. *a) Fitted bolted joint; b) Clamped bolted joint*

3 BOLTED JOINT LOAD CARRYING CAPACITY

Load carrying capacity of fitted bolted joints is limited by resistance to shear and contact pressure. Shear and contact pressure safety factors are given by expressions:

$$S_\tau = \frac{[\tau]}{\tau_s} = \frac{0.7R_e}{\frac{F_s}{A_s}} = \frac{0.7R_e D_2^2 \pi}{4\frac{F_t}{n}\xi_{ie}} = \frac{0.7R_e D_2^2 \pi n}{\frac{T}{D_o/2}\xi_{ie}} = \frac{0.7R_e D_2^2 \pi n D_o}{8T\xi_{ie}}, \quad (1)$$

$$S_p = \frac{[p]}{p} = \frac{1.2R_e}{\frac{F_p}{A_p}} = \frac{1.2R_e bD_2}{\frac{F_t}{n}\xi_{ie}} = \frac{1.2R_e bD_2 n}{\frac{T}{D_o/2}\xi_{ie}} = \frac{1.2R_e bD_2 nD_o}{2T\xi_{ie}}. \quad (2)$$

Since the number of bolts n, pitch diameter D_o, and torque T are constant, the ratio of equations (1) and (2) is:

$$\frac{S_p}{S_\tau} = \frac{4.8b}{0.7D_2\pi} = 2.1827\frac{b}{D_2}. \quad (3)$$

From the condition of equal volumetric and contact load carrying capacity of fitted bolts ($S_\tau = S_p$), based on equation (3), the length of contact between the bolt and joint member is $b = 0.4581D_2$. Hence, based on equation (3) it can be written as:

$$S_\tau = S_p = \frac{0.2749R_e D_2^2 nD_o}{T\xi_{ie}}. \quad (4)$$

Clamped bolted joints are loaded in the axial direction by the clamping force needed for the prevention of joint members' slip. Appropriate safety factor:

$$S_\sigma = \frac{[\sigma]}{\sigma} = \frac{R_e}{\frac{F_c}{A_{min}}} = \frac{R_e d_3^2\pi}{4\frac{F_1 S_\mu \xi_c}{\mu}} = \frac{R_e d_3^2\pi\mu}{4\frac{F_t S_\mu \xi_c}{n}\xi_{ie}} = \frac{R_e d_3^2\pi\mu n}{4\frac{TS_\mu\xi_c}{D_o/2}\xi_{ie}} = \frac{R_e d_3^2\pi\mu nD_o}{8TS_\mu\xi_c\xi_{ie}}. \quad (5)$$

The ratio of the load carrying capacity of fitted and clamped bolted joints for the same operating conditions can be represented as a ratio of safety factors given by equations (4) and (5):

$$\frac{S_f}{S_c} = \frac{S_\tau}{S_\sigma} = 0.7\frac{S_\mu\xi_c}{\mu}\left(\frac{D_2}{d_3}\right)^2 = C\left(\frac{D_2}{d_3}\right)^2. \quad (6)$$

The recommended value ranges of the slip safety factor of the clamped bolted joints, the friction coefficient between joint members, and the joint clamping factor are S_μ = 1.2 - 1.8; μ = 0.1 - 0.3; ξ_c = 1.5 - 2.0. According to these values, constant C in equation (6) has values in the range: C = 6 ... 36. Hence, equation (6) obtains the following form:

$$\frac{S_f}{S_c} = 0.7(6...36)\left(\frac{D_2}{d_3}\right)^2 = (4.2...25.2)\left(\frac{D_2}{d_3}\right)^2. \quad (7)$$

Based on this ratio, it can be concluded that the load carrying capacity ratio of fitted and clamped bolted joints depends on the geometrical parameters of threads and bolts, under the same operating conditions. The data of the analyzed bolts (M6 – M24) and obtained extreme safety factor ratios are given in Table 1. Dependencies from Table 1. are shown in Figure 3.

Table 1. *Extreme safety factor ratios of fitted and clamped bolted joints*

Thread diameter d (mm)	Fitted bolt diameter D_2 (mm)	Minor thread diameter d_3 (mm)	D_2/d_3	$(S_f/S_c)_{min}$	$(S_f/S_c)_{max}$
6	7.2	4.773	1.50849	9.557	57.343
8	9.2	6.466	1.42283	8.503	51.016
10	11.2	8.160	1.37255	7.912	47.474
12	13.2	9.853	1.33969	7.538	45.228
14	15.2	11.546	1.31647	7.279	43.674
16	17.2	13.546	1.26975	6.771	40.629
18	19.2	14.933	1.28574	6.943	41.659
20	21.3	16.933	1.25790	6.646	39.874
22	23.3	18.933	1.23066	6.361	38.166
24	25.3	20.319	1.24514	6.512	39.069

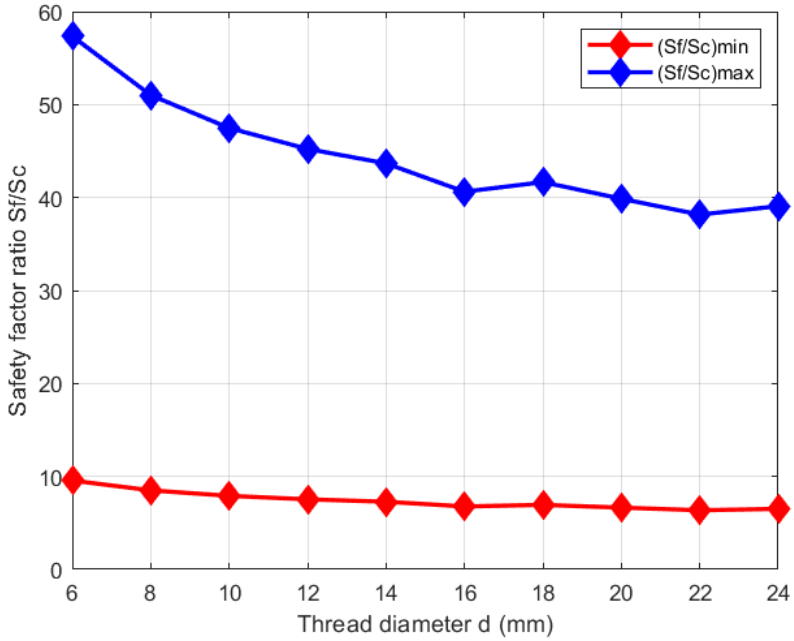

Figure 3. *Safety factor ratio vs. thread diameter*

4 CONCLUSIONS

Carried out analysis showed that the condition of equality of the surface and volumetric safety factor of the fitted bolted joints is that the length of contact between the bolt and joint member should be approximately 0.5 of the bolt diameter. The safety factor ratio of fitted and clamped group bolted joints S_f/S_c (for the same number of bolts on the same pitch diameter) varies in the interval from 6 to 60, depending on the value of the varied parameters (slip safety factor of the clamped bolted joints, the friction coefficient between joint members and the joint clamping factor) and the nominal thread diameter. Safety factor ratio S_f/S_c decreases with increasing bolt nominal thread diameter. The maximal safety factor ratio is more sensitive to changes in the nominal thread diameter.

ACKNOWLEDGEMENT

This work was supported by Ministry of Education, Science and Technological Development of the Republic of Serbia (Contract No. 451-03-68/2022-14/200135, dated 4 February 2022).

NOMENCLATURE

A_s shear area, mm^2
b length of contact between fitted bolt and joint member, mm
D_2 fitted bolt diameter, mm
d_3 minor thread diameter, mm
D_o group bolted joint pitch diameter, mm
F_1 load of single clamped bolted joint, N
F_c clamping load, N
F_s shear load, N
F_t group bolted joint load, N
n number of bolts in group bolted joint
p contact pressure between fitted bolt and joint member, N/mm^2
[p] critical contact pressure, mm
R_e yield stress, N/mm^2
T torque transferred by group bolted joint, Nmm
[τ] critical shear stress, N/mm^2
ξ_{ue} factor of load distribution inequality
max maximum
min minimum

LITERATURA

[1] Omar, R., Rani, M. A., Yunus, M. A. (2020). Representation of bolted joints in a structure using finite element modelling and model updating. *Journal of Mechanical Engineering and Sciences*, vol. 14, no. 3, p.p. 7141–7151.
[2] Frocht, M. M., Hill, H. N. (1940). Stress-concentration factors around a central circular hole in a plate loaded through pin in the hole.
[3] Bickford, J. H. (2007). *Introduction to the design and behavior of bolted joints: non-gasketed joints*, CRC press, Boca Raton, Florida.
[4] Budynas, R. G., Nisbett, J. K. (2011). *Shigley's mechanical engineering design*, McGraw-hill, New York.
[5] Mitrović, R., Ristivojević, M., Rosić, B. (2021). *Machine elements 1* (in Serbian), Faculty of Mechanical Engineering, University of Belgrade.
[6] Ognjanović, M. (2016). *Machine elements* (in Serbian), Faculty of Mechanical Engineering, University of Belgrade.