Determination of the load factor between screw and flange in screw connection realized with C-rail

M Kalinowski\textsuperscript{1,}\textsuperscript{*}, M Szczepanik\textsuperscript{2}

\textsuperscript{1} Alstom Konstal S.A., Metalowców Street No.9, 41-500 Chorzów, Poland
\textsuperscript{2} Silesian University of Technology in Gliwice, Faculty of Mechanical Engineering, Institute of Computational Mechanics and Engineering, Konarskiego Street No.18a, 44-100 Gliwice, Poland

Email: marcin.kalinowski@alstomgroup.com

Abstract. The article concerns determination of the loading factor between the screw and the flange in the screw connection realized with the C-rail. The exemplary screw joints applied in Alstom's trains will be analysed. The article will present the results of analytical calculations performed to evaluate of the loading factor in accordance with the standards VDI 2230 and NF E25-030 as well as the results of the finite elements analysis, by means of which the considered connection will be modelled. In addition, a comparison of the results obtained by means of both methods will be made.

1. Introduction

In the construction of railway vehicle boxes (trains, trams, subways), the location of attachment of the equipment should be provided. The equipment is attached under the chassis and on the roof of vehicles. The transformer, braking control unit, inverters, fire protection system, batteries, etc., can be classified to devices mounted under the chassis. On the other hand, air-conditioning units and pantographs are included to roof-mounted devices. In addition to the mentioned equipment in rail vehicles there are a lot of smaller devices mounted on the roof or underframe, which mainly belong to the group of pneumatic, electric or electronic devices (antennas, Wi-Fi transmitters, compressors, connectors, cable and pneumatic distributors, etc.).

This equipment is usually fastened with screw connections, which allow for easy assembly and disassembly of equipment, and allow for joining together two different types of materials (e.g. aluminum with steel), which would be impossible (or very difficult to implement) by means of welded connections.

In the steel car body shells of rail vehicles, the screw connection interfaces of the equipment with the structure are usually made by means of welded or spot-welded brackets, with longitudinal holes (for adjustment purposes).

This method of assembly allows the use of standard fasteners (screws, nuts, washers), without the need of custom elements (e.g. threaded blocks acting as a nut). However, it has a very significant disadvantage. At 200 interfaces with the different equipment, it is necessary to make 200 brackets and then weld / spot-weld them to the structure of the car body shell. This has a negative impact on the weight of the box, production time and reduces the fatigue properties of the joint.

In the car body shells of rail vehicles made of extruded aluminium profiles, the problem of fixing the equipment has been solved by specially made C-rails for this purpose, which are an integral part of
the profile (created in the extrusion process together with the structural part of the profile). Figure 1 presents an exemplary spot-welded bracket and aluminium extruded profile made with two C-rails.

![Figure 1](image_url)  
**Figure 1.** Example of a spot-welded bracket (a) and extruded aluminium profile with C-rails (b).

The use of C-rail saves time necessary for the design, manufacture and installation of brackets. It also improves the properties of static and fatigue strength, because in the case of aluminium, the presence of welds significantly reduces the yield strength of the joint. The disadvantage of this solution is the need to use non-standard fasteners. This refers to the need to use special threaded blocks located inside the C-rail and acting as a nut. These blocks are not standard parts and must be made of the same steel as the screw and with the same thread tolerance.

Due to the fact that custom components are used in the C-rail screw connection and the C-rail has a very long slot, the standard formulas defining the screw connection load factor may be inaccurate. The purpose of this article is to determine this difference after comparing the results of analytical calculations with the results of the FEM (Finite Element Method) analysis.

Various scientific publications focus on determination of the load factor in screwed connection. For example, in the articles [1] and [2] there is developed a method to calculate load factor for gasket flange connection, while article [3] concern on stress analysis (using finite element method) and the load factor determination of bolted joints consisting of dissimilar hollow cylinders under tensile loads.

Many papers have been carried out on the topic of determination of load factor in the screwed connection with the gasket, while the publications dealing with determination of the load factor in screwed connections with very long hole just like in the case of C-rail were not found by the authors.

2. Calculations of screw connections

Each screw connection can be divided into two main components, namely a screw and a flange. Calculations for screw connections can be made on the basis of the standards NF E25-030 [4], VDI 2230 [5] or also based on the standard EN 1993-1-8 [6]. All of these standards define unique calculation algorithms for screw connections (allowing to determine tensile strength, shear, etc.), but only standards [4] and [5] take into account the need to calculate the screw connection load factor ($\lambda$).

This coefficient is nothing else than the ratio of the stiffness of the screw to the stiffness of the flange (according to [4]) or the ratio of flange resilience to screw resilience (according to [5]). Its value is necessary to correctly calculate the distribution of the external axial force between the screw and the flange, which allows to precisely define the slip resistance and tensile strength of the screw connection.

It should be realized that in the pre-tensioned screw connection the external force acting in the axis of the screw will be transmitted by both the screw and the flange, and the proportion of its value will depend on the stiffness of both the screw and the flange. A schematic example of a loaded screw connection is shown in the Figure 2.
3. **Analytical determination of the load factor of an exemplary screw connection**

In this chapter the load factor of the screw connection obtained in accordance with standard [4] and [5] is presented. The analysed screw connection is shown in Figure 3. The connection consists of a cut piece of C-rail (made of aluminium alloy), threaded block (performing the function of a nut and made of steel), two plates (each with a thickness of 10 mm, made of steel), as well as M16 10.9 screw and a suitable flat washer. Components included in the analysed screw connection are listed in Table 1.

![Figure 3. Analysed screw connection.](image)

### Table 1. Components included in the analyzed screw connection.

| Component | Material              | Young’s modulus [MPa] | Thickness [mm] |
|-----------|-----------------------|-----------------------|----------------|
| Flat washer | steel | $E_{p1} = 210000$ | $t_1 = 3$ |
| Plate 1 | steel | $E_{p2} = 210000$ | $t_2 = 10$ |
| Plate 2 | steel | $E_{p3} = 210000$ | $t_3 = 10$ |
| C-rail | aluminium alloy | $E_{p4} = 70000$ | $t_4 = 4$ |

Results from analytical determination of the load factor according to two standards (NF E25-030 and VDI 2230) are presented in the Table 2.

![Figure 2. Schematic example of a loaded screw [4]](image)
Table 2. Components included in the analyzed screw connection.

|                              | Screw connection load factor (\(\lambda\)) |
|------------------------------|------------------------------------------|
| According to NF E25-030 [4]  | 0.165                                    |
| According to VDI 2230 [5]   | 0.174                                    |

4. FEM strength analysis

4.1. The FEM model used for strength calculations, boundary conditions and applied loads

Finite element calculations were carried out in the HyperWorks 14.0 software using the Optistruct solver, designed for linear and nonlinear structural analysis.

Two calculation models have been prepared as part of the FEM analysis. The first model concerns the calculation of the screw connection realized with the C-rail, which is the subject of this article. In the second one, the C-rail was replaced with a 4 mm thick round washer. This washer is made of aluminium alloy (material identical to the C-rail material), the outer diameter is equal to the width of the C-rail (41 mm) and the hole has a diameter of 19 mm (just like the slot width in the C-rail). The second calculation model was made in order to verify analytical calculations, because standards [4] and [5] do not take into account the calculation of the long slot, which is in the C-rail, therefore the obtained analytical results should be compared with the results obtained in the analysis of the screw connection with washer replacing the C-rail.

The FEM model used in the analysis is a solid model modelled mainly with the use of hex8 elements. The model has 1 element 1D in the form of a rigid element type RBE2, which is located on the upper surface of the screw head and which is used for applying the force. All technological elements that do not affect the results (such as chamfers, fillets, etc.) have been removed from the FEM model.

In order to determine the screw connection load factor, both analysed models were loaded in the same way with an axial force of 10 kN.

Figure 4. FEM models, applied loads and boundary conditions.

The way in which models are constrained differs from each other. In the case of calculations of the screw connection realized with the C-rail, the model was fixed on the bottom surfaces of the C-rail by taking away all translational degrees of freedom and also on the C-rail end surfaces by taking away the
possibility of translation along the X axis, as it is only a short part of the real object. In the case of calculations of a screw connection in which the C-rail was replaced by an aluminium washer, the model was fixed on the extreme surfaces of the bottom plate by constraining all translational degrees of freedom. Numbers given in brackets inform about constrained degrees of freedom (1 - constrained X axis translation, 2 - constrained Y axis translation, 3 - constrained Z axis translation).

The FEM model, applied loads and boundary conditions are presented in Figure 4.

4.2. Results of the analyses
The screw connection load factor ($\lambda$) has been determined in the FEM models by examining the change in force in the screw section during axial loading. In other words, the increment of axial force in the screw due to the applied force to the total value of this force was compared. The results of the analyses are presented in Table 3.

| Screw connection load factor ($\lambda$) | Screw connection with C-rail | Screw connection with washer replacing the C-rail |
|----------------------------------------|-----------------------------|---------------------------------------------|
| Increment of force in the screw for axial load 10 kN | $F_{bolt1} = 2180$ N | $F_{bolt2} = 1730$ N |

4.3. Interpretations
The screw connection load factor ($\lambda$) determined according to standards NF E25-030 [4] and VDI 2230 [5] is similar. For the calculations carried out according to the standard [4], the value of this coefficient was 0.165, while according to the standard [5] it was 0.174. However, the analytical calculations did not take into account the fact that the screw connection realized with the C-rail (subject of this article) has a very long slot, which reduces the stiffness of the flange. They also did not take into account the fact that the C-rail has a certain height, which when screw connection is loaded with axial force will also affect the distribution of forces between the screw and the flange.

The value of the screw connection load factor obtained in the FEM analysis for the screw connection with the washer replacing the C-rail was very similar to the value obtained as a result of analytical calculations according to the standard [4] and almost the same as the value obtained according to the standard [5]. This proves that analytical calculations can successfully replace the FEM analysis for determining the screw connection load factor ($\lambda$) for standard screwed connection (realized with round hole and with standard components such as washer, nuts, etc.).

Different situation occurs for analysis of screwed connections with custom components such as C-rail. The value of the screw connection load factor obtained in the FEM analysis for screw connection with the C-rail is about 25% greater than the value of this coefficient for screw connection with the washer replacing the C-rail. This is due to the fact that the C-rail flange has less stiffness than the flange with the washer.

In the Table 4 all results from analytical as well as finite element analysis are presented.

| Screw connection load factor ($\lambda$) | Analytical results | FEM results |
|----------------------------------------|--------------------|-------------|
| According to NF E25-030 [4]            | 0.165              | 0.173       |
| According to VDI 2230 [5]              | 0.174              |             |
| Screw connection with washer replacing the C-rail | 0.173              |             |
| Screw connection with C-rail           | 0.218              |             |
5. Conclusions
To sum up analytical methods of determination of the load factor don’t take into account very long slot and certain height of C-rail. Due to this fact results from FEM analysis with modelled C-rail is ca. 25% higher than results from FEM analysis with washer and both analytical analysis. This situation results in incorrect evaluation of the maximum axial force (in the tensioned screwed connection), which depends on value of screw connection load factor. Based on the formulas presented in the Figure 2, it can be concluded that the higher load factor is, the higher axial load is transferred via screw.

Using analytical methods is impossible to predict correct value of load factor for C-rails connection. This can lead to wrong evaluation of high tensioned screwed connection (especially in static load case with maximum vertical loading according to standard EN 12663, for which external axial loadings acting on the screws are the highest), and in the worst case to screw failure. Thus for screws in C-rails for which a tensile case is a critical one, it is recommended to recalculate value of load factor using FEM analysis or to increase value calculated with the standards [4] and [5] by 25%.

References
[1] Nagata S, Matsumoto M and Sawa T 2004 Load Factor Based Calculation for Bolt Load and Gasket Load Changes Due to Internal Pressure ASME/JSME 2004 Pressure Vessels and Piping Conference PVP2004-2626 pp 89-96
[2] Sawa T, Sato K and Mabuchi T 2018 A Simple Calculation Method of the Load Factor and a Bolt Preload Determination Satisfying Allowable Leak Late for Bolted Pipe Flange Connections With Gaskets Subjected to Internal Pressure ASME 2018 Pressure Vessels and Piping Conference PVP2018-84217
[3] Sawa S, Ishimura M, Sekiguchi Y and Sawa T 2017 FEM Stress Analysis and the Load Factor of Bolted Joints Consisting of Dissimilar Hollow Cylinders Under Tensile Loads ASME 2017 International Mechanical Engineering Congress and Exposition IMECE2017-70503
[4] NF E25-030 2014 Fixations - Assemblages vissés à filetage métrique ISO
[5] VDI 2230 2014 Systematic calculation of highly stressed bolted joints
[6] EN 1993-1-8 2006 Eurocode 3 - Design of steel structure - Part 1-8: Design of joints