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Strength Calculation of Prestressed Bolted Connections Analysis using Available Computational Software and FEM method

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Abstract. This paper deals with analytical calculations and FEM strength analysis of prestressed bolted connections as well as their experimental verification. Design engineers use in the strength calculation technical recommendation of fasteners sellers and fasteners manufacturers when designing of bolted joints. In industrial practice, it is now very often required to calculate the prestressed bolted connections according to the standard *VDI 2230*. [1] The calculation is usually performed using *KissSoft* or *MITCalc* programs on a personal computer.

Introduction

Actual tensile bolts prestress after *controlled tightening* ensures correct functioning of bolted joints during operation. There is defined the concept of controlled tightening of the presstresed bolted joints in the technical support of the company *Bossard*. [2] This tightening method of the presstresed bolted joints respects the variable value of the friction coefficient in the thread and the *stress relaxation* of the prestressed bolted connections after assembly.

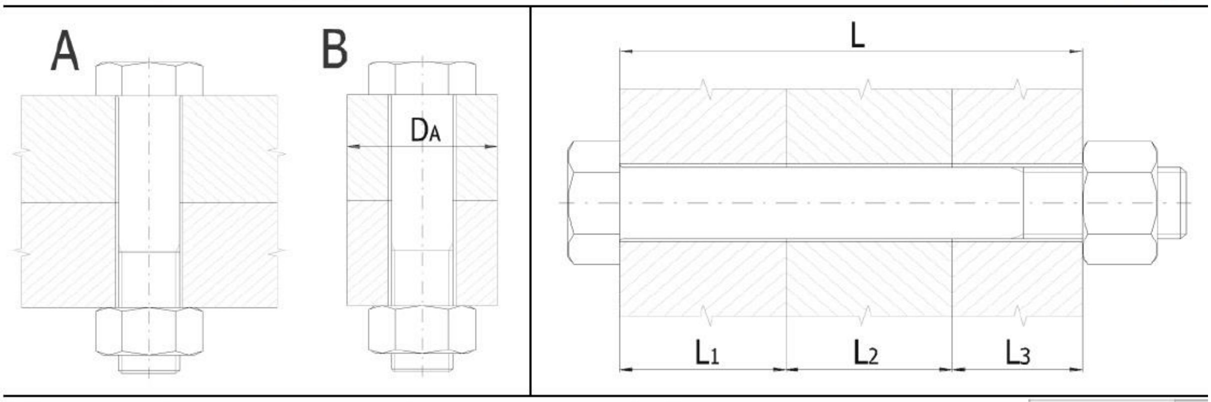
Strength Calculation of Prestressed Bolted Joints Using MITCalc Software

There are presented parts of the strength calculation of the prestressed bolted connection for bolt of size *M20*, strength class *12.9*, loaded by static axial force of *55 kN*, in Fig. 1, Fig. 2, Fig. 3 and Fig. 4. [3] The strength calculation was performed using the program *MITCalc*.

?	Input section			
1.0	☑ **Loading of the connection, basic parameters of the calculation.**			
1.6	**Loading of the connection**			
1.7	Maximum axial force	F_{amax}	55000,00	[N]
1.8	Minimum axial force	F_{amin}	55000,00	[N]
1.9	Maximum radial force	F_r	0,00	[N]
2.0	☑ **Operational and mounting parameters of the connection.**			
2.1	Desired coefficient of tightness (prestressing) of the connection	q_a	1,500	
2.2	Desired safety against side shift	q_r	1,000	
2.3	Required residual prestressing of clamped parts of the connectio	F_{2min}	82500,00	[N]
2.4	Desired safety of the bolt at the yield point	n_s	1,200	
2.5	Friction coefficient in threads	μ_t	0,130	

Fig. 1: Part of the strength calculation of the prestressed bolted connection for bolt of size *M20*, strength class *12.9*, loaded by static axial force of *55 kN* (*MITCalc* program) [3]

2.6	Friction coefficient in seating face of the head (nut) of the bolt	μ_c	0,130	
2.7	Friction coefficient between he connected surfaces	μ_q	0,200	
2.8	Consider additonal bending stresses		No	
2.9	Deviation of perpendicularity of the bolt head seating surface	δ	0,100	[°]
2.10	Assembly temperature	T_0	20,0	[° C]
2.11	Consider effects of operational temperature to connection prestressing		No	
2.12	Operational temperature of the bolt	T_b	148,9	[° C]
2.13	Operational temperature of the clamped parts	T_m	148,9	[° C]
2.14	☐ The connection is loaded only at the operational temperature			
2.15	Consider reduction of mounting prestressing using deformation of the joint		Yes	
2.16	Plastic pernament deformation (settlement) of the connection	ΔL	0,01400	[mm]
2.17	**Factor of implementation of operational force**			
2.18	○ Coefficient of implementation of the operational force	n	0,800	
2.19	◉ Distance of the point of action of the force from bolt head	L_{F1}	8,800	[mm]
2.20	Distance of the point of action of the force from the nut	L_{F2}	8,800	[mm]
3.0	☑ **Design, dimensions and material of connected parts.**			
3.1	Design of connected parts		A ... Plate	
3.2	Number of clamped parts	i	2	
3.5	Total height of the clamped parts	L	88,000	[mm]



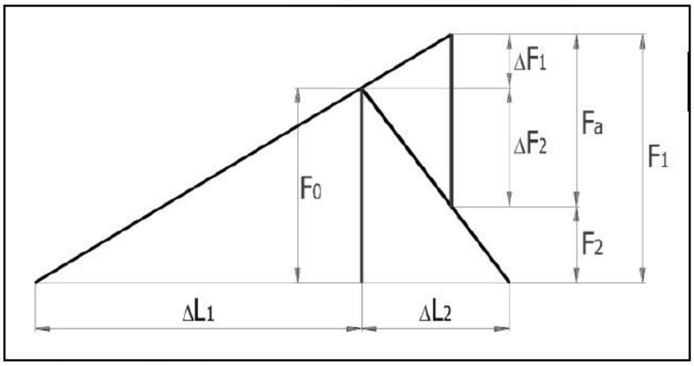
3.6	L_i	E	α	p_A	Material	EN
Part 1	55,000	169000	10,5	800	Ductile cast iron EN-GJS-500-7 [5.3200]	
Part 2	33,000	207000	11,1	490	Structual steel S235JR [1.0038]	

4.3	**Material of the bolt**			
4.4	Strength class (Material) of the bolt		Class 12.9	
4.5	Modulus of elasticity in tension	E	211000	[MPa]
4.6	Ultimate tensile strength	S_u	1220	[MPa]
4.7	Yield strength	S_y	1100	[MPa]
4.8	Heat expansion coefficient	α	11,5	[10^{-6}/°C]
4.9	Density	ρ	7850	[kg/m^3]
4.11	**Thread parameters**			
4.12	Thread type		Metric thread - Coarse series	
4.13	Automatic bolt design			
4.14	Thread size		M20	
4.15	Basic major diameter	d	20,0000	[mm]
4.16	Thread pitch	p	2,5000	[mm]
4.17	Minor diameter	d_r	16,9330	[mm]
4.18	Pitch diameter	d_m	18,3760	[mm]

Fig. 2: Part of the strength calculation of the prestressed bolted connection for bolt of size *M20*, strength class *12.9*, loaded by static axial force of *55 kN* (*MITCalc* program) [3]

Results section

5.0	☑ **Prestressing, force conditions and operational diagram of the connection.**			
5.1	**Stiffness constants of the connection**			
5.2	Stiffness of the connecting bolt	c_b	516875,36	[N/mm]
5.3	Stiffness of the clamped parts	c_m	3905885,41	[N/mm]
5.4	Resulting stiffness od the group of surcharged parts of the joint	c_1	503868,37	[N/mm]
5.5	Resulting stiffness of the group of relieved parts of the joint	c_2	4852461,57	[N/mm]
5.6	**Assembly preload of the bolt connection**			
5.7	Maximum axis component of the operational force	F_a	55000	[N]
5.8	Maximum radial component of the operational force	F_r	0	[N]
5.9	Minimum needed clamping force for transfer of the radial force	F_{cmin}	0	[N]
5.10	Part of the operational force additionally loading the bolt	ΔF_1	5173,83	[N]
5.11	Part of the operational force relieving the clamped parts	ΔF_2	49826,17	[N]
5.12	Minimum needed assembly preload of the joint	F_{0min}	138717	[N]
5.13	Assembly preload of the joint	F_0	138717,0	[N]
5.14	Tightening torque	M	452,06	[Nm]
5.15	**Force conditions of the loaded connection**			
5.16	Change of prestresssing due to heating of the connection	ΔF_{0T}	0,00	[N]
5.17	Loss of prestressing due to deformation of the connection	ΔF_{0L}	-6390,57	[N]
5.18	Operating prestressing of the joint	F_0'	132326,43	[N]
5.19	Residual prestressing of clamped parts of the connection	F_2	82500,26	[N]
5.20	Resulting internal axis force in the bolt	F_1	137500,26	[N]
5.21	Coefficient of tightness (prestressing) of the connection	q_a	1,500	
5.22	Safety against side shift	q_r	0,000	



6.0	☑ **Strength checks of statically loaded bolt connections.**			
6.1	**Strength check of connections in the working state**			
6.2	Internal axis force in the bolt	F_1	137500,26	[N]
6.3	Tensile stress in bolt core from the axis force	σ	561,70	[MPa]
6.4	Torsional stress in bolt core from tightening moment	τ	205,60	[MPa]
6.5	Additional bending stress	σ_b	0,00	[MPa]
6.6	Resulting reduced stress in the bolt core	σ_{red}	589,24	[MPa]
6.7	Yield point of the bolt material	S_y	1100	[MPa]
6.8	Safety at yield point	n	1,87	
6.9	**Strength check of connections in the assembly state**			
6.10	Assembly preload of the joint	F_0	138717,00	[N]
6.11	Tensile stress in bolt core from the assembly preload	σ	566,67	[MPa]
6.12	Resulting reduced stress in the bolt core	σ_{red}	669,27	[MPa]
6.13	Allowable stress (90% Sy)	σ_A	990	[MPa]

Fig. 3: Part of the strength calculation of the prestressed bolted connection for bolt of size *M20*, strength class *12.9*, loaded by static axial force of *55 kN* (*MITCalc* program) [3]

No.	Parameter	Symbol	Value	Value (max)	Unit
6.14	**Check of pressure in seating face of the bolt head**				
6.15	Pressure in the bolt head (nut) seating face	p	381,42		[MPa]
6.16	Permitted pressure in the marginal clamped part	p_A	490		[MPa]
6.17	**Strength check of connections for maximum prestressing**				
6.18	Maximum operating prestressing of the joint	F'_{0max}	138717,00		[N]
6.19	Maximum internal axis force in the bolt	F_{1max}	143890,83		[N]
6.20	Tensile stress in bolt core from the maximum axis force	σ_{max}	587,80		[MPa]
6.21	Resulting reduced stress in the bolt core	σ_{red}	614,18		[MPa]
6.22	Maximum pressure in the bolt head (nut) seating face	p_{max}	399,14		[MPa]
8.0	**Assembly parameters of the connection.**				
8.1	**Assembly preload of the joint**				
8.2	Minimum assembly preload	F_{0min}	138717,0		[N]
8.3	Tightening factor	α_A	1,70		
8.4	Maximum assembly preload	F_{0max}	235818,9		[N]
8.5	**Tightening torque**				
8.6	Friction coefficient in threads (min/max)		0,100	0,160	
8.7	Friction coefficient in seating face of the head (nut) of the bolt (min/max)		0,100	0,160	
8.8	Minimum possible tightening torque	M_{min}	360,31		[Nm]
8.9	Maximum possible tightening torque	M_{max}	924,65		[Nm]
8.10	**Strength check of connections in the assembly state**				
8.11	Tensile stress in bolt core from the assembly preload	σ_{max}	963,34		[MPa]
8.12	Torsional stress in bolt core from tightening moment	τ_{max}	410,56		[MPa]
8.13	Resulting reduced stress in the bolt core	σ_{red}	**1197,37**		[MPa]
8.14	Allowable stress (90% Sy)	σ_A	990		[MPa]
8.15	**Strength check of connections in the working state**				
8.16	Operating prestressing of the joint	F'_{0max}	229428,3		[N]
8.17	Internal axis force in the bolt	F_{1max}	234602,2		[N]
8.18	Tensile stress in bolt core from the axis force	σ_{max}	958,37		[MPa]
8.19	Resulting reduced stress in the bolt core	σ_{red}	1022,19		[MPa]
8.20	Yield point of the bolt material	S_y	1100		[MPa]
8.21	Safety at yield point	n	**1,08**		
8.22	**Check of pressure in seating face of the bolt head**				
8.23	Pressure in the bolt head (nut) seating face	p_{max}	**650,77**		[MPa]
8.24	Permitted pressure in the marginal clamped part	p_A	490		[MPa]
8.25	**Fatigue check of the connection**				
8.26	Medium cycle stress in the thread core	σ_m	958,37		[MPa]
8.27	Cycle stress amplitude in the thread core	σ_a	0,00		[MPa]
8.28	Max. fatigue strength of the bolt for the given course of loading	σ_A	17,38		[MPa]
8.29	Dynamic safety in tension	n_σ	---		

Fig. 4: Part of the strength calculation of the prestressed bolted connection for bolt of size *M20*, strength class *12.9*, loaded by static axial force of *55 kN* (*MITCalc* program) [3]

The following user settings of *MITCalc* program have been set: calculation of plate stiffness by the method of pressure cones according to *VDI 2230*; the torsional stress reduction coefficient was chosen to be 0,5; the calculated thread cross-section was chosen as the critical cross-section of the bolt (thread). The static external loading force *55 kN* for this strength calculation using *MITCalc* program was chosen so that the resulting internal force and tension in the bolt correspond to the results of the FEM analysis for the bolt *M20*, strength class *12.9*, see reference [4]. Subsequently, the results of the strength calculation performed in the *MITCalc* program were compared with the results of the stress analysis performed by the

FEM method. Creating FEM model of a bolted joint, the choice of main characteristics of the finite element model and more details about the performed FEM analysis are also described in reference [4].

FEM Analysis of the Prestressed Bolted Connections

It is possible to verify of the prestressed bolted connection design in two ways:
1) with the using of FEM analysis of the prestressed bolted connection (see Fig. 5),
2) by experimental evaluation or experimental testing - e.g. using a special sensors.

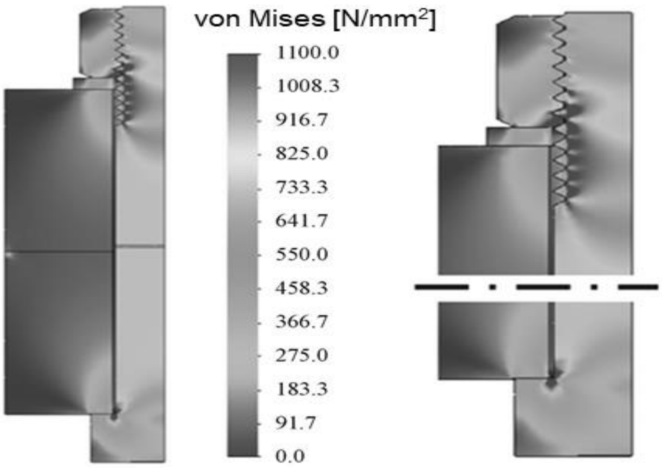


Fig. 5: Examples of FEM analysis of the prestressed bolted connection for bolt of size *M20*, strength class *12.9*, loaded by external static axial force of *55 kN* [4]

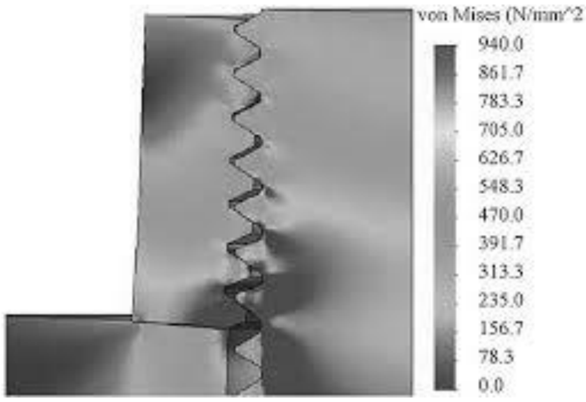


Fig. 6: Examples of FEM analysis of the prestressed bolted connection for bolt of size *M24*, strength class *10.9*, loaded only by assembly static preload of *312 kN* [4]

There is presented equivalent stresses in the bolted connection for bolt of size *M20*, strength class *12.9*, loaded by external static axial force of *55 kN*, in Fig. 5. The stress scale maximum was set to 1100 N/mm^2. And there is shown the radial deformation of the loaded nut in the bolted connection for bolt of size *M24*, strength class *10.9*, loaded only by assembly static preload of *312 kN*, in Fig. 6.

FEM analysis was performed at our Department of designing and machine elements for other cases of prestressed bolted connections recently (see Fig. 7).

The FEM full-model was created in SW *ANSA (Beta CEA systems)* and evaluation of the calculated data was created in SW *META (Beta CAE systems)*. FEM calculations were performed using school license SW *ABAQUS*. *ANSA* is an advanced multidisciplinary *CAE pre-processing tool* that provides all the necessary functionality for full-model build up, from CAD data to ready-to-run solver input file, in a single integrated environment. *META* is a powerful, intuitive *CAE post-processing tool* that works seamlessly with the leading finite element analysis solvers.

The CAD data of the bolt and nut did not contain a detailed modeled thread part. For the purposes of the FEM analysis, it was necessary to model the threaded part manually. The bolt and nut were created using *TETRA SOLID* elements of size 2 mm. In the area of the threads and under the screw head, the size of the elements is reduced to 1 mm. The connected boards are formed using *HEXA* and *PENTA SOLID* elements of size 5 mm. In the area of the screw hole, the size is locally softened to a size of 2 mm. Boundary conditions were realized by removing all degrees of freedom using the *BOUNDARY FIXED* function on the edges of the joined boards. During assembly and under loading, the screw connection elements interact with each other. In the FEM model, these interactions are modeled using the *CONTACT_PAIR* function with the corresponding values of the friction coefficients in the threads (μ_Z), under the screw head (μ_H) and under the nut (μ_M). The preload was introduced into the bolt using the *PRE-TENSION_SECTION* function. In the first step of the calculation, the required assembly preload of the prestressed bolted connection was entered. The area of external operating force was 6 mm below the surface of the joined boards (see Fig. 7). The external operating force was thus introduced symmetrically in these places under the screw head and under the nut. The magnitude of the force was budgeted to the appropriate number of nodes. For the case of static external force, the value of F_A was considered. The calculation consists of two separate steps. In the first step, the specified mounting preload was introduced into the bolt. In the second step, the preload was locked in the bolt and an external operating force was introduced into the bolt.

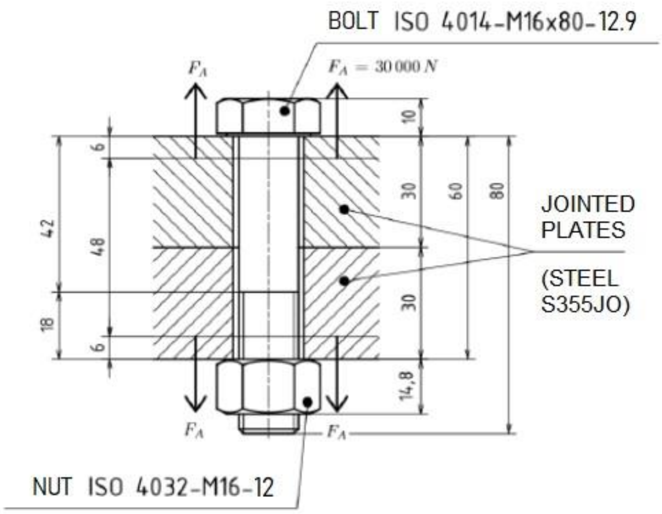


Fig. 7: Design of the prestressed bolted connection with bolt of size *M16*, strength class *12.9*, loaded by external static axial force of *40 kN* as a model for FEM stress analysis [Author]

There is presented equivalent stresses in the bolted connection for bolt of size *M16*, strength class *12.9*, loaded by external static axial force of *40 kN*, in Fig. 8 and Fig. 9. The stress scale maximum was set to 600 N/mm^2, (respectively 460 N/mm^2).

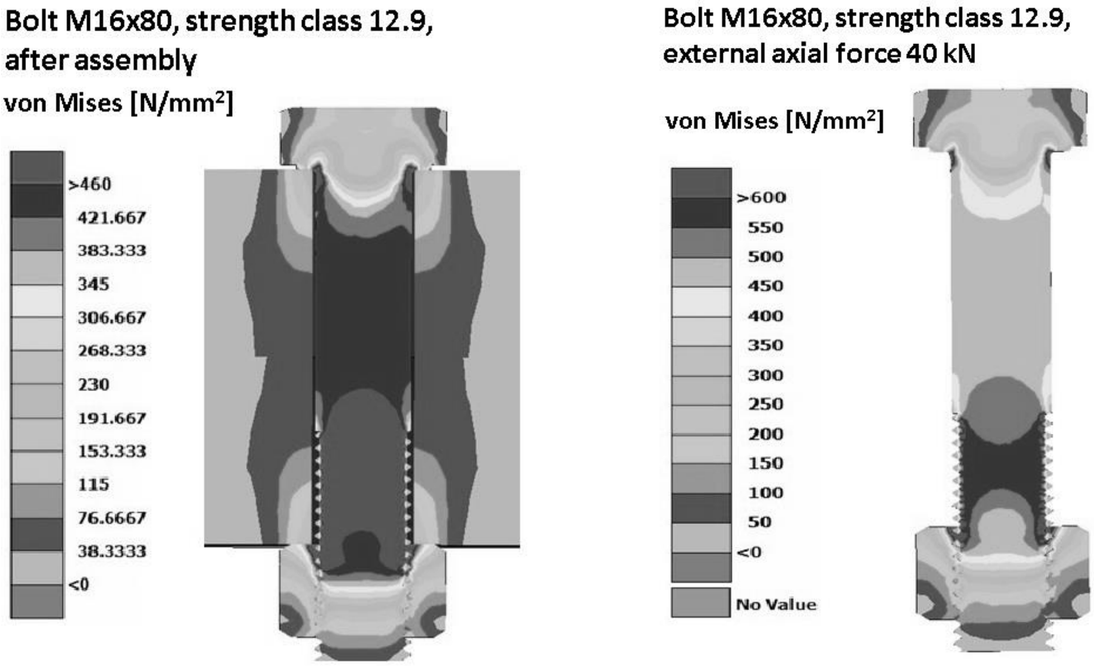


Fig. 8: Examples of FEM analysis of the prestressed bolted connection for bolt of size *M16*, strength class *12.9*, loaded by external static axial force of *40 kN*; equivalent stresses in the bolted connection for bolt of size *M16*, strength class *12.9*, loaded by external static axial force of *40 kN* [Author]

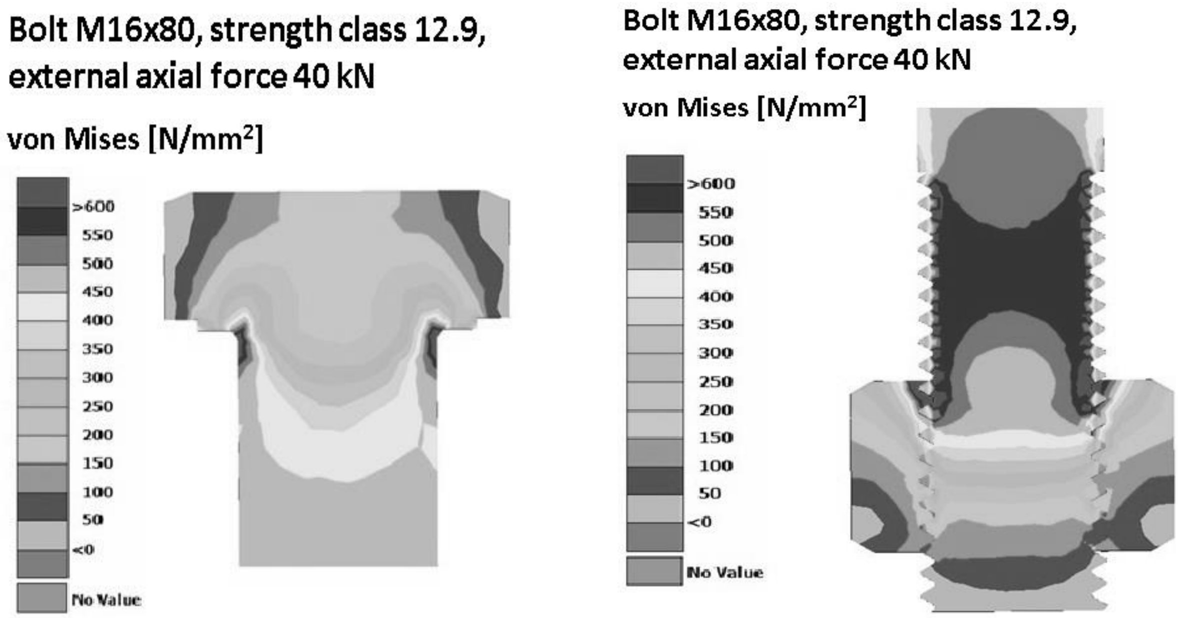


Fig. 9: Examples of FEM analysis of the prestressed bolted connection for bolt of size *M16*, strength class *12.9*, loaded by external static axial force of *40 kN* (detailed view); equivalent stresses in the bolt of size *M16*, strength class *12.9*, loaded by external static axial force of *40 kN* [Author]

Testing Equipment for Experimental Analysis of the prestressed bolted connection

Comparing the results of strength calculations of prestressed bolted joints using available software and stress analysis performed by the FEM method and experimental verification of the results is necessary in terms of refinement of design methods and strength control of prestressed bolted joints and in terms of development of modern fasteners.

In the development of threaded fastener materials, surface finishes, plating, coatings, and thread locking adhesives, it is necessary to measure and control the friction coefficients on both the threads and underhead regions of the fasteners. [1, 5]

Also, to verify the assembly process of bolted connections and to verify strength of the bolted connections is necessary to perform experiments on special test equipment. There is presented typical laboratory fastener test machine in Fig. 10. [5]

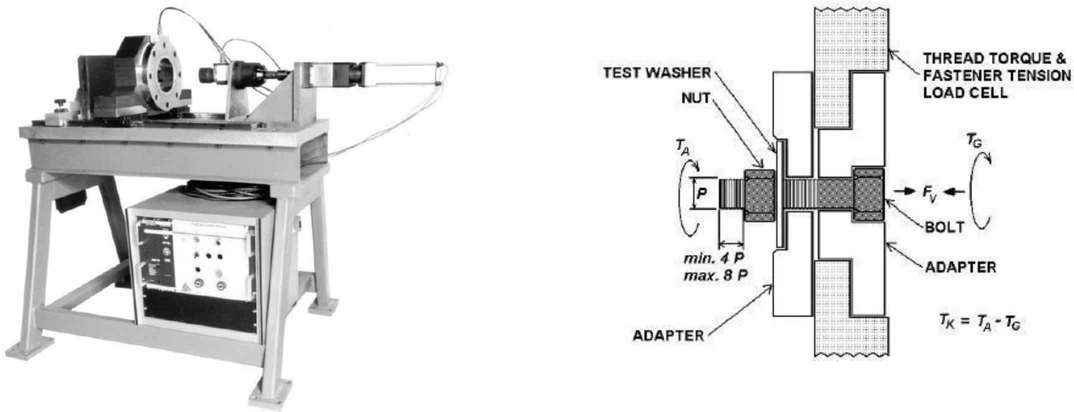


Fig. 10: Laboratory fastener test machine, typical, (on the left side). Torque-tension research head, (on the right side) [5]

Testing equipment for complex analysis of screw fasteners was designed, manufactured and is tested currently in the laboratory of our Department of designing and machine elements to verify the correctness of strength calculations and FEM analysis (see Fig. 11).

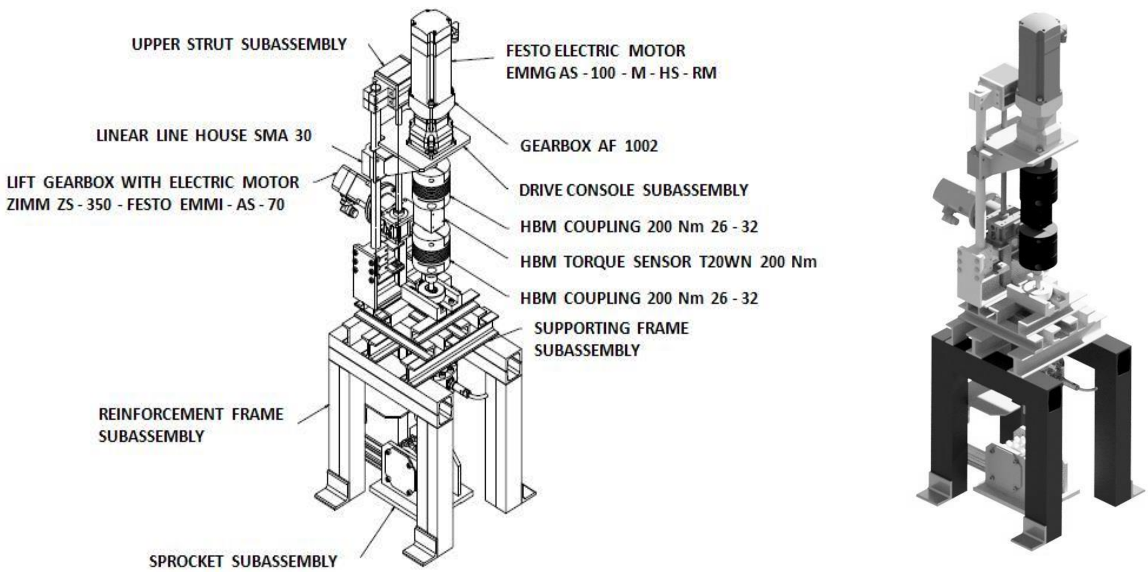


Fig. 11: Testing equipment for complex analysis of screw fasteners [Author]

On this testing equipment can be detected:
- value of the friction coefficient in the thread,
- value of the friction coefficient under bolt head (under nut),
- tension axial prestressed reduction (stress relaxation) after assembly in time,
- to evaluate the characteristics of individual fastener tightening processes, (Torque-angle curves),
- to verify the strength of the bolt connection.

Technical parameters of this testing equipment:
- maximum testing torque moment 185 Nm,
- maximum testing axial force 100 kN,
- maximum testing rotation speed 97 min^{-1},
- maximum testing stroke 300 mm.

Conclusions

Strength calculations of selected prestressed bolted connections were realized using available calculation software (*MITCalc* program) and FEM analysis of selected prestressed bolted connections were realized too. Results of strength calculations of prestressed bolted connections using *MITCalc* program and results of stress FEM analysis for prestressed bolted connection for bolt of size *M20,* strength class *12.9,* loaded by external static axial force of *55 kN* were compared.

The following results were obtained by calculating the prestressed bolted connection in the assembly state using the *MITCalc* program: tensile stress in bolt core from the assembly preload $\sigma_{max} = 963{,}34\ N/mm^2$, torsional stress in bolt core from tightening moment $\tau_{max} = 410{,}56\ N/mm^2$, reduced stress in the bolt core $\sigma_{red} = 1197{,}37\ N/mm^2$. And the following results were obtained by calculating the prestressed bolted connection in the working state using the *MITCalc* program: tensile stress in bolt core from the axis force $\sigma_{max} = 958{,}37\ N/mm^2$, torsional stress in bolt core from torque $0{,}5\cdot\tau_{max} = 205{,}28\ N/mm^2$, reduced stress in the bolt core $\sigma_{red} = 1022{,}19\ N/mm^2$ (see Fig. 4). If we compare the calculated reduced stresses with the results of the stress analysis performed by the FEM method, then the values of the reduced stress at the most exposed place of the bolt (place of first supporting thread) do not differ significantly. The difference between the reduced stresses determined by the FEM stress analysis and the reduced stresses determined using the *MITCalc* program was estimated at a maximum of 5 percent (see Fig. 4 and Fig. 5). Experimental verification of strength calculations and FEM analysis results of prestressed bolted connections will be performed in the laboratory of our Department using the developed testing equipment for complex analysis of screw fasteners in the near future (see Fig. 11).

Acknowledgements

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