DESIGN GUIDELINES FOR NON-STANDARD PLUGS

ANŽE ČELIK,[1] BORIS JERMAN,[2] FRANC MAJDIČ[2]
[1] Poclain Hydraulics d.o.o., Žiri, Slovenia
anze.celik@poclain.com
[2] University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia
boris.jerman@fs.uni-lj.si, franc.majdic@fs.uni-lj.si

The paper shows and explains activities performed to evaluate mechanical response of non-standard plug because of different loading type. In-depth understanding of plug behaviour helps to setup design guidelines for such components. In the first step, different non-standard plugs have been selected to consider size effect. Then, different materials have been selected in order to evaluate effect of plug material. For the purposes of experimental evaluation, plugs have been modified to allow installation of strain gauges. Thanks to detailed simulation model, mechanical response has been closely observed. Stress field helps to identify areas where design modifications are needed as well as to identify "hot-spots" on plug that affects structural integrity. Experimental activities have been performed with the aim to evaluate induced stresses and preload forces due to tightening torque, contact forces and piloting pressure due to spool shifting, etc. Tests have unrevealed several details regarding mechanical response on plug that have not been known previously.

Keywords:
non-standard plug, experimental investigation, numerical analysis, preload force, tightening torque, design guidelines

University of Maribor Press

DOI https://doi.org/10.18690/um.fs.5.2023.13
ISBN 978-961-286-781-2

1 Intruduction

1 Introduction – threaded plugs

From hydraulic point of view, plugs are mainly used to close manufacturing holes (e.g. blanking plugs) and other fluid channels and therefore prevent fluid external leakage. In addition, plugs are also used to limit spool stroke as well as preventing inner parts to leave working domain. See figure 1 for details.

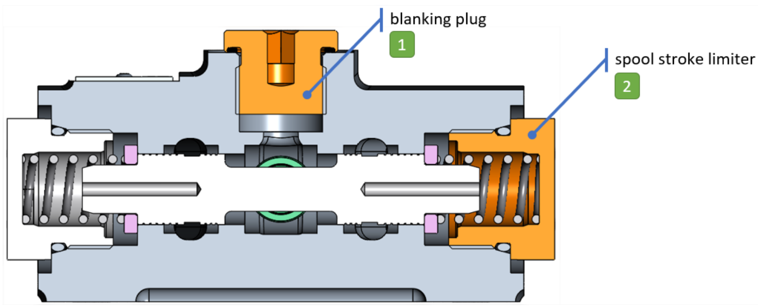

Figure 1: Plugs in different functions
Source: own

Plugs can be purchased from supplier catalogue (i.e. standard plugs, pos. 1 on figure 1) or designed manually (i.e. non-standard plugs, pos. 2 on figure 1). For the later, theory of screw joint is mainly used during the design stage. There are several different norms (e.g. ASTM, ISO, SAE …) and guidelines (e.g. VDI 2230) that support and guide the designer ([1], [2], [3]).

1.1 On threaded plugs used in Poclain

Standard plugs are widely used across many different products (e.g. hydraulic motors, pumps, valves, manifolds …). Different suppliers are used to fulfil production needs. Plug selection is usually done thanks to supplier catalogue data (example on figure 2).

Here, main design parameters are: plug size, working/rated pressure and surface protection. Designer has no need to define plug material or to validate plug integrity (if loads are within customer-defined range). It is supplier responsibility.

T1	D1	L1	L2	S1	Weight g/1 piece	Order code*	PN (bar)[1]	
							CF	A3C
M8×1	12	13.0	9.5	4	6	VSTI8X1OR	630	630
M10×1	13	13.5	9.5	5	8	VSTI10X1OR	630	630
M12×1.5	17	16.0	11.0	6	14	VSTI12X1.5OR	630	630
M14×1.5	19	16.0	11.0	6	20	VSTI14X1.5OR	630	630
M16×1.5	21	17.5	12.5	8	26	VSTI16X1.5OR	630	630
M18×1.5	23	19.0	14.0	8	37	VSTI18X1.5OR	630	630
M22×1.5	27	20.0	15.0	10	58	VSTI22X1.5OR	630	630
M26×1.5	31	21.0	16.0	12	77	VSTI26X1.5OR	400	400
M27×2	32	23.5	18.5	12	95	VSTI27X2OR	400	400
M33×2	38	25.0	18.5	14	148	VSTI33X2OR	400	400
M42×2	48	25.5	19.0	22	233	VSTI42X2OR	400	400
M48×2	55	28.0	21.5	24	336	VSTI48X2OR	400	400

Figure 2: Plug selection from supplier catalogue
Source: [4]

On the other hand, non-standard plugs (figure 3) have to be designed manually (internally) respecting aforementioned norms and guidelines. It is designer responsibility to make a device that satisfy design requirements with respect to integrity, functionality, legislation and regulation. Therefore, there is much more design freedom in the designer's hand but also much more responsibility in comparison using standard plugs.

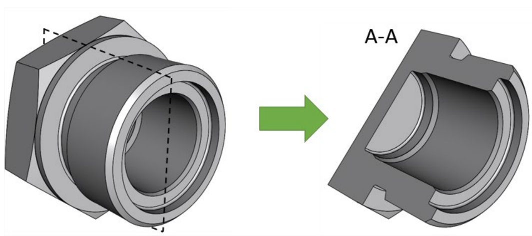

Figure 3: Typical non-standard plug
Source: own

Non-standard plugs are made from different, standardized materials, different sizes (e.g. M8 up to M33), different thread types (e.g. metric, UNF), different sealing solutions (e.g. O-ring seal, ED-seal) and with different surface protections (zinc-coating, painting). For study purposes, the following plugs sizes have been used: M19x1, M27x1,5 and M33x2.

Material is usually selected based on loading scenario: for heavy-duty applications, 42CrMo4 is mainly used, for medium duty applications, 11SMn30 or ETG100 are usually selected. Therefore, those materials have been used for study purposes as well.

1.2 On design method

Currently, non-standard plugs are designed according to theory of screw joint (i.e. VDI 2230) with some modifications and simplifications for plug. Due to plug specific geometry, the calculation of clamping force F_{PM} is simplified to the following equation:

$$F_{PM} = \frac{T_{PR}}{\left\{\frac{d_2}{2} \cdot \tan(\alpha + \rho`) + \mu_P \cdot \frac{d_m}{2}\right\}} \tag{1}$$

where $T_{PR}, d_2, \alpha, \rho, \mu_P, d_m$ are applied tightening torque, thread diameter, pitch angle, friction angle, friction coefficient under plug head and mean plug head diameter, respectively. See figure 4 for details.

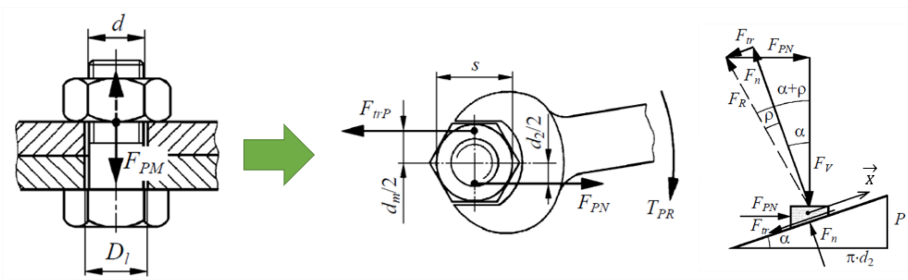

Figure 4: Parameters for calculation of screw preload force

Source: [5]

Beside geometrical parameters that depend on actual plug design, there are also contact parameters (friction coefficients under plug head and between threads). They are unknown, in general, but affect clamping force calculation at most. However, for some predefined scenarios, data are given in corresponding tables.

Materials	coefficient of friction [dimensionless]			
	dry		lubricated	
	static	sliding	static	sliding
Steel (mild) / Steel (mild)	0.74	0.57	-	0.09-0.19
Steel (hard) / Steel (hard)	0.78	0.42	0.05 -0.11	0.029-.12
Steel / Zinc (plated on steel)	0.5	0.45	-	-

Figure 5: Predefined coefficients of friction

Source: [6]

1.3 On denomination convention

For the purposes of this investigation, it makes sense to define common denomination convention for any kind of plug to prevent misunderstanding and confusion. Plug, as a functional device, could be split into different geometrical domains, namely: plug head, body, neck and plug end (figure 6).

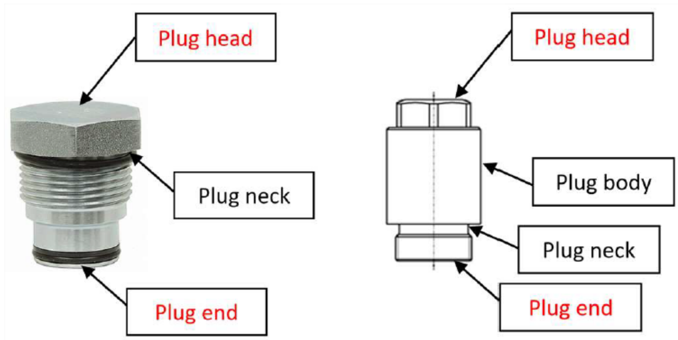

Figure 6: Denomination convention of plug domains
Source: own

Depends on non-standard plug design, plug body is not presented or clearly recognizable in some cases. For the purposes of this investigation, plug is always meant to be a threaded plug.

1.4 On applied loads

The following loads are applied on threaded assembly:

- clamping (preload) force on plug due the tightening torque,
- torsion moment on plug due the tightening torque,
- time-varying load on plug due to the spool-stopping function during the valve piloting action,
- loading due to hydrostatic (piloting) pressure.

Loads have been considered using experiments, numerical simulations and analytical calculations.

2 The scope of investigation

The aim of this investigation is to develop a design method for rapid sizing (fast dimensioning) of non-standard plugs. The method should take into account static and durability (i.e. fatigue) calculation, supported by the available norms. Finally, method should be provided to design team as a tool that allows reliable and straightforward design approach.

For that purposes, in-depth analysis of applied and induced loads as well as corresponding stresses and strains should be examined by means of experimental and/or numerical approach.

3 Experimental approach

There are several physical phenomena on preloaded plugs that have not been studied in detail neither accessible via published papers. Based on Poclain experiences, existing screw joint theory overestimate relationship between applied tightening torque and induced clamping force. Consequently, plug design is usually over-dimensioned in order to satisfy theoretical and/or numerical predictions (e.g. local stresses).

Therefore, significant effort has been made to evaluate mechanical response appropriately and accurately in plug under external loads. Several different experiments have been conducted.

3.1 Measurement of clamping (preload) force

One of those unknown parameters on preloaded plugs is a clamping force. It is induced as a consequence of applied tightening torque. Thus, it is essentially to measure applied tightening torque appropriately and accurately in order to be able to correctly measure clamping force as well.

3.1.1 Customized torque wrench

For such purposes, customized torque wrench for measurements of applied tightening torque with strain gauges attached has been developed internally. See figure 7 and figure 8 for details.

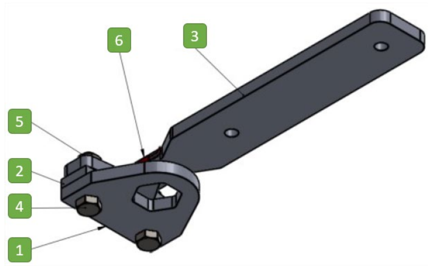

Figure 7: Internally developed torque wrench
Source: own

Positions on figure 7 refer to: (1) replaceable tool, (2), spacer, (3) hand tool, (4), screws, (5) nuts, (6) strain gauges.

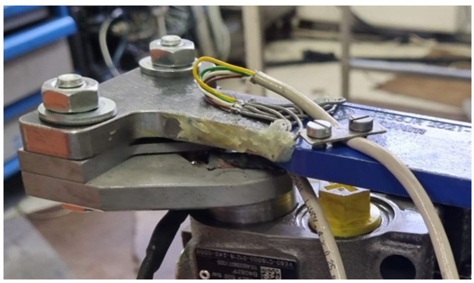

Figure 8: Strain gauges on torque wrench
Source: own

The strain gauges have been connected into a full bridge connection type in which two strain gauges have been loaded in tension and two in compression.
All the sensors have been connected with a data acquisition system and a measuring station (both from National Instruments Corporation).

3.1.1 Non-standard plug modifications

Due to the insufficient space available to attach strain gauges and in order to obtain appropriate stresses for strain gauge measurement, non-standard plugs have been redesigned and reworked. The plug neck (part of a shank) has been extended in axial direction to gain space for the strain gauges (figure 9). These extended necks were covered with bushings, which enabled to capture the axial forces including the preload force.

To protect the sensors from mechanical damage, the strain gauges were covered with a purposely designed silicone rubber.

Figure 9: Modified plug M33x2 equipped with strain gauges
Source: own

The appropriate dimensions of modified plugs have been obtained upon multiple finite element (FE) analyses, where stress-deformation states of the valve plugs at maximal expected loads have been simulated. While redesigning the plugs, caution has been paid that the construction changes do not significantly influence mechanical characteristics of the modified plugs with regard to the original plugs.

3.1.1 Calibration of plug force sensor

For calibration of the plug force sensors, a special system has been designed which enables application of tensile axial force on the plugs (figure 10). This system consisted of a lever arm and a bushing for fixation of the valve plugs.

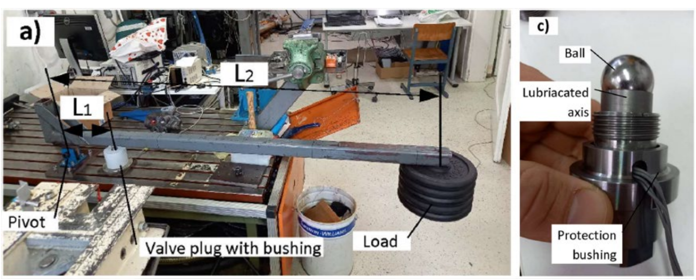

Figure 10: System to calibrate force sensors
Source: own

Figure 10a depicts system for calibration of force sensors on the plugs. The redesigned M33x2 plug with inserted loading axis and a steel ball for appropriate load application is depicted on figure 10c.

As an example, the characteristics of sensors of the M33x2 plug are presented on figure 11 including their approximation functions and R-squared values, which reflect a highly linear characteristic.

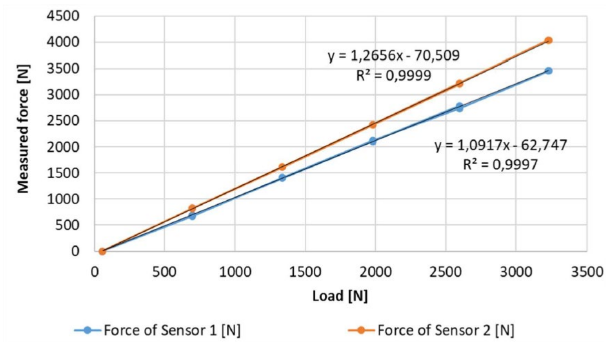

Figure 11: Characteristic of sensors 1a and 2 of the M33x2 plug
Source: own

3.1.1 Clamping force vs. tightening torque

Figure 12 depicts preload force versus tightening torque on plug M27x1,5 for minimal three consecutive fastenings separately (in lubricated and unlubricated conditions). In this figure, there is also the linear approximations (black solid lines) with its functions and R squared value of the average fastening curves.

There is one important feature that could be observed on figure 12: a minor difference of clamping force for lubricated and unlubricated conditions. This is a main difference compare to results of equation (1).

It also makes sense to note that for other two plugs (M19x1 and M33x2), higher scatter observed. However, it should be considered that the European standard EN 13001 assumes the scatter of preload force of ±23 % when it is applied using known tightening torque or rotation angle.

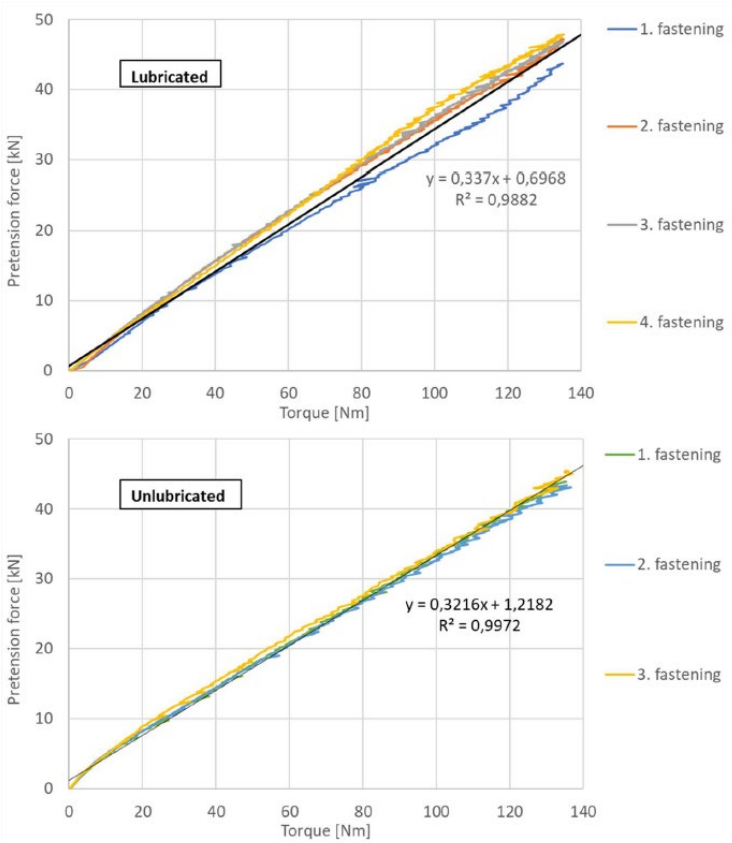

Figure 12: Preload (clamping) forces on the M27x1,5 plug
Source: own

3.2 Measurement of contact (dynamic) force

The next step during the investigation refers to the measurement of dynamic contact forces that are seen by the plug during spool shifting. Two scenarios have been evaluated: dynamic force on the plug head and plug end (refer to figure 6).

3.2.1 On Hydraulic test rig

Forces, acting on the plug have been measured at four different pilot pressures (20, 30, 40, 60 and 80 bar) and for two cases: with and without the counter pressure of 1 bar in the opposite pilot chamber (figure 13). Sampling frequency for all measured quantities is 10 kHz.

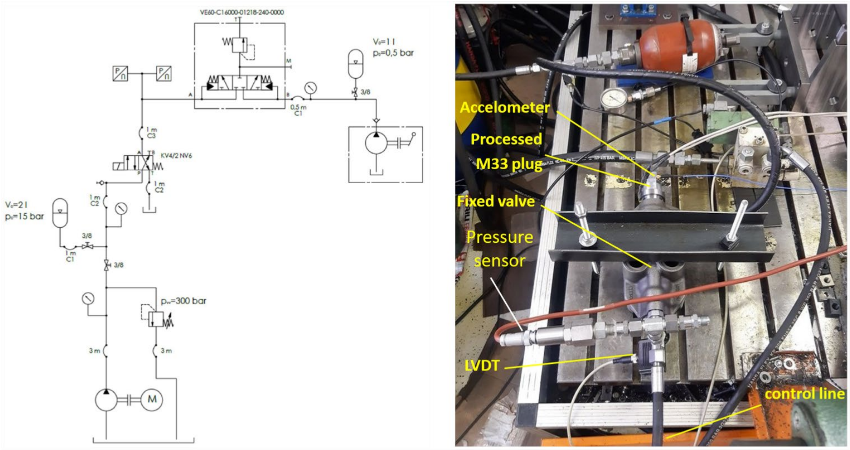

Figure 13: Measurement setup for the spool stroke measurements

Source: own

3.2.2 Dynamic forces at the plug head

Thanks to the plug equipped with strain gauges, the contact forces on the plug have been measured precisely. Figure 14 depicts five consecutive activations and deactivations of the external control valve (piloted with the frequency of 1 Hz). During each activation the preload force in the plug increases from its inactivated static value to its dynamic peak and then decreases to its activated static value and finally goes back to its inactivated static value. During each valve activation the plug head force changes in the similar way.

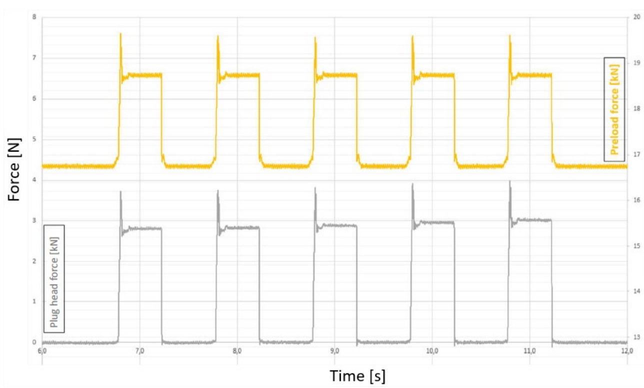

Figure 14: Dynamic forces on plug head for M33x2

Source: own

Several different transient phenomena could be observed from such a graph. One of those is load factor φ. According to VDI2230, the working force in the preloaded bolt (F_{SA}) is reduced by mentioned factor φ in relation to the externally applied force F_A, as introduced by the following equation:

$$F_{SA} = \varphi \cdot F_A \tag{2}$$

where F_{SA} refers to difference in the preloaded bolt overall tension force before and after the additional force F_A is applied to the screw joint.

For the case considered, the load factor φ is than calculated as:

$$\varphi = \frac{F_{SA}}{F_A} = 0.613 \tag{3}$$

The values given by equation (3) is much different compared to typical values for screw joint (which is usually between 0.1 and 0.4).

3.2.4 Dynamic forces at the plug end

Similarly, the dynamic forces on the plug end have also been examined in details. Results are not presented hereafter. However, similar trends have been observed and data post-processed in similar way (see figure 15). It is evident that results for all consecutive activations of the valve are almost the same.

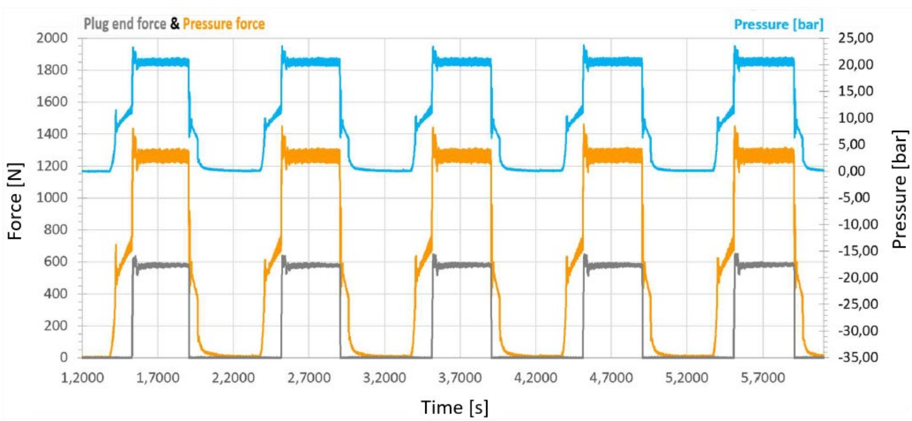

Figure 15: Dynamic forces on plug end for M33x2

Source: own

4 Numerical approach (FEA)

The main purpose of finite element analyses (FEA) on the plugs is to provide the detailed understanding of mechanical response (i.e. stress-strain state) on the plugs. Another important aspect of performed FEA is to compare mechanical response on the original and modified plug design. Then, forces given by measurements executed on the modified configurations can be interpreted for the original configurations. FEA has been performed using the Ansys Mechanical APDL software package.

4.1 Pre-processing stage

For each plug size, two versions of the plug design have been created and analysed (original and modified design). The following assumptions and simplifications have been made:

- axisymmetric model with axial symmetry along the plug longitudinal axis
- 2-dimensional PLANE42 elements with axial symmetry have been used
- plug threads have been modelled with a simplified equivalent circular model (without 3D helix)
- contact between threads on plug and housing has been made using couplings (of adjacent nodal pairs) in the normal direction; contact elements were therefore not used
- other contacts have been made in the same way

Two different materials have been used (namely for the plug and housing) with corresponding elasto-plastic properties. See figure 16 for details.

Material properties							
Element	Denomination (Standard)	W. Nr.	Youngs modulus [GPa]	Poisson ratio [–]	Yield strength [MPa]	Tangential modulus [GPa]	Elongation at break [%]
housing	EN GJS–600–3 (EN 1563)	5.3201	174	0,275	380	1,74	1,0
plug	11SMn30 (+C)* (EN 10087)[1]	1.0715	210	0,300	440	2,10	6,0

Figure 16: Material properties

Source: own

Local mesh refinement has been applied on areas of sharp corners, threads, necking etc. See figure 17 for clarity.

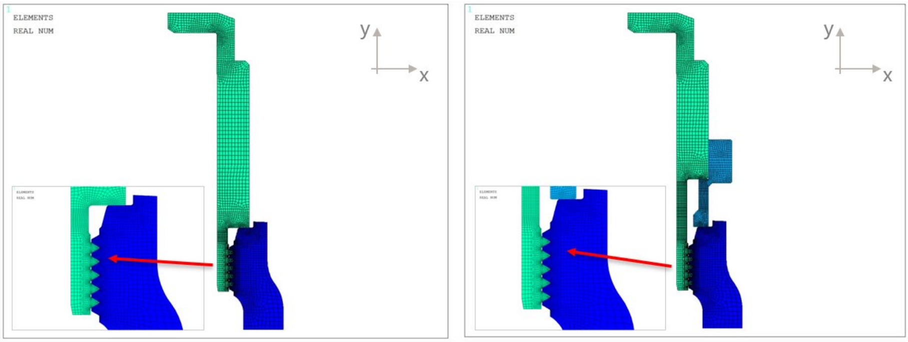

Figure 17: Axisymmetric model of plug M33x2 (left: original plug, right: modified plug)
Source: own

Five different load cases (LC) have been used, namely:

- LC1: inactive valve (spool initial position; preload force and initial spring compression force)
- LC2: active valve (impact on plug head; preload force, maximal spring force and contact force in steady-state piloted spool position)
- LC3: active valve (impact on plug head; preload force, maximal spring force and peak contact force in transient spool position)
- LC5: active valve (impact on plug end; preload force, maximal spring force and contact force in steady-state piloted spool position)
- LC6: active valve (impact on plug end; preload force, maximal spring force and peak contact force in transient spool position)

Impact force of the spool on the plug has been determined for the pilot pressure of 20 bar, which is the typical pilot pressure used in hydraulic closed-loop circuit.
Boundary conditions (in terms of restrain the node displacements) have been prescribed on housing free edge. The relative movement of the contact surfaces in the tangential direction has been considered as free, without taking friction into account.

4.2 Post-processing stage

It is out of the scope of this paper to present and explain the results of each load case separately. Instead, only few typical examples of FEA results are given hereafter. Figure 18 depicts stress-displacement response for plug M33x2 under the LC1 that refers to the simulation of plug tightening. The preload force due to the tightening of plug is modelled by means of temperature contraction on the plug neck in the longitudinal direction (Y axis) only.

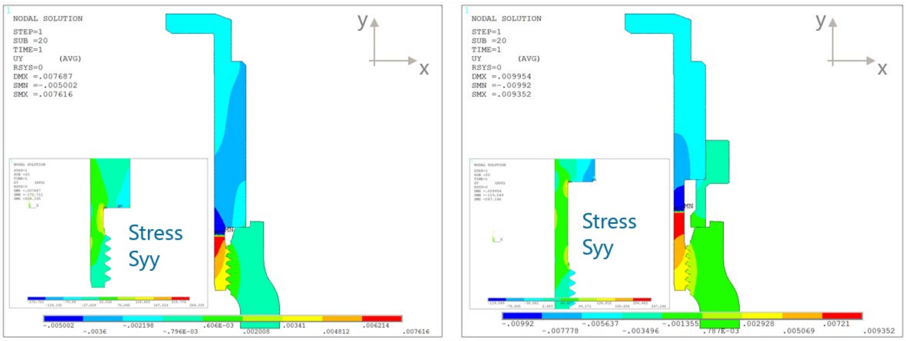

Figure 18: Simulation of tightening on plug M33x2 (temperature contraction)
Source: own

There are several benefits to use FEA in addition to the experimental approach. Mechanical FEA allows to make in-depth review of stresses (among other variables) in the entire component. Further, several different loading scenarios could be simulated relatively quickly and easily. On the other hand, experimental approach gives realistic values of forces, stresses etc. However, it requires more resources (e.g. time, human, cost) and usually enables limited amount of scenarios to test.

5 Design method and tool development

Method for fast dimensioning of the hydraulic plugs has been developed and described on the example of plug M33x2. As first, the fatigue calculation is introduced and after that also the static calculation is included.

5.1 Fatigue design

Fatigue calculations has been performed in accordance with the standard DIN 743 ("Calculation of load capacity of shafts and axles"), because in this standard the adequate details are given, the fatigue data for plug material in question are available and the adequate loadings are considered. The only disadvantage of this standard is that calculations are made for fatigue limit ($2x10^6$ or more loading cycles) whereas the plugs are usually loaded with $5x10^5$ of cycles. By doing so, the calculation stays conservative. The cross-section of the plug neck, containing the transition between the plug neck and plug body have been selected as fatigue critical cross-section (figure 19).

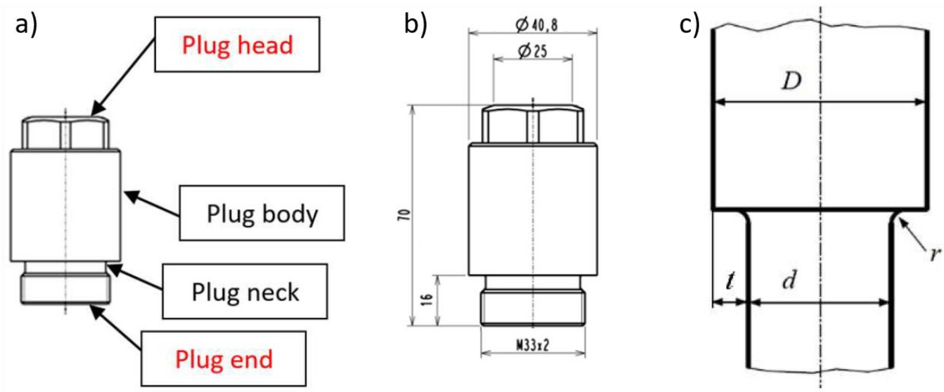

Figure 19: (a) plug parts, (b) plug drawing, (c) sketch of the standard detail
Source: own

5.2 Static design

Static safety factor regarding to yield strength has been calculated. The required minimal yield strength safety factor is defined in appropriate norm ($S_{min} = 1.2$). In static calculation, the torsion stress cannot be neglected, because the torsion stress due to the plug bolting and preloading can stay in the pug neck during whole lifetime and of course also because the plug must survive the loading case of bolting. Finally, the Excel-based tool has been developed for automatization of developed method for fast dimensioning of the hydraulic plugs (figure 20).

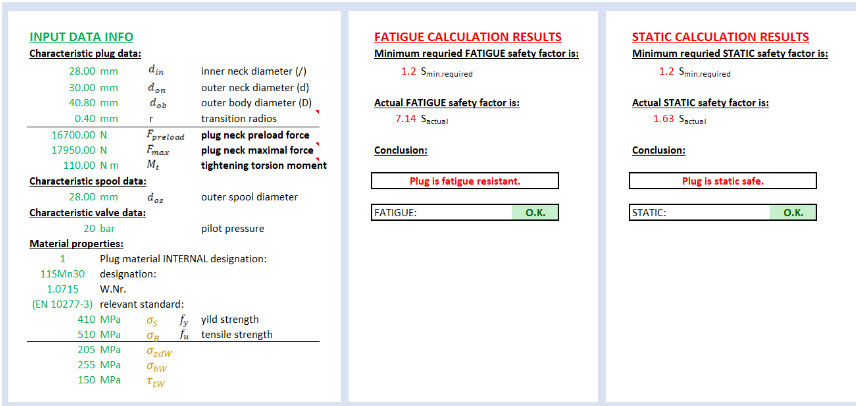

Figure 20: Plug calculation in Excel-based tool

Source: own

6 Conclusion

The aim of the investigation is to develop a design method for fast dimensioning of hydraulic plugs. The extensive measurements and numerical analyses have been realized on plugs M19x1, M27x1.5 and M33x2. The outputs of these activities enable to develop required design tool. Finally, Excel-based calculation tool was made for simpler, faster and more accurate usage of the developed method.

Extensive experimental approach has been performed which required highly skilled human resources. Some innovative solutions have been developed and implemented (e.g. torque wrench, plug modifications …) that allow precise and repeatable measurements of different variables.

Installation of strain gauges on the plugs allow to measure forces, stresses and strains on the plug neck, plug head and plug end. This has brought new added values to the existing know-how of Poclain development team. In addition, appropriate acquisition system allows to precisely capture transient phenomena during the spool shifting stage.

Main FEM analyses have been completed for modified and non-modified plugs to enable their comparison. As the most important it has been found out that the modifications of the plugs do not affect the measurement results significantly – typical influence is less than 2 %. For static dimensioning of the non-modified plugs, the loadings measured on the modified plugs can be used without causing relevant deviations.

Method for rapid sizing of hydraulic valve plugs has been developed, based on the analytical approach, as a preferable technique. In the analytical procedure the usage of standard diagrams is partially implemented. Method is based on DIN 743 procedure for shafts and axes from where the static and fatigue strength criteria have been adopted. In addition, method includes scenarios of spool acting on the plug-head and on the plug-end. Finally, Excel-based calculation tool has been made for simpler, faster and more accurate usage of the developed method for fast dimensioning of the plugs.

References

[1] https://www.boltscience.com/, last visited on 26.7.2023
[2] https://www.bossard.com/global-en/assembly-technology-expert/expert-design/calculation-of-bolted-joint/, last visited on 26.7.2023
[3] http://www.vdi2230.de/, last visited on 26.7.2023
[4] https://www.parker.com/parkerimages/euro_tfd/cat/english/C150.PDF, last visited on 26.7.2023
[5] https://www.scribd.com/doc/257813953/6-Vijacne-zveze#, last visited on 26.7.2023
[6] Simcenter Amesim Help, rev. 2021.2