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Technical aspects of nut design

Aspects techniques de conception des écrous

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Contents

Foreword

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ISO/TR 16224 was prepared by Technical Committee ISO/TC 2, *Fasteners*, Subcommittee SC 12, *Fasteners with metric internal thread*.

Technical aspects of nut design

1 Scope

This Technical Report gives information concerning the design criteria for nuts specified in ISO 898-2 so that, under static tensile overload, the stripping fracture mode is prevented.

The design criteria are also applicable to non-standardized nuts or internally threaded elements with ISO metric screw threads (in accordance with ISO 68-1) mating with bolts. However, dimensional factors such as the width across flats or other features related to rigidity of nuts, and thread tolerances can affect the loadability of the individual bolt and nut assemblies. Therefore, it is intended that verification tests be carried out.

NOTE The terms “bolt” and “nut” are used as the general terms for externally and internally threaded fasteners, respectively.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 68-1, *ISO general purpose screw threads — Basic profile — Part 1: Metric screw threads*

ISO 724, *ISO general-purpose metric screw threads — Basic dimensions*

ISO 898-1, *Mechanical properties of fasteners made of carbon steel and alloy steel — Part 1: Bolts, screws and studs with specified property classes — Coarse thread and fine pitch thread*

ISO 898-2, *Mechanical properties of fasteners made of carbon steel and alloy steel — Part 2: Nuts with specified property classes — Coarse thread and fine pitch thread*

ISO 18265, *Metallic materials — Conversion of hardness values*

3 Symbols

The following symbols apply in this Technical Report.

A_s	actual stress area of the bolt, in mm^2
$A_\mathrm{s,nom}$	nominal stress area of the bolt specified in ISO 898-1, in mm^2
A_Sb	shear area of the bolt threads, in mm^2
A_Sn	shear area of the nut threads, in mm^2
C_1	modification factor for nut dilation
C_2	modification factor for thread bending on the bolt stripping strength
C_3	modification factor for thread bending on the nut stripping strength
d	nominal thread diameter of the bolt, in mm
d_1	basic minor diameter conforming to ISO 724, in mm
d_2	basic pitch diameter of the thread according to ISO 724, in mm

d_3	minor (root) diameter of the bolt, in mm
d_A	equivalent diameter of the stress area A_s, in mm
D	nominal thread diameter of the nut, in mm
D_1	minor diameter of the nut, in mm
D_2	pitch diameter of the nut, in mm
D_c	countersink diameter of the nut, in mm
D_m	mean diameter of bell mouthed section of nut in the effective nut height or the length of thread engagement m_eff, in mm
F	tensile load, (general)
F_Bb	bolt breaking load, in N
F_m	ultimate tensile load, in N
F_p	proof load, in N
F_S	stripping load of bolt and nut assembly, in N
F_Sb	bolt thread stripping load, in N
F_Sn	nut thread stripping load, in N
F_u	ultimate clamp force, in N
F_y	yield clamp force, in N
h_c	height of chamfer per end, in mm
H	height of the fundamental triangle of the thread according to ISO 68-1, in mm
m	height of a nut, in mm
m_c	critical nut height giving same probabilities of stripping and breaking failure modes, in mm
m_eff	effective nut height, in mm
$m_\text{eff,c}$	critical effective nut height giving same probabilities of stripping and breaking failure modes, in mm
P	thread pitch, in mm
R_m	tensile strength of the bolt material according to ISO 898-1, in MPa
R_mn	tensile strength of the nut material, in MPa
R_s	strength ratio
s	width across flats of the nut, in mm
S_p	stress under proof load, in MPa
x	shear strength/tensile strength ratio
μ_th	coefficient of friction between threads
τ_Bb	shear strength of the bolt material, in MPa
τ_Bn	shear strength of the nut material, in MPa

4 Design principle

4.1 Possible fracture modes in bolt and nut assemblies subjected to tensile load

Three fracture modes can occur in bolt and nut assemblies under static tensile overload:

- bolt breaking when the length of thread engagement is long enough, and the strength of the nut or internal thread material is high enough;
- bolt thread stripping when the length of thread engagement is too short, and the strength of the nut or internal thread material is relatively high;
- nut thread stripping when the length of thread engagement is too short, and the strength of the nut or internal thread material is relatively low.

Of these fracture modes, bolt breaking is preferable since it indicates the full loadability (performance) of the bolt and nut assembly. Furthermore, the thread stripping partially induced in the tightening process is difficult to detect; therefore, it increases the risk of fracture due to the shortage of the clamp load and/or the loadability in service.

4.2 Calculation of the fracture loads in bolt and nut assemblies

4.2.1 General

As described in 4.1, in the event of static tensile overload during tightening a bolt, screw or stud together with a nut, three possible fracture modes characterized by three different fracture loads can occur:

- bolt breaking load (F_{Bb});
- bolt thread stripping load (F_{Sb});
- nut thread stripping load (F_{Sn}).

These three loads depend principally on the nut height, the hardness or the material tensile strength of the nut, the hardness or the material tensile strength of the bolt, and the diameter, pitch and effective length of thread engagement between bolt and nut.

Furthermore, these three loads are linked; this means that an increase in the hardness of the nut, for example, induces an increase in the bolt thread stripping load.

E. M. Alexander[5] defined an analogical model which allows the calculation of these three loads. A bolt and nut assembly conforming to ISO 898-1 and ISO 898-2 is basically designed in such a way that the assembly should not fail in the stripping fracture mode when static tensile overload is present, because such a failure could go undetected. This means that the breaking load in the bolt should be the minimum value between these three loads.

This is the reason different ranges of nut heights and hardness values are defined for regular nuts (style 1) and high nuts (style 2) as specified in ISO 898-2.

4.2.2 Bolt breaking load (F_{Bb})

4.2.2.1 General

Breaking normally occurs at the middle of the free threaded length in grip; therefore, the breaking load has nothing to do with the specifications of nuts.

4.2.2.2 Bolt breaking load for purely tensile loading

For bolts in accordance with ISO 898-1, the tensile strength is defined as the ultimate tensile load divided by the nominal stress area $A_{\mathrm{s,nom}}$:

$$R_{\mathrm{m}} = \frac{F_{\mathrm{m}}}{A_{\mathrm{s,nom}}} \tag{1}$$

with

$$A_{\mathrm{s,nom}} = \frac{\pi}{4}\left(\frac{d_2 + d_3}{2}\right)$$

where

d_2 is the basic pitch diameter of the thread according to ISO 724;

d_3 is the minor diameter of the thread;

$$d_3 = d_1 - \frac{H}{6}$$

where

d_1 is the basic minor diameter according to ISO 724;

H is the height of the fundamental triangle of the thread according to ISO 68-1.

According to Equation (1), the stress area $A_{\mathrm{s,nom}}$ is used as an index to convert the load into stress, or vice versa. The tensile strength R_{m} obtained by using Equation (1) for full-size bolt does not perfectly coincide with the material property. For example, smaller bolts of a certain property class, in which the fundamental deviations of d_2 and d_1 are relatively larger, need higher hardness or material tensile strength than larger bolts of the same property class.

Therefore, in the design procedure, the actual stress area A_{s} is used instead of $A_{\mathrm{s,nom}}$, using the actual dimensions of d_2 and d_1. The breaking load F_{Bb} can then be obtained as:

$$F_{\mathrm{Bb}} = R_{\mathrm{m}} \cdot A_{\mathrm{s}} \tag{2}$$

However, this does not mean that the real stress area can be determined only from the geometry of the thread, i.e. from the pitch diameter and the minor diameter. It is well known that the loadability of a bolt is affected not only by dimensions but also by the permanent strain distribution in the free threaded portion, induced by the stress concentration effect[6]. The free threaded length affects the permanent strain distribution, and therefore, the loadability of a bolt. The bolt with a shorter free threaded length tends to endure higher tensile load.

4.2.2.3 Bolt breaking load for tightening loading with the combination of tension and torsion

VDI 2230[7] gives the following Equation (3) for the calculation of yield clamp force F_{y}:

$$F_{\mathrm{y}} = \frac{R_{\mathrm{p0,2}} A_{\mathrm{s}}}{\sqrt{1 + 3\left\{\frac{3}{2}\frac{d_2}{d_{\mathrm{A}}}\left(\frac{P}{\pi d_2} + 1{,}155\mu_{\mathrm{th}}\right)\right\}^2}} \tag{3}$$

Equation (3) is based on the maximum distortion energy theory, and assuming the constant yield torsional stress on the whole sectional area. By using this fracture theory, the bolt breaking load for tightening loading, i.e. ultimate clamp force F_{u} can be calculated by substituting R_{m} for $R_{\mathrm{p0,2}}$:

$$F_{\mathrm{u}} = \frac{R_{\mathrm{m}} A_{\mathrm{s}}}{\sqrt{1 + 3\left\{\frac{3}{2}\frac{d_2}{d_{\mathrm{A}}}\left(\frac{P}{\pi d_2} + 1{,}155\mu_{\mathrm{th}}\right)\right\}^2}} \tag{4}$$

4.2.3 Stripping loads (F_{Sb}, F_{Sn})

4.2.3.1 Stripping load for purely tensile loading

According to Alexander's theory[5], the stripping loads F_{Sb} and F_{Sn} for bolt and nut threads can be obtained as follows:

$$\begin{cases} F_{\mathrm{Sb}} = 0{,}6 \cdot R_{\mathrm{m}} \cdot A_{\mathrm{Sb}} \cdot C_1 \cdot C_2 \\ F_{\mathrm{Sn}} = 0{,}6 \cdot R_{\mathrm{mn}} \cdot A_{\mathrm{Sn}} \cdot C_1 \cdot C_3 \end{cases} \tag{5}$$

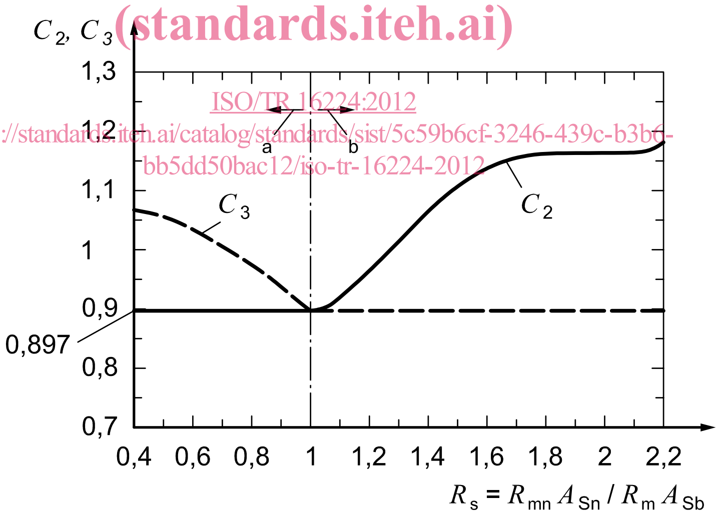
where

C_1 is the modification factor for nut dilation;

C_2 and C_3 are the modification factors for the thread bending effect, which can be obtained as follows:

$$\begin{cases} C_1 = -(s/D)^2 + 3{,}8(s/D) - 2{,}6 \quad (\text{for } 1{,}4 \le s/D < 1{,}9) \\ C_2 = 5{,}594 - 13{,}682R_{\mathrm{s}} + 14{,}107{R_{\mathrm{s}}}^2 - 6{,}057{R_{\mathrm{s}}}^3 + 0{,}9353{R_{\mathrm{s}}}^4 \quad (\text{for } 1 < R_{\mathrm{s}} < 2{,}2) \\ \quad = 0{,}897 \quad (\text{for } R_{\mathrm{s}} \le 1) \\ C_3 = 0{,}728 + 1{,}769R_{\mathrm{s}} - 2{,}896{R_{\mathrm{s}}}^2 + 1{,}296{R_{\mathrm{s}}}^3 \quad (\text{for } 0{,}4 < R_{\mathrm{s}} < 1) \\ \quad = 0{,}897 \quad (\text{for } R_{\mathrm{s}} \ge 1) \end{cases} \tag{6}$$

with $R_{\mathrm{s}} = \dfrac{R_{\mathrm{mn}} \cdot A_{\mathrm{Sn}}}{R_{\mathrm{m}} \cdot A_{\mathrm{Sb}}}$.



[a] Nut thread stripping.

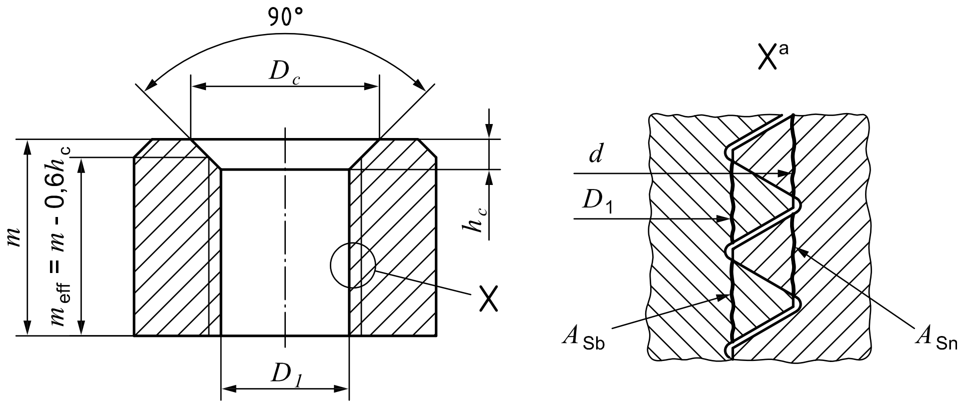
[b] Bolt thread stripping.

Figure 1 — Factors C_2 and C_3 for thread bending

Figure 1 shows the relationship between the factors C_2 and C_3 in relation to the strength ratio R_{s}. This shows that the strength ratio R_{s} determines which thread (bolt or nut) will be stripped when stripping fracture mode occurs although the stripping load is affected by the strength of the mated part (bolt or nut).

NOTE The experimental and analytical study using FEM[8] shows that the factor C_1 calculated by Equation (6) gives conservative (too small) values for nuts with smaller width across flats. This means that the calculated results for nuts with small width across flats tend to be safer.

For the calculation of the shear areas in Equation (5), the assumption is that 40 % of the chamfer height is effective for the actual length of thread engagement m_{eff}; see Figure 2.



Key

d	major diameter of the bolt
D_1	minor diameter of the nut
D_c	countersink diameter of the nut
h_c	height of chamfer per end
m	actual measured nut height
m_eff	effective nut height (= effective length of thread engagement)

[a] Detailed sketch of a joint with external and internal thread.

Figure 2 — Effective nut height m_eff for hexagon nuts

Considering the assumption shown in Figure 2, the shear areas A_Sb and A_Sn for bolt and nut, respectively, can be calculated according to Equation (7):

$$\begin{cases} A_\mathrm{Sb} = \dfrac{0{,}6m_\mathrm{eff}}{P}\cdot\pi\cdot D_1\cdot\left\{\dfrac{P}{2}+\left(d_2-D_1\right)\dfrac{1}{\sqrt{3}}\right\} \\ \qquad +\dfrac{0{,}4m_\mathrm{eff}}{P}\cdot\pi\cdot D_\mathrm{m}\cdot\left\{\dfrac{P}{2}+\left(d_2-D_\mathrm{m}\right)\dfrac{1}{\sqrt{3}}\right\} \\ \qquad D_\mathrm{m} = 1{,}026D_1 \\ A_\mathrm{Sn} = \dfrac{m_\mathrm{eff}}{P}\cdot\pi\cdot d\cdot\left\{\dfrac{P}{2}+\left(d-D_2\right)\dfrac{1}{\sqrt{3}}\right\} \end{cases} \qquad (7)$$

with $m_\mathrm{eff} = m - 0{,}6h_\mathrm{c}$ (for nuts with chamfer on one end) and $m_\mathrm{eff} = m - 1{,}2h_\mathrm{c}$ (for nuts with chamfers on both ends).

4.2.3.2 Stripping load for tightening loading

The major effect of the tightening loading on the stripping load is assumed to be the decrease of the shear areas for both the bolt and nut due to the increase of the nut dilation during the sliding action between threads and bearing surfaces; see also 4.3.2.3 and 5.2.

On the other hand, the breaking load in tightening [F_u in Equation (4)] also decreases normally by 15 % to 20 %.

4.3 Influencing factors on the loadability of bolt and nut assemblies

4.3.1 Influencing factors based on Alexander’s theory

Table 1 summarizes the influencing factors on Alexander’s theory for the three possible fracture modes described in 4.2.1, where the magnitude of the effect (direct/indirect/no effect) is indicated for three different fracture loads as well as for the variable directly concerned.

Table 1 — Summary of the factors affecting the loadability of bolt and nut assemblies

Item	Factor	Variable(s) concerned	Effect on		
			F_{Bb}	F_{Sb}	F_{Sn}
Bolt	Property class (Hardness)	Tensile strength, R_{m} Shear strength, 0,6 R_{m} Factors, C_2, C_3	○	○	●
Nut	Hardness	Shear strength, 0,6 R_{mn} Factors C_2, C_3	–	●	○
Nut	Height	Shear areas, A_{Sb}, A_{Sn}	–	○	○
Nut	Width across the flats	Factor C_1	–	●	●
Bolt	Thread tolerance class	Actual stress area, A_{s} Shear areas, A_{Sb}, A_{Sn}	○	○	○
Nut	Thread tolerance class	Shear areas, A_{Sb}, A_{Sn}	–	○	○
Nut	Chamfered height/angle	Shear areas, A_{Sb}, A_{Sn}	–	○	○
Bolt/nut	D/P	Actual stress area, A_{s} Shear areas, A_{Sb}, A_{Sn}	○	○	○

○ Direct or major effect.

● Indirect or minor effect.

– No effect.

4.3.2 Other factors which are not taken into account in Alexander's theory but may affect the loadability of bolt and nut assemblies

4.3.2.1 Shear strength/tensile strength ratio of the material

In Equation (5), the shear strength/tensile strength ratio x (= $\tau_{\mathrm{Bb}}/R_{\mathrm{m}}$ or $\tau_{\mathrm{Bn}}/R_{\mathrm{mn}}$) is specified to 0,6 for all fasteners made of carbon and alloy steels. It is known, however, the shear strength/tensile strength ratio x is dependent upon the material and its property class. VDI 2230[7] recommends the shear strength/tensile strength ratio x shown in Table 2.

Table 2 — Relation between the shear strength/tensile strength ratio x and the property class of bolts specified in ISO 898-1[7]

Property class	4.6	5.6	8.8	10.9	12.9
$x = \tau_{\mathrm{Bb}}/R_{\mathrm{m}}$	0,70	0,70	0,65	0,62	0,60

These results may be understood as the fact that making the calculation in accordance with Equation (5) gives the "conservative" results, on the safer side for the bolts (and nuts) of lower property classes. It should be noted, however, that the influencing factors C_2 and C_3 were empirically determined. Therefore, the effect of the shear strength/tensile strength ratio x might be taken into account to some extent in Equation (5).

For other materials (such as stainless steel and non-ferrous metals), the appropriate values of x should be considered; see Reference [7].

4.3.2.2 Thread pitch difference (error) between bolt and nut

The analytical results by FEM[8] have shown that thread stripping initially occurs at the first mating thread nearest the bearing surface of a nut since the highest load acts on the smallest shear area at the first mating thread for the bolt and nut assembly without a thread pitch difference between bolt and nut. Therefore, for bolt and nut assemblies with a thread pitch difference, the stripping loads F_{Sb} and F_{Sn} can be different from those