Verification of the Design Concept on Nuts in Bolt/Nut Assembly for the Revision of ISO 898-2 and ISO 898-6*

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Abstract

The ISO nuts of styles 1 and 2 specified in ISO 898-2 and ISO 898-6 are designed to prevent the thread stripping failure mode based on the calculation method called the Alexander’s theory. However, it has been pointed out that the thread stripping sometimes occurs in over-loaded bolt/nut assemblies of certain sizes and property classes due to the inadequate specifications in the relevant International Standards. This paper treats the design concepts on ISO nuts for the revision of the above ISO Standards, which is now taking place. The simulation program has been reproduced based on the Alexander’s theory, and the calculated values were compared with the specified ones. The results clearly show that there are both over-designed specifications and insufficiently designed ones with higher risk of stripping. Therefore, the possible ways to exclude such problems have been considered based on the distribution of the bolt/nut thread strength ratio calculated. Finally, it is shown that the most practical way is to change the hardness range of nut, and the program to obtain the adequate specifications is proposed with verification.

Key words: Fixing Element, Nut, Bolt/nut Assembly, Design Concept, Mechanical Property, ISO Standard, Specified Value, Failure Mode, Alexander’s Theory

1. Introduction

The ISO nuts of styles 1 and 2 specified in ISO 898-2(1) and ISO 898-6(2) are designed to control the thread stripping failure mode based on the Alexander’s theory(3), in which the minimum nut height and the proof load value are calculated from the geometrical conditions of bolt/nut assembly and the mechanical properties of their materials. The applicability of the Alexander’s theory had been verified by experiments using the staircase method(4) and the FEM analysis taking into account the effects of the nut dilation and the thread bending(5). However, in the relevant ISO Standards, the nut heights for individual styles and sizes are unified for all the property classes and the types of thread (coarse or fine pitch). This may result in the inadequate combination of bolt/nut assemblies.

The aim of this study is to present the rational basis for the revision of the above ISO Standards, which is now taking place in ISO/TC 2/SC 1/WG 10. First of all, the simulation based on the Alexander’s theory has been performed to point out the problems in the present specifications, and to consider the possible way to exclude the problems. Then the method to amend the specified values is discussed.
2. Nomenclature

\( A_{sb} \): Shear area for bolt threads
\( A_{sn} \): Shear area for nut threads
\( A_s \): Stress area of bolt
\( C_1 \): Modification factor for nut dilation
\( C_2 \): Modification factor for thread bending applied for bolt
\( C_3 \): Modification factor for thread bending applied for nut
\( D \): Nominal diameter (of nut)
\( D_1 \): Minor diameter of nut
\( D_2 \): Pitch diameter of nut
\( D_c \): Countersink diameter of nut
\( d \): Major diameter of bolt
\( d_2 \): Pitch diameter of bolt
\( d_3 \): Minor (root) diameter of bolt
\( F_B \): Breaking load of bolt
\( F_S \): Stripping load for bolt/nut assembly
\( F_{Sb} \): Stripping load for bolt threads
\( F_{Sn} \): Stripping load for nut threads
\( m \): Nut height
\( m^* \): Effective nut height for the calculation of stripping load
\( m_c \): Critical nut height having same probabilities of stripping and breaking
\( P \): Pitch of the thread
\( r \): Root radius of bolt thread
\( s \): Width across the flats of nut
\( \sigma_{tb} \): Tensile strength of bolt material
\( \sigma_{tn} \): Tensile strength of nut material

3. The Alexander’s Theory

3.1 Principle and Basic Formulae

Figure 1 summarizes the concept of the Alexander’s theory. For the bolt/nut assembly having a specific material property combination, the thread stripping load \( F_S \) is proportional to the shear area of the mating threads, i.e., the effective nut height \( m^* \) or the number of threads mated while the breaking load \( F_B \) has nothing to do with it. Therefore, we can control the failure mode of a bolt/nut assembly by choosing the nut height as a parameter.

The failure loads can be calculated by using the following formulae assuming that the shear strength is 60% of the tensile strength both for bolt and nut materials:

\[
F_S = F_B \\
F_{Sb} = F_{Sn} = F_S = F_B
\]

\( m^* \) Critical nut height

\( m_c \) Critical nut height having same probabilities of stripping and breaking

\( D \) Diameter

Fig. 1 The relationship among failure loads \( F_S \) and \( F_B \) and the effective nut height \( m^* \)
Table 1 Assumed deviations for variable concerned

<table>
<thead>
<tr>
<th>Variables</th>
<th>For nuts</th>
<th>For bolts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>$\sigma_{bn}$</td>
<td>$\sigma_{bb}$</td>
</tr>
<tr>
<td>Major diameter</td>
<td>$D$</td>
<td>$d$</td>
</tr>
<tr>
<td>Pitch diameter</td>
<td>$D_2$</td>
<td>$d_2$</td>
</tr>
<tr>
<td>Minor diameter</td>
<td>$D_1$</td>
<td>$d_1$</td>
</tr>
<tr>
<td>Root radius</td>
<td>$r$</td>
<td>$0.01$</td>
</tr>
<tr>
<td>Nut height</td>
<td>$m$</td>
<td>$-$</td>
</tr>
<tr>
<td>Countersink angle</td>
<td>$-$</td>
<td>$5^\circ$</td>
</tr>
<tr>
<td>Countersink diameter</td>
<td>$D_c$</td>
<td>$0.01 D$</td>
</tr>
</tbody>
</table>

In the simulation for obtaining the minimum nut height, the deviations shown in Table 1 are assumed for the variables concerned, and each distribution is placed in the tolerance zone so that the stripping is more likely to occur. Moreover, the breaking load is reduced to $0.95F_B$ considering the case of tightening loading.

3.2 Influencing Factors

In Eq. (1), the following three modification factors are introduced:

\[
\begin{align*}
F_{bn} &= \sigma_{bn} \cdot A_s \\
F_{sb} &= 0.6 \cdot \sigma_{sb} \cdot A_{sb} \cdot C_1 \cdot C_2 \\
F_{sa} &= 0.6 \cdot \sigma_{sa} \cdot A_{sa} \cdot C_1 \cdot C_3 \\
F_s &= \min(F_{bn}, F_{sb}) \\
F_b &= \min(F_{sa}, F_{sb})
\end{align*}
\]  

(1)

The factor $C_1$ is for nut dilation affecting on the reduction of the shear area, and the factors $C_2$ and $C_3$ are for thread bending related to the strength ratio $R_s (= \sigma_{bs} A_{bs}/\sigma_{bb} A_{sb})$ of bolt and nut threads, respectively.

Figure 2 shows the relationship among the factors $C_2$ and $C_3$, and the strength ratio $R_s$. It is important to note that $R_s$ value is only the decisive element for failure modes even though the stripping loads change a little bit due to the factors $C_2$ or $C_3$.

4.1 Minimum Nut Height $m_{\text{min}}$

Figure 3 shows the relationship between the distribution of the critical nut height $m_c$ and the specified minimum nut height $m_{\text{min}}$. According to the Alexander's theory, the minimum nut height shall be set to 10 percentile of the critical nut height simulated. However, we can also see two undesirable cases where $m_{\text{min}}$ is placed below the ±3σ range of $m_c$ such as for M10 and larger style 2 nuts with property class 9, and $m_{\text{min}}$ is placed above the ±3σ range of $m_c$ such as for M16 and smaller style 2 nuts with property class 12. The latter case is over-designed situation and has no harmful effect on their applications, but the former case increases the risk of stripping which should be avoided.

Tables 2 and 3 show the distributions of the strength ratio $R_s$ in the simulation, where the colors indicate the following categories:

- Insufficient design (minimum nut height should be increased);
- Over design (minimum nut height had better be decreased);
- Acceptable design.

The insufficient design conditions for certain property classes and sizes may be caused by the inadequate selection of nut material in the standardization processes.
Table 3 Distribution of the strength ratio $R_s$ for nuts specified in ISO 898-6

<table>
<thead>
<tr>
<th>Thread $d\times P$</th>
<th>Property classes</th>
<th>8</th>
<th>10</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>style 1</td>
<td>style 2</td>
<td>style 1</td>
<td>style 2</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>M 8×1</td>
<td>1.12</td>
<td>1.28</td>
<td>0.86</td>
<td>0.95</td>
</tr>
<tr>
<td>M10×1</td>
<td>1.12</td>
<td>1.26</td>
<td>0.85</td>
<td>0.94</td>
</tr>
<tr>
<td>M10×1.25</td>
<td>1.10</td>
<td>1.26</td>
<td>0.84</td>
<td>0.94</td>
</tr>
<tr>
<td>M12×1.25</td>
<td>1.10</td>
<td>1.26</td>
<td>0.83</td>
<td>0.93</td>
</tr>
<tr>
<td>M16×1.5</td>
<td>1.10</td>
<td>1.24</td>
<td>0.84</td>
<td>0.93</td>
</tr>
<tr>
<td>M20×1.5</td>
<td>1.23</td>
<td>1.38</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>M24×2</td>
<td>1.23</td>
<td>1.39</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>M30×2</td>
<td>1.24</td>
<td>1.39</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>M36×3</td>
<td>1.22</td>
<td>1.37</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

4.2 Proof Load $F_p$

Figure 4 represents the comparison of the stress under proof load $S_p$ between calculation and specification. In the simulation, the proof load is calculated for the combination of the hardened mandrel and nut, and the proof load is determined based on the minimum stripping load $F_{Sn}$ for nut threads.

Considering the fact that the stress under proof load $S_p$ is defined as the proof load divided by the nominal stress area $A_s$ of bolt, it seems to be greater than the specified minimum tensile strength of the bolt mated. However, such a condition is not always realized as long as we maintain the design concept based on the Alexander's theory since the proof load is calculated for the weakest nut having the combination of minimum nut height, minimum nut shear area, and minimum nut hardness, which would, in practice, never exist.

It should also be noted that the stress under proof load $S_p$ tends to be smaller for nuts with smaller size due to the relatively large fundamental deviations.

4.3 Policies to be Taken for the Revision

Considering the facts mentioned above, we have to make a decision from the following
options for the amendment of specified values in ISO 898-2 and ISO898-6 to prevent the stripping failure mode:

(A) Optimize (amend) the nut height in accordance with the Alexander's theory.
(B) Fix the nut heights as they are, and amend the hardness ranges for some property classes and styles.

From the practical point of view, the option (B) is more preferable since the hardness ranges are specified only in ISO 898-2 and ISO 898-6 while the nut heights or "styles" are specified in the individual product standards such as ISO 4032(6), ISO 4033(7), ISO 8673(8), and ISO 8674(9). From Fig. 2, we can see that the stripping load $F_s$ would increase by increasing the strength ratio $R_s$ up to 1.6 even when $R_s$ is more than unity. The results in Tables 2 and 3 show the possibility to control the failure modes of bolt/nut assemblies by selecting the adequate $R_s$ values or minimum hardness of nuts.

5. Proposal on the Procedures for Obtaining the Nut Hardness Range

5.1 Simplified Calculation Method

Based on the Alexander's simulation program, the adequate hardness range for nuts could only be obtained by trial and error. Therefore, the simplified and formulated method should be developed to maintain both the efficiency of the revision work and the clarity of the procedure to ensure the consistency for the future revision.

The proposed method is based on the assumptions that the hardness reversely calculated by using the mean values of variables obtained from Table 1 under the condition of $0.95F_{sh} = F_S$ gives the mean hardness value, and that the 60 N/mm² deviation of $\sigma_{sh}$ in Table 1 can be applied to obtain the minimum hardness value.

For the reverse calculation, Eq. (1) is transformed as,

$$\begin{align*}
F_{sh} &= 0.6 \cdot \sigma_{sh} \cdot A_{sh} \cdot C_1 \cdot C_2 \\
F_{hs} &= 0.6 \cdot \sigma_{hs} \cdot A_{hs} \cdot C_1 \cdot C_3 = 0.6 \cdot \sigma_{hs} \cdot A_{hs} \cdot C_1 \cdot C_3^* \\
\{F_s &= 0.6 \cdot \sigma_{sh} \cdot A_{sh} \cdot C_1 \cdot C_n \\
C_n &= \min(C_2, C_3^*)
\end{align*}$$

or,

$$\begin{align*}
F_s &= 0.6 \cdot \sigma_{sh} \cdot A_{sh} \cdot C_1 \cdot C_n \\
C_n &= \min(C_2, C_3^*)
\end{align*}$$

By applying the condition of $0.95F_{sh} = F_S$, and the inverse functions of $C_2$ and $C_3^*$, the strength ratio $R_s$ can be obtained as,

$$\begin{align*}
R_s &= \frac{-47.146 + 139.5C_n - 135.61C_n^2 + 44.535C_n^3}{44.535C_n^3} \quad (\text{for } R_s < 1) \quad (4 - a) \\
R_s &= 1.005 - 3.468C_n + 6.080C_n^2 - 2.472C_n^3 \quad (\text{for } R_s > 1) \quad (4 - b)
\end{align*}$$

where,

$$C_n = \frac{0.95 \cdot A_{sh}}{0.6 \cdot A_{hs} \cdot C_1} \quad (5)$$

Then the tensile strength of nuts obtained from $R_s$ value can be converted to the Vickers hardness values ($HV$) by using the conversion table such as in SAE J 417(10) via Brinell hardness ($HB$) as,

$$\sigma_n \approx 3.45 \cdot HB \quad (6)$$

Tables 4 and 5 summarize the proposal for the minimum hardness of nuts. The colors are remained also in these tables as in Tables 2 and 3, and almost all the values correspond to the following categories:
Higher hardness value (for insufficient design situation);  
Lower hardness value (for over design situation);  
Almost the same hardness value (for acceptable design situation).

This fact highlights the usefulness of the proposed method as a whole.

Concerning the specifications for the maximum hardness of nuts, it should be determined by taking into account the process control abilities in manufacturing nuts. In the present Standards, the tolerances for hardness are set to 60 to 120 Vickers units, and the maximum hardness is limited to 353 HV. Therefore, the maximum hardness limit may be reconsidered for nuts that need the minimum hardness greater than 300 HV.

Furthermore, it is advised that the reduction of the minimum hardness which results in the decrease of the proof load is, of course, not always necessary for this revision.

5.2 Verification of the Results

Figure 5 shows the results of the Alexander's simulation using the amended hardness ranges obtained from the method described in 5.1. In all the cases, the specified nut heights fall into the lower part of the individual critical nut height distributions. This shows that the specified hardness ranges are adequate.

<table>
<thead>
<tr>
<th>Property classes</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>12</th>
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<tr>
<td>Std</td>
<td>Cal</td>
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<td>Std</td>
</tr>
<tr>
<td>M 5</td>
<td>181</td>
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<td>178</td>
<td>224</td>
</tr>
<tr>
<td>M 6</td>
<td>189</td>
<td>–</td>
<td>181</td>
<td>231</td>
</tr>
<tr>
<td>M 8</td>
<td>202</td>
<td>–</td>
<td>194</td>
<td>246</td>
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<tr>
<td>M10</td>
<td>211</td>
<td>–</td>
<td>198</td>
<td>258</td>
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<td>M12</td>
<td>211</td>
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<td>258</td>
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<tr>
<td>M16</td>
<td>206</td>
<td>–</td>
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<td>252</td>
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<td>M20</td>
<td>236</td>
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<td>273</td>
</tr>
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<td>240</td>
<td>191</td>
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<td>278</td>
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<td>193</td>
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</table>

*: Specified values in the present International Standard.
**: Calculated minimum values for the revision.

<table>
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<td>M36×3</td>
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</table>

*: Specified values in the present International Standard.
**: Calculated minimum values for the revision.
Fig. 5 Distribution of the critical nut height $m_c$ for nuts specified in ISO 898-2 after modifying the hardness range

6. Conclusions

The main conclusions obtained in this study are summarized as follows:

1. The Alexander's simulation has been performed for nuts specified in ISO 898-2 and ISO 898-6, and the nuts having inadequate specifications were pointed out.
2. The policies for the revision have been considered from the practical point of view, and the most adequate method to amend the hardness range of nuts was proposed.
3. It has been verified by the simulation that the amended specifications are suitable for the purpose of the relevant International Standards.

References

(6) ISO 4032:1999, Hexagon nuts, style 1 – Product grades A and B.
(7) ISO 4033:1999, Hexagon nuts, style 2 – Product grades A and B.
(8) ISO 8673:1999, Hexagon nuts, style 1, with metric fine pitch thread – Product grades A and B.
(9) ISO 8674:1999, Hexagon nuts, style 2, with metric fine pitch thread – Product grades A and B.