A new approach to the checking of the tightness of bolted connections

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ABSTRACT

Ensuring that nuts and bolts are sufficiently tight plays a vital role in ensuring the structural integrity of many types of equipment. Traditionally this is done by determining the torque needed to rotate the nut/bolt slightly in the tightening direction and comparing this value to the original torque specification. The torque applied to tighten a bolt and the load subsequently induced into it, are largely dependent upon the friction present between the rotating surfaces on the fastener. Changes in the friction conditions over time will affect the torque to rotate the bolt and make this approach to checking the tightness of bolts problematic.

In the majority of applications, where bolts and nuts are used, it is the clamp force provided by tightening the bolts that is the crucial factor in determining the structural integrity, or otherwise, of the joint. Until now, comparing the measured torque to the original specification has been the only practical way of assessing the tightness of a bolted connection. This paper shows an alternative means which, by measuring the torque needed to rotate the nut/bolt in the tightening and then immediately in the untightening direction, allows the load present in the bolt to be determined.

Keywords: Fasteners, Friction and Wear, Machine Elements, Maintenance

1. INTRODUCTION

In many applications the clamping force provided by tightening bolted connections is of critical importance in determining the success, or otherwise, of the structural integrity of an assembly. A great deal of attention is often placed on ensuring that bolted connections are installed in a controlled manner such that a predictable clamping force is achieved. In the majority of applications the bolts are required to provide a minimum clamping force such that the joint will be capable of resisting the external forces so that joint separation and joint movement are prevented.

The most popular method of tightening a threaded fastener is by applying a specific tightening torque. Below the yield point of the fastener, the relationship between the applied tightening torque and the subsequent clamp force provided by the fastener, is a function of its geometry (thread details and bearing face dimensions) and the coefficient of friction acting between the mating threads and between the bearing face of the fastener and the joint surface. Once tightened, the clamp force provided by a bolted connection can decrease. The decrease can occur without any rotation of the thread, as in the case of stress relaxation, embedding, creep and similar effects, or, the bolt or nut may rotate decreasing the clamp force as in the case of self-loosening. Research has shown that self-loosening of bolts/nuts is normally the result of repeated transverse displacement of the joint. Such loosening can be prevented by ensuring that the bolts provide sufficiently high clamp force to resist the external forces being applied to the joint. Subsequently, concern over the loosening of bolts, in many applications, necessitates the checking of their tightness. Tightness, in this context, is the magnitude of the clamp force being provided by the bolt or a threaded fastener in general.

Currently, the tightness of a bolt/nut assembly is usually assessed by a torque based method, the approach is referred to as torque auditing, the current approaches being discussed in references [1-3]. Torque auditing is usually completed by one of three torque methods:

1. On-torque method: Measuring the torque needed to rotate the bolt/nut by a small angle (typically 2 to 10 degrees) in the tightening direction.
2. Off-torque method: Measuring the torque needed to rotate the bolt/nut in the untightening direction.
3. Marked fastener method: Marking the position of the bolt/nut relative to the joint, untightening it by an angle of approximately 30 degrees, then measuring the torque needed to tighten the bolt back to the marked position.

Each of these three methods have their deficiencies. The key assumption in each method is that the torque value measured is a true assessment of the tightness of the connection. The critical flaw in each of these methods is the assumption that the coefficient of friction has not changed between the tightening of the bolt/nut and the completion of the checking process. Changes in temperature, humidity and the effects of corrosion after the bolt/nut was originally tightened will affect the magnitude of the coefficient of friction. A change in the coefficient of friction since the original tightening can change the torque - clamp force relationship making invalid the assumption that the torque value is a true assessment of the bolt's tightness.

Other tightness checking methods are used less frequently than torque based methods. These include length measurement, either by physically measuring the overall length of the threaded fastener or by use of an ultrasonic transducer. These methods have limited applicability to the checking of the tightness of a previously tightened bolt/nut due to the difficulties in establishing the fastener extension. To establish the extension, the overall length of bolt is measured, in-situ, in the tightened condition and then is completely untightened and the overall length re-measured. The extension can then be computed from the two length measurements. Using this information, the clamp force that was created by the bolt in the tightened condition, can be estimated based upon some assumptions regarding the effective grip length and the properties of the part. Considering that bolt extensions are typically in the range 0.1 mm to 0.2 mm, deviations in the flatness of the bolt head and at the end of the thread, make this approach both time consuming and problematic.

The method described here is to improve upon the present tightness checking methods to allow the clamp force being provided by a previously bolted connection to be assessed and, potentially, corrected. This is achieved by performing a tightening-untightening-retightening sequence (referred to as the 'On-Off-On' method) on the bolt/nut involving the measurement of torque. The On-Off-On tightening sequence can provide information as to the clamp force provided by the bolt, which allows a better indication of the structural integrity of the joint than existing methods.

2. BACKGROUND TO THE METHOD

The torque $T_{on}$ needed to induce a clamp force $F$ between the part, or parts, when a bolt/nut is tightened, is given by the relationship [4]:

$$T_{on} = \frac{F}{2} \left[ \frac{\mu_t d_2}{\cos \beta} + \frac{D_e \mu_n}{\pi} \right]$$

where:

- $T_{on}$        Tightening torque
- $F$            Clamp force provided by the bolt
- $\mu_t$        Coefficient of friction for the threads
- $d_2$          The basic pitch diameter of the thread
- $\beta$        The half included angle for the threads (30 degrees for Unified and metric thread forms)
- $p$            Pitch of the thread
- $\mu_n$        Coefficient of friction for the nut face or bolt head
- $D_e$          The effective bearing diameter of the nut (or bolt, if the bolt is rotated). This can be taken as the mean $d_o$ of $d_i$ and $d_i$
- $d_o$          The outer bearing diameter of the nut
- $d_i$          The inner bearing diameter of the nut face

Certain nuts and bolts have a prevailing torque feature used to resist loosening. When such fasteners are used the tightening torque needs to be increased by the prevailing torque $T_p$ so that clamp force $F$ is achieved.
When untightening the bolt/nut, a torque lower than the tightening torque is needed since the thread extension torque component assists the untightening process. To untighten the threaded fastener a torque \( T_{\text{off}} \) is required which can be described by the relationship:

\[
T_{\text{off}} = \frac{F}{2} \left( \frac{\mu_d}{\cos \beta} - \frac{p}{\pi} + D_e \mu_n \right)
\]

If the torque is measured that is needed to further tighten the bolt by a small incremental amount and then subsequently the torque needed to untighten the bolt, the following relationship is obtained:

\[
T_{\text{on}} - T_{\text{off}} = F \left( \frac{p}{\pi} \right)
\]

The relationship can be re-arranged to give the clamp force \( F \):

\[
F = \frac{p}{\pi} \left[ T_{\text{on}} - T_{\text{off}} \right]
\]

Hence the clamp force \( F \) provided by a previously tightened bolt can be determined by measuring the torques \( T_{\text{on}} \) and \( T_{\text{off}} \). Based upon these torque measurements it is also possible to determine the coefficient of total friction \( \mu_{\text{tot}} \) (the weighted mean of the thread and nut face coefficients of friction) by:

\[
\mu_{\text{tot}} = \frac{\frac{\pi}{p} \left( T_{\text{on}} - T_{\text{off}} \right)}{\frac{d^2}{2} + \frac{D_e}{2}} - \frac{p}{2\pi}
\]

Apart from the \( T_{\text{on}} \) and \( T_{\text{off}} \) torque values, the other terms can be established from bolt dimensional measurements.

The torque coefficient (historically called the nut factor) is sometimes used in threaded fastener torque calculations. The torque coefficient \( K \) is a factor used to represent the fastener friction conditions and is used in, and defined by, the equation:

\[
T = F \cdot d \cdot K
\]

where \( F \) is the clamp force provided by a tightening torque \( T \), applied to a threaded fastener of diameter \( d \). Since this tightness checking approach can allow the clamp force \( F \) to be determined, the torque coefficient \( K \) can be determined from the on-torque and off-torque values by the equation:

\[
K = \frac{\frac{p}{\pi} T_{\text{on}}}{\pi d \left( T_{\text{on}} - T_{\text{off}} \right)}
\]

The primary advantage of the torque coefficient approach relative to the full torque-tension equation, which uses the coefficient of friction, is that it is much simpler to apply. The primary disadvantage is that it is applicable to a particular type and pitch of fastener and strictly to a particular thread size. In spite of these issues, it is very widely used to determine the torque to be applied to a fastener.

A key assumption in the approach is that the friction in the tightening direction is the same as in the untightening direction. A series of tests were conducted on a range of bolt sizes, types and lubrication conditions to assess the efficacy of the method under different circumstances.
3. TESTS TO INVESTIGATE THE TIGHTNESS CHECKING METHOD

3.1. Tests to determine the coefficient of friction in the tightening and untightening directions

A series of torque tension tests were conducted which involved measuring the torque in the tightening and untightening directions whilst simultaneously measuring the clamp force provided by the bolt. The approach is illustrated in figure 1. The torque transducer and load cell were connected to an analogue to digital convertor and into a computer, allowing torque and clamp load values to be sampled during the tightening and untightening operations and recorded. Tests have been completed on M12 and M16 fasteners having a range of finish/lubrication conditions. Either a 100 Nm or 500 Nm torque transducer was used with either a load cell to match the fastener size being tested (M12 or M16). The tests reported here are a subset of the tests performed on different types of M12, M16 and M20 bolts and nuts which displayed similar results to the results presented here.

Based upon the measured torque and clamp load values it is possible to determine the coefficient of total friction \( \mu_{\text{tot}} \) for the fastener using the following equation (derived from the torque-tension equation previously discussed):

\[
\mu_{\text{tot}} = \frac{(T - T_p) p}{F \left( \frac{2 \pi}{d_z} + \frac{D_z}{2} \right) 2 \cos \beta}
\]

The terms used are as those previously defined. In the tests reported here, all the fasteners had metric threads, accordingly the above equation can be simplified to:

\[
\mu_{\text{tot}} = \frac{(T - T_p) - 0.159 p}{0.577 d_z + \frac{D_z}{2}}
\]
3.2. Tests on M12 bolts and nuts having a low coefficient of friction

A set of tests were conducted on M12 standard hexagon headed nuts and bolts with an electro-zinc plated finish with a high performance grease applied to the threads and the nut face. A summary of the results are provided in table 1, the torque-tension graphs in figure 2.

Table 1: Test results for M12 zinc plated bolts and nuts with Lubrisilk #2 EP synthetic grease applied.

<table>
<thead>
<tr>
<th>Test</th>
<th>Max On-Torque (Nm)</th>
<th>Max Bolt Load (kN)</th>
<th>Max Off-Torque (Nm)</th>
<th>Coefficient of Friction</th>
<th>Predicted Preload (kN)</th>
<th>Bolt Load Prediction Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tightening</td>
<td>Untightening</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>29.9</td>
<td>25.55</td>
<td>16.1</td>
<td>0.065</td>
<td>0.071</td>
<td>24.77</td>
</tr>
<tr>
<td>2</td>
<td>29.4</td>
<td>25.35</td>
<td>16.0</td>
<td>0.065</td>
<td>0.073</td>
<td>24.05</td>
</tr>
<tr>
<td>3</td>
<td>28.7</td>
<td>25.55</td>
<td>14.9</td>
<td>0.060</td>
<td>0.068</td>
<td>24.77</td>
</tr>
<tr>
<td>4</td>
<td>29.6</td>
<td>25.72</td>
<td>15.9</td>
<td>0.061</td>
<td>0.071</td>
<td>24.59</td>
</tr>
<tr>
<td>5</td>
<td>28.3</td>
<td>25.35</td>
<td>14.9</td>
<td>0.058</td>
<td>0.069</td>
<td>24.05</td>
</tr>
<tr>
<td>6</td>
<td>28.6</td>
<td>25.76</td>
<td>14.3</td>
<td>0.059</td>
<td>0.067</td>
<td>25.67</td>
</tr>
<tr>
<td>7</td>
<td>27.8</td>
<td>25.20</td>
<td>14.3</td>
<td>0.057</td>
<td>0.065</td>
<td>24.23</td>
</tr>
<tr>
<td>8</td>
<td>28.0</td>
<td>25.21</td>
<td>14.8</td>
<td>0.058</td>
<td>0.069</td>
<td>23.69</td>
</tr>
<tr>
<td>9</td>
<td>30.8</td>
<td>25.25</td>
<td>17.0</td>
<td>0.066</td>
<td>0.072</td>
<td>24.77</td>
</tr>
<tr>
<td>10</td>
<td>30.2</td>
<td>25.18</td>
<td>16.7</td>
<td>0.062</td>
<td>0.074</td>
<td>24.23</td>
</tr>
<tr>
<td>Mean</td>
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<td>25.41</td>
<td>15.5</td>
<td>0.061</td>
<td>0.070</td>
<td>24.48</td>
</tr>
<tr>
<td>Std-Dev</td>
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<td>0.2</td>
<td>1.0</td>
<td>0.0033</td>
<td>0.0028</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Figure 2: Torque-Tension Graphs for M12 EZP Fasteners with Lubrisilk 2 EP synthetic grease applied
3.3. Tests on M12 flange headed bolts and nuts

A set of tests were conducted on M12 flanged headed bolts and nuts which had a zinc flake finish with a thin layer (approximately 1 µm) of PTFE to control the friction characteristics (these are the standard type used for automotive structural fasteners and are increasingly used in other industries). The results are presented in table 2.

### Table 2: Test results for M12 flanged headed bolts and nuts with a zinc flake finish

<table>
<thead>
<tr>
<th>Test</th>
<th>Max On-Torque (Nm)</th>
<th>Max Bolt Load (kN)</th>
<th>Max Off-Torque (Nm)</th>
<th>Coefficient of Friction</th>
<th>Predicted Bolt Load (kN)</th>
<th>Bolt Load Prediction Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tightening</td>
<td>Untightening</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>87.8</td>
<td>40.5</td>
<td>63.2</td>
<td>0.132</td>
<td>0.176</td>
<td>44.2</td>
</tr>
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<td>2</td>
<td>80.8</td>
<td>40.6</td>
<td>58.4</td>
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<td>0.149</td>
<td>40.2</td>
</tr>
<tr>
<td>3</td>
<td>67.7</td>
<td>40.8</td>
<td>52.2</td>
<td>0.109</td>
<td>0.136</td>
<td>33.4</td>
</tr>
<tr>
<td>4</td>
<td>75.5</td>
<td>40.7</td>
<td>56.9</td>
<td>0.109</td>
<td>0.136</td>
<td>33.4</td>
</tr>
<tr>
<td>5</td>
<td>76.6</td>
<td>41.3</td>
<td>55.6</td>
<td>0.110</td>
<td>0.124</td>
<td>34.5</td>
</tr>
<tr>
<td>6</td>
<td>73.3</td>
<td>40.6</td>
<td>54.1</td>
<td>0.102</td>
<td>0.124</td>
<td>34.5</td>
</tr>
<tr>
<td>7</td>
<td>83.5</td>
<td>41.4</td>
<td>64.2</td>
<td>0.121</td>
<td>0.150</td>
<td>34.6</td>
</tr>
<tr>
<td>8</td>
<td>83.0</td>
<td>41.1</td>
<td>63.9</td>
<td>0.123</td>
<td>0.152</td>
<td>34.3</td>
</tr>
<tr>
<td>9</td>
<td>82.2</td>
<td>40.8</td>
<td>64.5</td>
<td>0.117</td>
<td>0.145</td>
<td>31.8</td>
</tr>
<tr>
<td>10</td>
<td>82.0</td>
<td>40.9</td>
<td>62.0</td>
<td>0.114</td>
<td>0.139</td>
<td>35.9</td>
</tr>
<tr>
<td>Mean</td>
<td>79.2</td>
<td>40.9</td>
<td>59.5</td>
<td>0.115</td>
<td>0.143</td>
<td>35.4</td>
</tr>
<tr>
<td>Std-Dev</td>
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<td>0.3</td>
<td>4.6</td>
<td>0.011</td>
<td>0.016</td>
<td>4.5</td>
</tr>
</tbody>
</table>

3.4. Tests on M16 bolts and nuts with a self-finish with oiled surfaces

A set of tests were conducted on M16 bolts and nuts with a self-finish and oiled surfaces. Such fasteners are used in general machinery and in the power generation industry. The results are presented in table 3.

### Table 3: Test results for M16 bolts and nuts with a self-finish with oiled surfaces

<table>
<thead>
<tr>
<th>Test</th>
<th>Max On-Torque (Nm)</th>
<th>Max Bolt Load (kN)</th>
<th>Max Off-Torque (Nm)</th>
<th>Coefficient of Friction</th>
<th>Predicted Bolt Load (kN)</th>
<th>Bolt Load Prediction Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tightening</td>
<td>Untightening</td>
<td></td>
</tr>
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<td>220.2</td>
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<td>0.112</td>
<td>0.117</td>
<td>78.9</td>
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<td>146.5</td>
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<td>87.2</td>
</tr>
<tr>
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<td>170.0</td>
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<td>0.116</td>
<td>90.8</td>
</tr>
<tr>
<td>4</td>
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<td>171.5</td>
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<td>74.6</td>
</tr>
<tr>
<td>5</td>
<td>233.8</td>
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<td>176.5</td>
<td>0.119</td>
<td>0.120</td>
<td>90.0</td>
</tr>
<tr>
<td>6</td>
<td>257.7</td>
<td>94.6</td>
<td>208.1</td>
<td>0.130</td>
<td>0.136</td>
<td>77.9</td>
</tr>
<tr>
<td>7</td>
<td>254.1</td>
<td>96.3</td>
<td>188.2</td>
<td>0.126</td>
<td>0.123</td>
<td>103.5</td>
</tr>
<tr>
<td>8</td>
<td>243.4</td>
<td>95.0</td>
<td>174.0</td>
<td>0.121</td>
<td>0.116</td>
<td>109.0</td>
</tr>
<tr>
<td>9</td>
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<td>207.3</td>
<td>0.130</td>
<td>0.134</td>
<td>82.8</td>
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<tr>
<td>10</td>
<td>269.3</td>
<td>95.7</td>
<td>218.5</td>
<td>0.135</td>
<td>0.141</td>
<td>79.8</td>
</tr>
<tr>
<td>Mean</td>
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<td>94.5</td>
<td>183.1</td>
<td>0.119</td>
<td>0.122</td>
<td>87.4</td>
</tr>
<tr>
<td>Std-Dev</td>
<td>21.7</td>
<td>1.4</td>
<td>22.2</td>
<td>0.011</td>
<td>0.012</td>
<td>11.3</td>
</tr>
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</table>
4. PRACTICAL IMPLEMENTATION OF THE TIGHTNESS CHECKING METHOD

To apply the On-Off-On method to establish the tightness of the bolted connection, the torque needed to incrementally rotate the nut in the tightening direction is measured, then measured in the untightening direction, before final retightening. Depending upon the relative value of the thread frictional torque to the head frictional torque, the bolt head may need to be held whilst the nut is rotated. The torque applied to retighten the bolt can be based upon the measured torque value, the original torque specification value or alternatively, a derived torque based upon the clamp force/friction condition measured. Alternatively, the bolt can be re-tightened back to the original position relative to the joint.

Software has been developed to facilitate the implementation of the On-Off-On method. By measuring the on-torque and off-torque values in real time, the software assists a user to retighten the fastener to either a pre-determined torque value or a torque value to achieve a specific clamp force computed from the on-torque and off-torque values. Figure 3 shows a torque trace recorded using the software. In this example, the on-torque and off-torque values were measured followed by retightening to 45 Nm. The software also records the on-torque, off-torque and the on re-torque values for statistical process control purposes. The software can be implemented into existing electronic torque control systems since, essentially, it measures torque values and does a small amount of computation based upon the recorded values. The coefficient of friction and the torque coefficient can also be computed based upon the on-torque and off-torque values and the fastener geometry.

![Torque Trace](image)

Figure 3: A On-Off-On torque trace on a previously installed bolt/nut assembly

5. THE EFFECT OF MAGNITUDE OF THE COEFFICIENT OF FRICTION

As can be observed from the torque-tension equation, the magnitude of the torque needed to stretch the fastener is a function of the clamp force \( F \) and the thread pitch \( p \). It is not a function of the friction conditions. As the coefficient of friction exhibited by the fastener increases so does the proportion of the applied torque that is being absorbed by friction and hence, the percentage of the applied torque that is being used to stretch the fastener decreases. This is illustrated in figure 4. With a highly effective lubricant, the coefficient of friction is in the order of 0.06. Under these conditions, 25% or so of the applied torque is used to stretch the fastener. Accordingly, normal variation in the friction conditions of the fastener system between the tightening and untightening directions that will reflect in differences in the on-torque and off-torque values, will result in the On-Off-On auditing check remaining reasonably accurate.
At the other extreme, when the coefficient of friction is 0.35 or higher, which is typical of dry galvanized fasteners or fasteners which have experienced some corrosion, the proportion of the applied torque being absorbed by friction is in the order of 95%. As such, slight changes in the coefficient of friction that can occur between the tightening and untightening phases of the auditing process, can have a significant effect on the accuracy of the clamp force prediction.

![Figure 4](image)

In actual practice, the majority of fasteners tightened for the first time typically have a range in the coefficient of friction of between 0.08 to 0.18. Limits on the upper value of the coefficient of friction are based upon two main considerations:

1. Higher friction means that a higher torque value is required to achieve a given clamp force. High torque values require larger tools and/or more effort.
2. Higher thread friction results in a higher torsional stress in the thread. High torsional stresses can suppress the clamp force that can be delivered by a fastener since yielding occurs as a consequence of the tensile stress (from the clamp force) and torsional stress (from the thread friction). A higher torsional stress reduces the tensile stress component under yield conditions with the subsequent reduction in the achievable clamp force.

There is a concern at very low values of the coefficient of friction (<0.08) that the fasteners will readily self-loosen. These two factors are the reason why the majority of the major automotive manufacturers specify that fasteners which they use have to have a coefficient of friction in the range 0.08 to 0.18. (Different manufacturers have different ranges, a typical range being 0.12 to 0.18.)

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

Depending upon the method of applying the torque [5], the scatter in the bolt load can vary between $\pm 17\%$ (precision torque wrench with the torque value experimentally determined) to $\pm 33\%$ (applied with a torque wrench with the torque determined by estimation of the friction conditions). The variation in bolt load is largely due to the variation in the fastener's coefficient of friction rather than the accuracy of the applied torque value. The typical accuracy of the On-Off-On tightness auditing method is well within these limits.

The tests conducted indicate that when the fastener coefficient of friction is low (<0.08), the On-Off-On tightness auditing method is an accurate prediction of the load in the bolt. With fasteners displaying typical values of the
coefficient of friction (0.12 to 0.18), the tests indicate that the method is a good indicator of the bolt load. At high friction values (>0.25), such as may be displayed by corroded bolts, the approach has limited potential.

There are some anomalies in the test results. Typically the coefficient of friction determined for the tightening direction is less than that in the untightening direction. This may be due to friction changes due to surface damage [4] or an increase in the effective nut bearing diameter in the untightening direction.

The On-Off-On tightness auditing method is more accurate when:
- Well lubricated fasteners are used which have inherently low friction values.
- The auditing process is conducted after a relatively short period of time after the fastener installation.

The on-off-on tightness auditing method would tend to be less accurate when:
- The fasteners are not lubricated and have an inherently high friction, for example, a galvanized finish without a lubricant being used.
- A significant period of time has elapsed since the fastener installation and the operating environment is such that corrosion is likely to occur.

Establishing what load/torque that the bolts in a joint should be tightened to can be problematic for some maintenance activities. Hot bolting is a term that is used to describe the process in which one or more bolts are replaced from an existing joint in-situ, often with the joint under load and, potentially, at an elevated temperature. Good practice is to complete a risk assessment but risk cannot be eliminated due to the difficulties in establishing what load the bolts should be tightened to allowing for the influences of temperature and loading. The On-Off-On method could potentially provide important information about the load the existing bolts are sustaining allowing the torque that a new bolt should be tightened to be better estimated.

Measuring the on-torque alone can be a poor indicator of the retained clamp force of the joint. It is frequently used since usually there is no practical alternative. In short, for most applications the conventional torque auditing approach can be effectively used (that is, measuring the torque needed to fractionally rotate the fastener in the tightening direction), the On-Off-On tightness auditing method can also be implemented. A major advantage of the on-off-on tightness auditing approach is that additional information can be derived regarding the integrity of the joint without a significant change being made to existing working practices. Establishing the likely retained clamp force present in a joint can be a crucial factor in determining whether the structural integrity of the assembly is likely to be satisfactory, or likely to be impaired. As such, this new approach is an important tool in ensuring product safety and reliability. There are limitations to this new approach to fastener tightness auditing, principally its accuracy in high friction conditions, but it is a useful indicator as to the retained fastener clamp force in many circumstances.

REFERENCES