Experimental and theoretical investigation of bending over sheave fatigue life of stranded steel wire rope

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Steel wire ropes are used in elevators, cranes, mine hoistings, bridges, offshore and aerial ropeway systems. In this study, bending over sheave (BoS) fatigue lifetimes of 6 × 36 Warrington-Seale steel wire ropes have been determined theoretically and experimentally. Experimental studies have been performed to show effects of tensile load and sheave diameter parameters on BoS fatigue lifetimes of 6 × 36 Warrington-Seale steel wire ropes. Besides, a multiple linear regression model has been devised and novel theoretical BoS fatigue life prediction equation has been presented by using the least square method. The results indicate that there is a powerful correlation between the results obtained by theoretical model and experimental data. The BoS fatigue lifetime results can be used in the range of specific tensile loads investigated and diameter ratios used with acceptable error.

Keywords: Bending over sheave, Fatigue, Steel wire rope, Regression analysis

Steel wire ropes are frequently used in elevators, cranes, mine hoistings, bridges, offshore and aerial ropeway systems. Steel wire ropes include many wires that wrapped to the fibre or wire core in order to form a strand. Several of strands are then twisted together to form rope. There has been great interest in rope technology area since application area of steel wire ropes becomes vast. In the application area, steel wire ropes are mainly subjected to fatigue since either ropes incur to the altering loads with time such as bridge or repetitive move on the sheaves such as cranes. First issue is called by tension-tension fatigue where ropes incur to the altering tensile load. Second issue is called by BoS fatigue where ropes incur to the repetitive bending combined with static tensile load. Schematic illustration of test machines that includes two stress regimes (tension-tension fatigue and BoS fatigue) for steel wire ropes has been shown in Fig. 1. Authors investigated BoS fatigue lifetimes of steel wire ropes. Many investigations have been conducted to identifying effect of BoS fatigue to the lifetime of the steel wire ropes. Ridge et al. examined effects of simulated degradations (wire breaks, abrasive wear, slack wires, slack strands, plastic wear, corrosion, torsional imbalance) to the BoS fatigue endurance of steel wire ropes. Urchegui et al. examined wear evolution in a 6 × 19 Seale stranded rope subjected to bending fatigue. Torkar and Arzensek conducted bending fatigue tests of wires located in outer strands of 6 × 19 Seale rope. Gorbatov et al. investigated effects of some parameters (core type of wire rope, lubricant type, tensile load) to the bending fatigue life of 6 × 36 Warrington-Seale rope with 16 mm diameter. Feyrer's book presented state of art review and experimental test results of steel wire ropes.
subjected to BoS fatigue. Author examined effects of various parameters (rope core type, lubrication, tensile load, bending length, sheave diameter, zinc coating, sheave geometry and material, side deflection, winding angle) to the BoS fatigue life of steel wire ropes. Giglio and Manes\textsuperscript{7} investigated effect of winding angle parameter between rope and sheave to the bending fatigue life of $19 \times 7$ non-rotating rope, which may be used in aircraft rescue hoists, that has nineteen strands and each strand has seven wires. Argatov \textit{et al.}\textsuperscript{8} focused on fretting wear severity and contact patches have a significant influence on rope degradation and fatigue life. Kurashov \textit{et al.}\textsuperscript{9} performed comparative tests to investigate bending fatigue life of steel wire ropes with various types of core and impregnated with various preservative compounds. Zhihui and Jiquan\textsuperscript{10} put effort to improve security and efficiently using of wire ropes and therefore authors discussed fatigue failure behaviors of wire ropes caused by bending over sheave focusing on analysis of mechanisms of wire rope mechanical damage caused by fleet angle and angle of wrap.

Effects of tensile load ($S$) and sheave diameter ($D$) to the BoS fatigue lifetimes of $6 \times 36$ Warrington-Seale steel wire ropes have been determined experimentally. Experimental findings have critical importance in identifying behaviour of wire rope subjected to bending over sheave fatigue. Eight different tensile loads and two sheaves with different diameters have been employed for BoS fatigue tests. Feyrer equations have been used to predict lifetime theoretically of $6 \times 36$ Warrington-Seale rope subjected to BoS fatigue. In addition a multiple linear regression model has been devised by using experimental test data and a novel theoretical BoS fatigue life prediction equation has been presented.

**Experimental Procedure**

**Test machine**

Experimental tests have been performed in the Rope Technology Laboratory of Institute of Mechanical Handling and Logistics (Institut für Fördertechnik und Logistik (IFT), University of Stuttgart, Germany) so as to determine effects of tensile load and sheave diameter to the BoS fatigue life of steel wire rope running with sheaves. Figure 2 shows test machine used in this study.

BoS fatigue test bench comprises of electric motor, test sheave, drive sheave, leverage, rotation speed adjustment button (4) and additional machine elements helping to run. Motor (3) produces the power on test machine. Samples are located between drive sheave (1) and test sheave (2) by means of lead casting end connections. Constant tensile load, $S$, on the test sheave is maintained by leverage (5) and additional weights in order to simulate real working conditions. Thus, rope samples are loaded by constant tensile during the test. The bigger sheave is drive sheave which drives the rope sample at the certain cyclic length and smaller one is test sheave. BoS fatigue occurs at the contact length between test sheave and rope which is $30d$ in length ($d$ is diameter of rope in mm). Rotation speed was 1250 rev/h for experimental tests\textsuperscript{2}.

**Investigated rope**

In this study, steel wire rope samples with 10 mm in diameter ($d$) have been used. Investigated steel wire rope construction is $6 \times 36$ Warrington-Seale (WS) rope with Independent Wire Rope Core (IWRC). Characteristic properties of rope samples are given in Table 1. Investigated rope construction has six strands around a steel core which is a wire rope itself. $6 \times 36$ Warrington-Seale rope with IWRC can be used by mine hoisting, oil industry, cranes etc. $6 \times 36$ Warrington-Seale rope construction offers optimum resistance in fatigue and crushing. Cross-section of $6 \times 36$ Warrington-Seale rope with IWRC used in this study is shown in Fig. 3.

**Bending over sheave fatigue tests**

BoS fatigue tests have been conducted by test machines which are located in Rope Technology Laboratory of Institute of Mechanical Handling and Logistics (Institut für Fördertechnik und Logistik

<table>
<thead>
<tr>
<th>Table 1—Technical properties of $6 \times 36$ Warrington-Seale rope\textsuperscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strand number</strong></td>
</tr>
<tr>
<td><strong>Construction</strong></td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
</tr>
<tr>
<td><strong>Wire grade</strong></td>
</tr>
<tr>
<td><strong>Lay type</strong></td>
</tr>
<tr>
<td><strong>Filling factor</strong></td>
</tr>
<tr>
<td><strong>Minimum breaking load (MBL)</strong></td>
</tr>
</tbody>
</table>
Rope samples were moulded by lead casting cones on each end and connected to backing rope so as to form a loop which is necessary for the test. In this study, eight different tensile loads and two sheaves with different diameters have been employed for BoS fatigue tests to determine effects of tensile load and sheave diameter to the BoS fatigue lifetimes of 6 × 36 WS rope with 10 mm diameter. Sheaves with 250 mm and 100 mm in diameter have been used. Tensile loads which are 15 kN, 20 kN, 25 kN and 30 kN have been employed when sheave with 250 mm in diameter is used and tensile loads which
are 10 kN, 15 kN, 20 kN and 25 kN have been employed when sheave with 100 mm in diameter is used in the BoS fatigue tests. It is noted that tensile load and sheave diameter affect to the BoS fatigue lifetime of steel wire ropes. Therefore, identical sheave diameter shall be used if effect of tensile load to the BoS fatigue lifetime is wanted to determine. In addition identical tensile load shall be used if effect of sheave diameter to the BoS fatigue lifetime is wanted to determine. Consequently, effect of sheave diameter to the BoS fatigue lifetime have been obtained by holding certain tensile loads as identical which are 15 kN, 20 kN and 25 kN and effect of tensile load to the BoS fatigue lifetime have been obtained by holding sheave diameter as identical in the experimental tests.

**Theoretical Investigations**

**Feyrer estimation**

Theoretical BoS fatigue life estimations have been done by using Feyrer equations that are given in Eqs (1) and (2). First equation includes specific tensile load (\(S/d^2\)), diameter ratio (\(D/d\)) parameters and unit tensile load and unit diameter are considered as \(S_0 = 1\) N, \(d_0 = 1\) mm respectively.

\[
\log(N) = a_0 + a_1 \log\left(\frac{S d_0^2}{S_0^2 d^2}\right) + a_2.
\]

... (1)

\[
\log\left(\frac{D}{d}\right) + a_3 \log\left(\frac{S d_0^2}{S_0^2 d^2}\right) \log\left(\frac{D}{d}\right)
\]

Second equation includes specific tensile load, diameter ratio, wire grade (\(R_o\)), bending length (\(l\)) and rope diameter (\(d\)) parameters that are parameters affecting to the rope’s lifetime.

\[
\log(N) = b_0 + b_1 \log\left(\frac{S}{d^2}\right) - 0.4 b_1 \log\left(\frac{R_o}{1770}\right) + b_2 \log\left(\frac{D}{d}\right) + b_3 \log(d)
\]

... (2)

\[
+ b_4 \log\left(\frac{S}{d^2}\right) \log\left(\frac{D}{d}\right) - 0.4 b_4.
\]

\[
\log\left(\frac{D}{d}\right) \log\left(\frac{R_o}{1770}\right) + \frac{1}{b_5} \log\left(\frac{l}{d}\right)
\]

The constants (\(a_i, b_i\)) produced in Eqs (1) and (2) are given in Feyrer's book\(^6\). Constants and parameters for 6 × 36 WS rope are given in Table 2.

Feyrer proposes that the numbers of bending cycles calculated by means of using constants in Table 2 are valid for up to a few million bending cycles under the following conditions: the wire rope samples are well-lubricated, the sheaves have steel grooves, groove radius-rope diameter ratio (\(r/d\)) is 0.53, there is no side deflection, it is in dry environment. If there are different conditions in operation correction factors must be used to determine final BoS fatigue life calculation. As a specific condition for 6 × 36 WS rope investigated there must be an addition correction factor since constants presented in Table 2 are for 8 × 36 Warrington-Seale rope with IWRC core. Rope investigated in this study has 6 strands so that theoretically predicted results have been corrected by multiplying with 0.81. This correction factor also has been presented in Feyrer's book\(^6\).

**Regression analysis**

Regression analysis is used to investigate the relation between dependant variable and independent variable(s). First phase of the regression analysis is to find the best mathematical model definition. In this study, dependent variable is BoS fatigue life, \(N\), of 6 × 36 WS rope. There are two independent variables which are specific tensile load (\(S/d^2\)) and diameter ratio (\(D/d\)). Since there are multiple independent variables authors propose multiple linear regression model adhering to the Feyrer equations. General form of multiple linear regression model has been shown in Eq. (3)\(^1\).

\[
\log(N_i) = a_0 + a_1 \log(x_i) + a_2 \log(y_i) + a_3 \log(z_i) \log(y_i) + \epsilon_i
\]

... (3)

where \(a_i\)'s are constants, \(x_i\) is dimensionless specific tensile load \(S.d_o^2/S_o^2 d^2\) (N/mm\(^2\)), \(y_i\) is diameter ratio \(D/d\), \(\epsilon_i\) is residual term. To expedite regression analysis progress, Eq. (3) can be expressed as Eq. (4).

| Table 2—Constants and parameters used for 6 × 36 Warrington-Seale rope |
|---|---|
| \(d\) (mm) | 10 |
| \(R_o\) (N/mm\(^2\)) | 1960 |
| \(l\) (mm) | 600 |
| \(a_0\) | 1.277 |
| \(a_1\) | 0.029 |
| \(a_2\) | 6.241 |
| \(a_4\) | -1.613 |
| \(b_0\) | 1.327 |
| \(b_1\) | 0.029 |
| \(b_2\) | 6.241 |
| \(b_3\) | -0.32 |
| \(b_4\) | -1.613 |
| \(b_5\) | 1.2 |
\[ \log(N_i) = a_0 + a_1x_i + a_2y_i + a_3z_i + \epsilon_i \quad \ldots (4) \]

where \(\log(x_i) = x_i, \log(y_i) = y_i\) and \(\log(z_i) = z_i\).

To constitute a novel theoretical prediction equation authors used the least square method. The least square method is the one of the most convenient method for curve fitting. The best fit in the least square method means that minimize the sum of squared residuals. Minimum of the sum of residual squares is found by resolving the gradient and equalizing them to zero. Four equations can be obtained including consecutive sum of the terms containing \(N_i, x_i, y_i\) and \(z_i\). Final equation set is given in Eq. (5).

\[
\sum_{i=1}^{n} \log(N_i) = a_0n + a_1\sum_{i=1}^{n} x_i + a_2\sum_{i=1}^{n} y_i + a_3\sum_{i=1}^{n} z_i \\
\sum_{i=1}^{n} x_i \log(N_i) = a_0\sum_{i=1}^{n} x_i + a_1\sum_{i=1}^{n} x_i^2 + a_2\sum_{i=1}^{n} x_i y_i + a_3\sum_{i=1}^{n} x_i z_i \\
\sum_{i=1}^{n} y_i \log(N_i) = a_0\sum_{i=1}^{n} y_i + a_1\sum_{i=1}^{n} y_i x_i + a_2\sum_{i=1}^{n} y_i^2 + a_3\sum_{i=1}^{n} y_i z_i \\
\sum_{i=1}^{n} z_i \log(N_i) = a_0\sum_{i=1}^{n} z_i + a_1\sum_{i=1}^{n} z_i x_i + a_2\sum_{i=1}^{n} z_i y_i + a_3\sum_{i=1}^{n} z_i^2 \\
\]

where \(n\) is the number of experiments.

Thus \(a_i\) terms can be found by solving Eq. (3). The experimental results are shown in Table 3. These experimental results have been used to determine constants.

### Table 3—Logarithmic test results for \(6 \times 36\) Warrington-Seale rope

<table>
<thead>
<tr>
<th>(\log(N_i))</th>
<th>(x_i)</th>
<th>(y_i)</th>
<th>(z_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.213</td>
<td>2.176</td>
<td>1.398</td>
<td>3.042</td>
</tr>
<tr>
<td>4.938</td>
<td>2.301</td>
<td>1.398</td>
<td>3.216</td>
</tr>
<tr>
<td>4.842</td>
<td>2.398</td>
<td>1.398</td>
<td>3.352</td>
</tr>
<tr>
<td>4.585</td>
<td>2.477</td>
<td>1.398</td>
<td>3.462</td>
</tr>
<tr>
<td>4.512</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4.443</td>
<td>2.176</td>
<td>1</td>
<td>2.176</td>
</tr>
<tr>
<td>4.119</td>
<td>2.301</td>
<td>1</td>
<td>2.301</td>
</tr>
<tr>
<td>3.670</td>
<td>2.398</td>
<td>1</td>
<td>2.398</td>
</tr>
</tbody>
</table>

Experimental BoS fatigue life results for \(6 \times 36\) Warrington-Seale rope are given in Table 5.

### Table 4—Consecutive sum of the terms

<table>
<thead>
<tr>
<th>(\sum x_i)</th>
<th>(\sum y_i)</th>
<th>(\sum z_i)</th>
<th>(\sum x_i^2)</th>
<th>(\sum y_i^2)</th>
<th>(\sum z_i^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sum x_i y_i)</td>
<td>(\sum x_i z_i)</td>
<td>(\sum y_i z_i)</td>
<td>(\sum \log(N_i))</td>
<td>(\sum x_i \log(N_i))</td>
<td>(\sum y_i \log(N_i))</td>
</tr>
<tr>
<td>21.9491</td>
<td>50.41286</td>
<td>27.14966</td>
<td>36.322</td>
<td>82.64443</td>
<td>44.11404</td>
</tr>
<tr>
<td>(\sum z_i \log(N_i))</td>
<td>100.8127</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Experimental results have been used to determine \(N_i, x_i, y_i\) and \(z_i\) is given in Table 4. The novel theoretical prediction equation by using the least square method is given in Eq. (6).

\[
\log(N) = 6.7674 - 2.2308.\log\left(\frac{S}{d^2}\right) + 1.941.\log\left(\frac{D}{d}\right)
+ 0.1925.\log\left(\frac{S}{d^2}\right).\log\left(\frac{D}{d}\right) \\
\]

### Results and Discussion

Experimental tests have been performed in compliance with DIN 15020-2 standard. BoS fatigue lifetimes \(N\) of \(6 \times 36\) WS ropes which are obtained by reading counter device when one outer strand break occurs in simple bending cycles have been presented. BoS fatigue lifetime results of \(6 \times 36\) Warrington-Seale ropes are given in Table 5.

It can be concluded that BoS fatigue lifetime of \(6 \times 36\) WS rope reduces as tensile load increases. BoS fatigue lifetime reduces 47% if tensile load is increased from 15 kN to 20 kN (for \(D=250\) mm). BoS fatigue lifetime reduces 20% if tensile load is increased from 20 kN to 25 kN (for \(D=250\) mm). BoS fatigue lifetime reduces 45% if tensile load is increased from 25 kN to 30 kN (for \(D=250\) mm). BoS fatigue lifetime reduces 15% if tensile load is increased from 10 kN to 15 kN (for \(D=100\) mm). BoS fatigue lifetime reduces 53% if tensile load is increased from 15 kN to 20 kN (for \(D=100\) mm). BoS
Experimental tests. Feyrer’s theoretical estimation have been used to compare the results obtained by holding certain tensile loads as identical which are 15 kN, 20 kN and 25 kN. BoS fatigue test results for 6 × 36 WS rope indicates that BoS fatigue lifetime reduces 93% if tensile load becomes 25 kN and in case of using the sheave with 100 mm in diameter instead of using the sheave with 250 mm in diameter. BoS fatigue lifetime reduces 85% if tensile load becomes 25 kN and in case of using the sheave with 100 mm in diameter instead of using the sheave with 250 mm in diameter. BoS fatigue lifetime reduces 93% if tensile load becomes 25 kN and in case of using the sheave with 100 mm in diameter instead of using the sheave with 250 mm in diameter. Results indicate that BoS fatigue lifetime of 6 × 36 WS rope reduces substantially when the sheave with smaller diameter is used.

In addition to experimental studies Feyrer equations have been used to compare the results obtained by experimental tests. Feyrer’s theoretical estimation results for same parameter pertained to experimental studies are given in Table 6. Where \( N_{\text{feyrer1}} \) is the theoretical results obtained by using Eq. (1), \( N_{\text{feyrer2}} \) is the theoretical results obtained by using Eq. (2). \( R_0 \) is wire grade (N/mm²), \( l \) is bending length (mm).

It can be observed from Table 6 that Feyrer’s estimation equation presented in Eq. (2) for 6 × 36 WS rope gives more reliable results than Eq. (1). Feyrer’s second estimation equation (Eq. (2)) includes addition parameters affecting to the rope’s lifetime such as rope diameter, bending length and wire grade than Feyrer’s first estimation equation (Eq. (1)). Apart from the condition that specific tensile load \( (S/d^2) \) becomes 250 N/mm² and diameter ratio \( (D/d) \) becomes 10 all of the Feyrer’s theoretical prediction results become less than experimental results.

Therefore it can be concluded that Feyrer’s theoretical estimation results can be used by acceptable error considering safety requirements.

The results obtained by using novel theoretical prediction equation (Eq. (6)) and the experimental results are given in Table 7.

In statistics, in order to check the validity of the theoretical prediction equation the coefficient of determination \( (r^2) \) and correlation coefficient \( (r) \) are determined. These coefficients are obtained by using equations reported elsewhere. The coefficient of determination \( (r^2) \) and the correlation coefficient \( (r) \) have been found as 0.95 and -0.974, respectively. Negative value for the correlation coefficient means that experimental results are direction of descending. There is a powerful correlation between the results obtained by theoretical model presented and the experiment results since the correlation coefficient converges to 1. When correlation coefficient becomes 1 there is absolute perfection. It is impossible in nature.

Theoretical and experimental results including regression analysis results are shown in Fig. 4.

Where Feyrер1 is theoretical results obtained by using Feyrer’s first estimation equation (Eq. (1)). These results are given in Table 6 as \( N_{\text{feyrer1}} \). Feyrer2 is theoretical results obtained by using Feyrer’s second estimation equation (Eq. (2)). These results are given in Table 6 as \( N_{\text{feyrer2}} \). Theoretical denotes in Table 7 as \( N_{\text{theoretical}} \).

In this study, certain tensile loads and the sheave diameters have been used to determine BoS fatigue lifetime of 6 × 36 WS rope. There is a way to generalize the results by using the specific tensile load \( (S/d^2) \) and diameter ratio \( (D/d) \) parameters instead of using tensile load \( (S) \) and sheave diameter \( (D) \) parameters. Theoretical and experimental results can be generalized by means of Fig. 4. For example if

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
S/d^2 & D/d & N_{\text{feyrer1}} & N_{\text{feyrer2}} & N_{\text{test}} & N_{\text{theoretical}} \\
\hline
150 & 25 & 11073 & 60 & 5272 & 4684 \\
200 & 25 & 11073 & 60 & 5272 & 4684 \\
250 & 25 & 11073 & 60 & 5272 & 4684 \\
300 & 25 & 11073 & 60 & 5272 & 4684 \\
350 & 25 & 11073 & 60 & 5272 & 4684 \\
400 & 25 & 11073 & 60 & 5272 & 4684 \\
450 & 25 & 11073 & 60 & 5272 & 4684 \\
500 & 25 & 11073 & 60 & 5272 & 4684 \\
550 & 25 & 11073 & 60 & 5272 & 4684 \\
600 & 25 & 11073 & 60 & 5272 & 4684 \\
650 & 25 & 11073 & 60 & 5272 & 4684 \\
700 & 25 & 11073 & 60 & 5272 & 4684 \\
750 & 25 & 11073 & 60 & 5272 & 4684 \\
800 & 25 & 11073 & 60 & 5272 & 4684 \\
850 & 25 & 11073 & 60 & 5272 & 4684 \\
900 & 25 & 11073 & 60 & 5272 & 4684 \\
950 & 25 & 11073 & 60 & 5272 & 4684 \\
1000 & 25 & 11073 & 60 & 5272 & 4684 \\
1050 & 25 & 11073 & 60 & 5272 & 4684 \\
1100 & 25 & 11073 & 60 & 5272 & 4684 \\
1150 & 25 & 11073 & 60 & 5272 & 4684 \\
1200 & 25 & 11073 & 60 & 5272 & 4684 \\
1250 & 25 & 11073 & 60 & 5272 & 4684 \\
1300 & 25 & 11073 & 60 & 5272 & 4684 \\
1350 & 25 & 11073 & 60 & 5272 & 4684 \\
1400 & 25 & 11073 & 60 & 5272 & 4684 \\
1450 & 25 & 11073 & 60 & 5272 & 4684 \\
1500 & 25 & 11073 & 60 & 5272 & 4684 \\
\hline
\end{array}
\]
6 × 36 Warrington-Seale rope is 16 mm in diameter, sheave diameter is 400 mm in diameter and tensile load is 38.40 kN, results presented in this study can be used since authors presented the BoS fatigue lifetime results for the identical parameters that are \( S/d^2 = 150 \) and \( D/d = 25 \). Figure 4 presents the BoS fatigue lifetime results in the range of 150 N/mm\(^2\) - 300 N/mm\(^2\) specific tensile loads for \( D/d = 25 \) and in the range of 100 N/mm\(^2\) - 250 N/mm\(^2\) for \( D/d = 10 \). BoS fatigue life results can be used in the range of specific tensile loads investigated and diameter ratios \( (D/d) \) used with acceptable error.

**Conclusions**

Tensile load and the sheave diameter affect to the BoS fatigue lifetime substantially. BoS fatigue life reduces as tensile load increases. The BoS fatigue lifetime reduces as the sheave with smaller diameter is used. Feyrer’s theoretical estimation equations can be used by acceptable error considering safety requirements. Presented theoretical prediction equation has powerful correlation with experimental results. The BoS fatigue lifetime results can be used in the range of specific tensile loads \( (S/d^2) \) investigated and diameter ratios \( (D/d) \) used with acceptable error.

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