ABSTRACT: This research through the tests of bending property of a certain steel wire rope in the conditions of no tension state and tension state, obtained a correlation between the bending performance and wire rope tension, defined a gain tension coefficient (k) to the bending stiffness of wire rope, then open a way to research steel wire rope, and developed steel wire rope tension measurement method by three points bending.

1 INSTRUCTION

Wire rope, which belongs to important special equipment in our country, is the key component of elevator and crane, which’s number accounts for over 50% of the national special equipment. And wire rope is also an important part of a mine hoist. In the coal industry, wire rope break accident ranks the third, followed closely flooding and gas accident. Wire rope fracture accidents have occurred frequently, the fundamental reason is lack of reliable wire rope safety inspection and evaluation standards.[1]

Wire rope tension measurement, developed nearly 100 years, from the original concatenated sensor to three points bending test, and then to electromagnetic nondestructive testing, tension measuring method renewed with each passing day. But due to the special structure of steel wire rope, structural changes that happen in use, accurate measurement of tension is a still international engineering problem.

Based on the principle of tension test by three points bending on the wire rope, we researched the bending properties in two kinds of working condition, as no tension state and tension state, got the new formula for measuring, and the three points bending method has been developed.[2][3]

2 EXPERIMENT

2.1 Experiment preparation

The three point bending test experiment mainly divided into two parts, under no tension state and tension state. Three point bending test is that put a certain length of the specimen on two parallel rolls, then apply pressure downward vertically above the specimen in the central, make the specimen bend under two rollers and a pressure head, as shown in figure 1. The displacement and stress curve of pressure head in the central can reflects the bending properties of the specimens.

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2.2 Test preparation

Wire rope: Cut two specimens randomly from a steel wire rope which’s diameter is 16mm and type is 6x37 SZ+IWR. One is for no tensile test, which’s total length is 310mm; another one is for tension test, which’s total length is 1400mm.
The experiment was carried out in an electronic universal testing machine, which can provide vertical downward pressure; but for applying transverse tension on the both ends of specimens, we need to build a stretch test-bed at the bottom of the machine. The method of applying transverse tension on steel wire rope is as fig.2.

Form both ends of the wire rope into rings, locked the rope buckles on, left ring set on the fixed bracket, the right ring link into a ring nut, which linked into a lead screw, which goes through a hollow tension-compression sensor, which pressures on the right bracket, then tighten nut on the right of sensor to make wire rope in a state of tension. So the tension S in the wire rope is converting to pressure on sensor. As shown in figure 2:

2.3 Three point bending test under no tension state:

Take the rope which is 310mm long on the rollers belongs to three point bending tester, changed span to 120mm, 140mm and 160mm, and measured the bending property on each span repeating three times. It’s turned out that the curves of repeated bending test under the same span are almost exactly the same. Thus, list one P-y curve of each same span in the three groups of test, as shown in figure 4.

Data curves showed that after the transient nonlinear phase in the initial of bending, there comes a very stable linear relationship the stress P and deflection y.

As the deflection differential equation from Mechanics of Materials: \[ y(x) = \frac{Pbx}{6EI} \left( l^3 - x^3 - b^3 \right) (0 \leq x \leq a) \]

Take the linear phases of P-y curve for calculation, then:

\[ EI = \frac{l^3}{48} \frac{\Delta P}{\Delta y} \]

The \( \Delta P \) refers to the load increase of the midpoint, and the \( \Delta y \) refers to the deflection increase of the midpoint.

In the linear phase of the experiment, the value of \( \Delta P/\Delta y \) is listed in the following table1:

<table>
<thead>
<tr>
<th>l (mm)</th>
<th>( \Delta P/\Delta y (N/mm) )</th>
<th>EI(N.mm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>23.743</td>
<td>854730</td>
</tr>
<tr>
<td>140</td>
<td>15.31</td>
<td>875221</td>
</tr>
<tr>
<td>160</td>
<td>10.28</td>
<td>877226</td>
</tr>
</tbody>
</table>

Summary: under the span of 120-160, the differences amongst stiffness values are far smaller. We can assume the stiffness of wire rope is stable, in the span range of 120-160, in the no tension condition.
2.4 Three points bending test under tension state:

2.4.1 The first group: test setting span as 160mm
Take the 1400mm long wire rope, form both ends of the wire rope into rings, then put it on the stretch test-bed which is in the intermediate position at the bottom of the universal testing machine, then set the span to 160mm, load different tension, measured bending properties by the universal testing machine. As shown in figure 6:

In the experiment, press down the pressure head (value is P) to bend the wire rope, at midpoint the deflection y increase, tension S increased gradually at the same time, but in a small range, and there also is obvious linear phases in the P-y curves of tests, the experiments take the average tension of the linear phase as reference value.

Adjust the span to 160mm; apply a certain tension S as initial value.

Apply different initial tensions; do three point bending tests, select 7 sets of data from the experiments randomly at a certain tension interval which is from 0.2kN to 0.6kN. The tension S labeled after the test number is average tension of P-y curves in the linear stages.

In the absence of tension cases (i.e., tension S is 0), P-y curve is expressed by the formula (a). In view of this, try to use a similar formula to represent curves when the tension is not 0, in the linear phase:

Make the \( (EI)/S = EI/k \), let the coefficient k be a function of tension S, EI is wire rope’s bending stiffness value under no tension. Calculation formula about k is as follows:

\[
k = \frac{P^3}{48EI} \left( \frac{1}{\Delta y / \Delta P} \right)
\]

At the right of equation above, the value of span l and static stiffness EI are both known, in the case of known tension S, test to get the corresponding value of \( \Delta y / \Delta P \), so you can calculate the value of coefficient k, as the table 2.

Analysis turns out that tension S have very stable linear relationship with coefficient k, the fitting result is as figure 9:

The fitting results: \( k_{160}=3.9S+2.7 \)

Substituted,

\[
3.9S + 2.7 = \frac{P^3}{48EI} \cdot \frac{\Delta P}{\Delta y}
\]

This formula is fitted by three point bending test when the span is 160mm, to measure the wire rope tension.

Summary:

With no tension, bending formula is

\[
y = \frac{P l^3}{48EI}
\]

With tension, bending formula is

\[
y = \frac{P l^3}{48(EI)/S} = \frac{P l^3}{48EIk} (k = 3.9S + 2.7)
\]

Coefficient k expressed the gain effect well of wire rope bending stiffness EI under the influence of tension S.

When S = 0, two formulas are not the same, this may be due to the special structure of the steel wire
rope, therefore the empirical formula has a certain scope of application.

Similarly, obtained formulas by experiments setting span as 140mm, 120mm, and specific process is as follows:

2.4.2 The second group: test setting span as 140 mm
List 8 sets of data from the experiments setting span as 140mm in the figure10.
As the test data, calculated values of k list in the table3.
The fitting results: \( k_{140} = 3.4S + 2 \)
Substituted,
\[
3.4S + 2 = \frac{f^3}{48EI} \cdot \frac{\Delta P}{\Delta y}
\]
This formula is fitted by three point bending test when the span is 140mm, to measure the wire rope tension.
Similarly, tension S has very stable linear relationship with coefficient k, fitted in figure12.

2.4.3 The third group: span test of 120mm span
List 8 sets of data from the experiments setting span as 120mm as in fig.13.
As the test data, calculate values of k and list in the table 4.
Similarly, tension S has very stable linear relationship with coefficient k, fitted as fig.15.
The fitting results: \( k_{120} = 2.87S + 2 \)
Substituted,
\[
2.9S + 2 = \frac{f^3}{48EI} \cdot \frac{\Delta P}{\Delta y}
\]
This formula is fitted by three point bending test when the span is 120mm, to measure the wire rope tension.

![Figure 12. Relationships between coefficient k and tension.](image)

![Figure 10. Stretch bending curve under 140mm span.](image)

![Figure 11. Linear relationship of \( \Delta y/\Delta P \) and \( 1/S \).](image)

![Figure 13. Stretch bending curve under 120mm span.](image)

![Figure 14. Linear relationship of \( \Delta y/\Delta P \) and \( 1/S \).](image)

<table>
<thead>
<tr>
<th>Table 3. Values of k while span is 140mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S(kN)</td>
</tr>
<tr>
<td>1.23</td>
</tr>
<tr>
<td>1.69</td>
</tr>
<tr>
<td>2.09</td>
</tr>
<tr>
<td>2.47</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4. Values of k while span is 120mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S(kN)</td>
</tr>
<tr>
<td>1.10</td>
</tr>
<tr>
<td>1.48</td>
</tr>
<tr>
<td>1.73</td>
</tr>
<tr>
<td>2.09</td>
</tr>
</tbody>
</table>
3 RESULTS AND DISCUSSION

3.1 Three groups of results

Integrated the fitting results of three groups of experiments in the table:

Table 5. Fitting results of three groups of combination of stretch bending test.

<table>
<thead>
<tr>
<th>Span l (mm)</th>
<th>Direct fitting formula</th>
<th>((EI)_S = EI k = \frac{P}{48} \cdot \frac{\Delta P}{\Delta y})</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>(\frac{\Delta y}{\Delta P} = \frac{13}{S} + 2.78)</td>
<td>k=4S+2.5</td>
</tr>
<tr>
<td>140</td>
<td>(\frac{\Delta y}{\Delta P} = \frac{9.29}{S} + 2.65)</td>
<td>k=3.25+2.4</td>
</tr>
<tr>
<td>120</td>
<td>(\frac{\Delta y}{\Delta P} = \frac{8}{S} + 1.33)</td>
<td>k=2.95+2</td>
</tr>
</tbody>
</table>

3.2 Analysis of test

As stretch bending curves of the three groups of stretch bending tests showed, \(\Delta y/\Delta P\) ratio decreases when tension \(S\) increases in the linear phase. Looked into the figures of linear relationship of \(\Delta y/\Delta P\) and 1/S of three groups of experiments, it turns out that \(\Delta y/\Delta P\) ratio have a linear relationship with the reciprocal of tension \(S\) (i.e. 1/S) in the linear phase.

4 CONCLUSIONS

1. Defined the stiffness gain coefficient \(k\) through test, and got quantitative description about the appearances of stiffness’ increasing related to the axial tension.

2. In bending test under tension state, the wire rope’s P-y curve has very obvious linear phase.

3. In linear phase, values of \(\Delta y/\Delta P\) have very stable linear relationship with 1/S, so this can set up empirical formula, obtained tension \(S\) from values of \(\Delta y/\Delta P\).

4. The experiments get two kinds of feasible methods for measuring internal wire rope tension: one is through the bending test with known tension values, calibrate the relationship between \(\Delta y/\Delta P\) and 1/S, get the fitting formula, then measure tension \(S\) by value of \(\Delta y/\Delta P\); another one is through the determination of bending stiffness \(EI\) in the no tension condition, calibrate stiffness gain coefficient \(k\), and measure \(\Delta y/\Delta P\) under tension state, then get the internal tension of wire rope.

REFERENCES

[1] AQSIQ of China’s report about national special equipment safety conditions in 2013 [R].(2014)