Fatigue tests of railway axles.

Miroslav Novosad*, Rostislav Fajkošb, Bohuslav Řeha, a Rudolf Řezníčekb

*aBonatrans Group, a.s., Revoluční 1234, Bohumín, 73594, Czech Republic
bŽilinská univerzita v Žiline, Univerzitná 1, 01026 Žilina, Slovakia

Received 3 March 2010; revised 12 March 2010; accepted 15 March 2010

Abstract

Fatigue life of the railway axles is till today very actual topic. Design, calculations and testing of the axles has been developed before long time and basic procedures are anchored in the European standards EN. Due to the service of high speed trains and due to the higher demands on safety are these procedures continually precised and thereby is safety in service improved. There were built new fatigue testing facilities especially for testing of full scale axles and wheels. On this special testing machines must be effectively realised high cycle fatigue tests of material and also full scale parts, because presumed life – cycle of railway axles is till thirty years. In this paper are discussed results of fatigue tests of produced railway axles and are compared with tests on small specimens and with demands of railway standards. All this measurements and calculations showed effort of railway axles producers aimed at higher safety and better fatigue properties of railway axles.

Keywords: railway axe; fatigue; durability; material characteristics; European standards

1. Introduction.

Increasing demands on speeds and safety of railway vehicles in recent years are reflected in European standards. These Standards defined not only sort of used steel and its treating but also procedures for ensuring safety in service. Very important part of this effort creates fatigue tests both small and full scale specimen. All this measurements and calculations showed effort of railway axles producers aimed at higher safety and better fatigue properties of railway axles.

2. Material characteristics.

Detailed study on the resistance of various materials of railway axles against fatigue failure was already started about 150 years ago by a German engineer August Wöhler who studied the influence of material fatigue in relation to fractures and cracks in railway axles [1]. In present days exist European standards that are concerned with design and calculation of the axles [2] and [3], with definition of steel grades, mechanical properties and verification of fatigue properties [4] and [5].

* corresponding author. E-mail address: mnovosad@bonatrans.cz

1877-7058 © 2010 Published by Elsevier Ltd. Open access under CC BY-NC-ND license, doi:10.1016/j.proeng.2010.03.242
In this paper we are trying to show what was done in the last years for fulfilling demands of European standards and for securing of railway axles maximal safety level.

European railway axles are mostly made from steel grades EA1N and EA4T that are defined by European standards. For special purposes as are high speed trains is used steel 30CrNiMo6 in accordance with DIN 10083 or similar steels.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EA1N</td>
<td>0.40</td>
<td>0.50</td>
<td>1.20</td>
<td>0.02</td>
<td>0.02</td>
<td>0.30</td>
<td>0.30</td>
<td>0.08</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>EA4T</td>
<td>0.22</td>
<td>0.15</td>
<td>0.50</td>
<td>0.02</td>
<td>0.02</td>
<td>0.30</td>
<td>0.30</td>
<td>0.06</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>34CrNiMo6</td>
<td>0.30</td>
<td>0.40</td>
<td>0.80</td>
<td>0.020</td>
<td>0.015</td>
<td>1.20</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Maer.2 Mechanical properties of steels for railway axles at +20°C in accordance EN 13261:2009 and DIN 10083.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EA1N</td>
<td>Min. 320</td>
<td>550 – 650</td>
<td>min.22</td>
<td>Not defined</td>
<td>Min.30</td>
<td>Min. 20</td>
</tr>
<tr>
<td>EA4T</td>
<td>Min.420</td>
<td>650 - 800</td>
<td>min.18</td>
<td>Not defined</td>
<td>Min.40</td>
<td>Min. 25</td>
</tr>
<tr>
<td>34CrNiMo6 acc. to DIN10083</td>
<td>Min.600</td>
<td>800 - 950</td>
<td>min.13</td>
<td>Min.55</td>
<td>Min.45</td>
<td>-</td>
</tr>
</tbody>
</table>

Where:
- Re = yield strength
- Rm = ultimate strength
- A = Elongation
- KUlongit = impact test, longitudinal test piece
- KUtransv = impact test, transversal test piece

3. Required fatigue limits of steels for railway axles.

Fatigue limit of used steel grades is defined by standard EN 14261:March2009 with emphasis on determining of notch sensitivity coefficient q, which is needed for calculation the safety parameter S.

Table 3. – The fatigue to be achieved in accordance with EN 13261 are given:

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>RfL [MPa]</th>
<th>RfE [MPa]</th>
<th>q [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA1N</td>
<td>Min. 250</td>
<td>Min. 170</td>
<td>Max. 1.47</td>
</tr>
<tr>
<td>EA4T</td>
<td>Min. 350</td>
<td>Min. 215</td>
<td>Max. 1.63</td>
</tr>
</tbody>
</table>

Where:
- RfL = fatigue limit determined from smooth surface small test piece
- RfE = fatigue limit determined from notched small test piece
- q = notch sensitivity coefficient

The fatigue test is done on minimally 15 pieces of smooth test bars with diameter 10 mm (RfL) and the same number of bars with a notch of 0.1 mm depth, opening angle 30°and notch root radius r=0.04 mm (RfE). The test is performed with machines that induce rotating bending stress on the tested part of the test bars of 10 mm diameter. The test bars are taken from the axle as near as possible to the surface of the axle body. The RfL and RfE values are determinate for 10⁷ cycles and the test results are evaluated by statistical “staircase” method defined in the ISO 12107 for the 50 percent probability of failure.
4. Design and calculation.

Railway axles were among the first train components to give rise to fatigue problems. Many years ago, specific methods were developed in order to design these axles. They were based on a feedback process from the service behaviour of axles combined with the examination of failures and on fatigue tests conducted in the laboratory, so as to characterize and optimize the design and materials used for axles.

At present time the procedures for design and calculation of the axles are defined by European standards EN 13103 and EN13104 [2] and [3]. Bending strain of the axle is calculated from loading forces – vertical (weight of the wagon and load), horizontal (from curves and crossings and braking forces). From bending moments are then calculated bending stresses in all cross sections of the axle. Calculated stresses must be smaller than permissible stress, that is determined as fatigue limit of the axle (F1 see Tab. 4) divided by safety factor.

5. Fatigue test on small test pieces.

For prediction the behaviour of the axle under in-service stresses, there is necessary estimate the fatigue limits in the critical areas of the axle.

There is made by:

1) estimation of fatigue limits for the material on reduced test pieces with diameter 10 mm.
2) checking fatigue parameter on the product. Tests are made on full size test pieces of axles, for which the dimensions and technology of manufacture are similar to the final product and its associated permissible fabrication defects.

The fatigue limits defined by reduced test pieces are used to verify that the notch effect of the material used for the fabrication of the axle is in accordance with the security coefficient "S" defined in design standards EN 13103 and EN 13104. They are determined from:

- test pieces with smooth surface (without notch) (fatigue limit RfL);
- test pieces with notch (fatigue limit RfE).

Tested values RfL, RfE and q in accordance with EN 1326 are given in table 3. RfL and RfE shall be determined for \(10^7\) cycles for a non-fracture probability of 50 %, which requires the use of at least 15 test pieces for each limit and a statistical method for the interpretation of the results.

Tests are made on fatigue test machines that on the body of test specimens create bending moment. The loading is made by weight or by spring and induced bending forces are then measured by strain gauges. With this gadget loading are equipped testing machines produced by firma Sincotec.

Test of reduced specimen are made in accordance with demands of the standard ISO 12107 [7], and evaluate in accordance with staircase method written in this standard or improved staircase method described by Hück [7], that enables to take in calculation all tested specimens.

Values that corresponds fatigue limits of the relevant material are used in calculations of the axles. Fatigue limits have to be derived from value S of security coefficient in order to obtain the maximum permissible stresses. The values of the maximum permissible stresses for solid axles are given in the table. Minimal value of safety coefficient is in accordance with standard EN 13104 equal 1,2 and for driven axle is higher because of torsion, vibrations, dynamic forces and so on.

### Table 4: Values of permissible stresses that can be used in strength calculations of the railway axle.

<table>
<thead>
<tr>
<th>AXLE</th>
<th>S</th>
<th>F1 – fatigue on the free surface</th>
<th>F3 – fatigue in fitting part</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F1 = 200 MPa</td>
<td>F3 = 120 MPa</td>
</tr>
<tr>
<td>Non-powered (EN 13103)</td>
<td>1.2</td>
<td>166</td>
<td>100</td>
</tr>
<tr>
<td>Powered axle (EN 13104)</td>
<td>1.5</td>
<td>133</td>
<td>80</td>
</tr>
<tr>
<td>Other parts acc. With EN 13104</td>
<td>1.3</td>
<td>154</td>
<td>92</td>
</tr>
</tbody>
</table>

In this picture are displayed results of testing of reduced specimen made from steel type EA1N used for non-powered railway axles.
Fig. 1 Fatigue test of small specimen in accordance with staircase method.

Tab. 5. Evaluation of fatigue test of small test pieces by Staircase method:

<table>
<thead>
<tr>
<th>i</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>9</td>
<td>22</td>
<td>18</td>
<td>3</td>
<td>52</td>
</tr>
<tr>
<td>(i \times Ni)</td>
<td>0</td>
<td>22</td>
<td>36</td>
<td>9</td>
<td>67</td>
</tr>
<tr>
<td>(i \times i \times Ni)</td>
<td>0</td>
<td>22</td>
<td>72</td>
<td>27</td>
<td>121</td>
</tr>
<tr>
<td>(\sigma_{\text{level}})</td>
<td>255</td>
<td>270</td>
<td>285</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

Calculation from all tests:

\[
R_{fL} = \sigma_0 + \text{STEP} \times (A/N) \\
R_{fL} = 274,327 \ \text{MPa} \\
S_{\text{modch}} = 12,3681 \ \text{MPa}
\]

Very important parameter of railway axle steel is notch effect \(q = R_{fL} / R_{fE}\) that gives information about notch sensitivity of steel and has influence on value of safe factor used in calculation. From evaluated fatigue limit \(R_{fL}\) and standard deviation \(S_{\text{modch}}\) we can display probabilistic curve of fatigue strength. (see fig. 3).
Dependence of fatigue limit of smooth (RfL) and notched (RfE) test specimen from steel EA1N on the strength limit Rm.

Fig. 2. Dependence of fatigue limits RfL and RfE on the strength of material A1N.

From evaluated fatigue limit RfL and standard deviation smo we can display probabilistic curve of fatigue strength. (see fig. 3).

Fig. 3. Distribution of fatigue test results of small scale specimen.

6. Verification of fatigue properties on full scale axles.

The full size axles fatigue tests are carried out in order to verify the calculation and are made to prove that the axle meets the parameters defined in the standards EN 13261 and EN 13260.
Tab. 6: The fatigue values to be achieved in accordance with EN 13261 and EN 13260 are given:

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>F1 [MPa]</th>
<th>F3 [MPa]</th>
<th>F4 [MPa]</th>
<th>For hollow axle</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA1N</td>
<td>200</td>
<td>120</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>EA4T</td>
<td>240</td>
<td>215</td>
<td>132</td>
<td></td>
</tr>
</tbody>
</table>

where:  
F1 ... Limit value on the free surface of the axle  
F3 ... Limit value under the fitted part of the axle  
F4 ... Limit value under the fitted part of the hollow axle

For each limit is verified that on three tested pieces of axles there occurs no crack after $10^7$ cycles of load that generates a surface stress level equal to F1 or F3. The test is performed with machines that induce rotating bending stress in the area where fatigue crack can be initiated. The area where fatigue crack can be initiated shall have similar geometry and surface roughness to those of the axle areas that have to be analysed. The test piece has to come from the same fabrication process as is used for the delivered axle for customer. These fatigue tests are done either on the test machine with rotated axle or more frequently on the resonance test machines type Sincotec.

Resonance testing machine induced rotating bending stresses in the axle body that is firmly clamped to the basement block. On the upper axle seat is assembled loading head with rotating eccentric mass that create rotating bending load.

Test is controlled by control strain gauges glued on the axle body near the tested place and on the free axle surface. The test is finished after $10^7$ cycles or when testing frequency drops by 0,5 Hz.

Service load acting on the axle evoke bending moment and in cases of driving axles also torsion moment. Stresses that respond to this bending moment are in various cross sections of the axle checked by means of calculation. Then there are used additional tests to be verified, if maximal allowable stresses in every cross section are not exceed.
\[ \sigma = \frac{M}{W} \quad \text{[MPa]} \]  

Where:

- \( \sigma \) ... bending stress [MPa]
- \( M \) ... bending moment [Nm]
- \( W \) ... cross section moment [m³]

Table 7: Surface roughness in accordance with EN 13261

<table>
<thead>
<tr>
<th>Part of the axle</th>
<th>Axle journal</th>
<th>Wheel seat</th>
<th>Transitional part seat / shaft</th>
<th>Shaft of the axle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface roughness in microns</td>
<td>0,8</td>
<td>0,8 – 1,6</td>
<td>1,6</td>
<td>3,2</td>
</tr>
</tbody>
</table>

Only rarely can designer obtain the information about railway axle life in service. From time to time can obtain designer some information about axle cracks from repair workshops or railway crash. For instance AAR during years 1991 – 2000 had on the railway axles discover some cracks during axle NDT inspections.

Table 8 – Axle with cracks found in AAR net from 1991 to 2001 [9]:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Failures</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Formerly also in Czechoslovakia were axles very carefully inspected and from statistic data we can see types of failures. [3]:

![Scrapped axles ČSD with defects after inspections in years 1981 - 1978 in percent.](image)

Fig. 5 - Rejected ČSD axles with defects after US inspection.

Defects:

1. Defect of dust guard seat - 3,41 %
2. Defect of wheel seat - 72,78 %
3. Defect of journal - 19,44 %
4. Defect of journal - seizure - 1,07 %
5. Fatigue of shaft - 1,03 %
6. Material defect - 1,90 %
7. Ring WJ - 0,36 %

From the picture we can see that cracks and failures of the axles originate in critical parts of the axle. Critical parts of the axle are seat of the wheel hub and transition part from seat to shaft. The real critical point depends on the ratio of diameter. But a large number of damage of the axles is caused by external forces or by corrosion.

Verification of the fatigue characteristics is essential in order to obtain a correctly dimensioned axle. The satisfactory performance of an axle in service depends upon these characteristics. The defined values are used for...
the calculation of the maximum permissible stresses that are according to the design rules of EN 13103 and EN 13104.

The limits determined on full size test pieces are used to verify that the axle fatigue characteristics are in accordance with those limits that are used for the calculation of the maximum permissible stresses stated in design standards EN 13103 and EN 13104.

The tests is prescribed to be performed with machines that induce rotating bending stresses in the area where could be initiated a fatigue crack.

For fatigue limit on free surface $F_1$ is needed to be verified that for three test pieces of axles there occurs no crack after $10^7$ cycles of load that generates a surface stress level equal to $F_1$.

Fig. 6  Railway axle prepared for fatigue test.

In testing praxis there were made not only verification of fatigue parameters in accordance with standards but was verified also estimated fatigue limit of the axle steel type EA1N.

Probability of fatigue failure of this steel is in the figure below:

Fig. 7. Distribution of fatigue test results for full scale specimen made from A1N steel.
\[ \text{SigPa} = \text{Sig50\%} + up \times \text{smo} \]

Mean value of fatigue limit (with 50% probability of crack initiation) \( \text{Sig50\%} = 242,549 \text{ MPa} \)

Standard deviation \( \text{smo} = 12,6336 \text{ MPa} \)

Fig. 8. Distribution of fatigue values of full scale railway axles from steel EAIN.

From the result of the test we can conclude, that on the stress level 200 MPa exists probability about 0,05 % that due to this loading would happen failure of the axle. It means that in service from 10 000 axles’ five axles can failure. Suppose that only in Germany there are about 600 000 axles in service then there are large number of potentially dangerous axles.

For the guaranty of safety service conditions there are undertaken the various measures.

Firstly in production of railway axles there is given strong accent on quality of material –chemical composition, microstructure, good mechanical values, cleanliness, good surface conditions and small scatter of fatigue properties, speak nothing of accent on exact design based on the good knowledge of service conditions.

In service there is necessary to make inspections ensuring that the stressed material of axles has the same properties as on the beginning. From this reasons are checked the axles of ČSD freight wagons by ultrasound every 60 000 km or every year.

Today reached high speed trains yearly run of till 500 000 km. Originally were intervals of axle inspections 240 000 – 300 000 km, but after crack out of the axle in ICE3 train on 9th July 2009 in Köln in Germany, railway office EBA in Bonn changed this intervals after every 60 000 km of run. This decision leads from beginning to the undesired shortage of HST trains in the personnel transport.

Railway authorities require lifetime of railway axle for a period of 30 years. But ensuring the same service and loading conditions for which axle was designed for that whole long time is questionable. The very negative and tragic example of this is case of broken axle at Viareggio on 29th June 2009. That axle was 34 years old and was designed for another vehicle and probably also for another service conditions.

It’s obvious that railway operator must possess drawing; calculation, eventually test report for part used in service and plan of inspections (procedures and intervals) and every individual axle must be used in service in conformity with these documents.
7. Conclusion

For securing safety of railway axles in service were calculated values and were verified fatigue properties of the axles by very large number of fatigue tests. But unfortunately a full scale test of real axle is very expensive test and there always remains some very small part of uncertainty of the obtained results. Some problems are represented also by clarifying of demands and definitions given in standards for railway axles and also by small differences between testing laboratories.

The fatigue test enables verification of calculation model and parameters used in calculation. From test results designer obtains information about fatigue properties of material and of full scale axle properties. This information about fatigue parameters of full scale specimen already contains important information about design, scale, surface quality and production process. This system of tests in accordance with European standards saves time and money in process of design of new type axles. This article tried to contribute for understanding of used testing methods and tested values in practice, which are also used in testing laboratory of BONATRANS GROUP a.s.

References