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Experimental Stress Analysis

Fatigue tests of railway axles

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Abstract: Fatigue strength of railway axles is till today very important topic. Design and tests of railway axles develops many years, but we must admit that this process is never ending story. There is necessary verify fatigue parameters and safety coefficient that are used in calculations for all new designs. Procedures of dimensioning and verifying fatigue parameters are defined by European standards. Thought the railway standards were developed many years, after putting high speed trains in operation arose new demands and it shows, that is necessary more exactly specified and unambiguous defined demands on proposal and tests of a new railway axle. For evaluating a lifetime of railway axle there are important tests of used materials and full scale test of axles.

Keywords: Fatigue, Railway Axle, Fatigue tests

1. Introduction

Fatigue strength of railway axles is from time of August Wöhler till today very important topic. Wöhler was first who made fatigue tests in years from 1858 till 1870. In last fifty years there are used nearly the same steel sorts of railway axles for use in railway traffic. Proposal of new design of railway axle is made through the use of standardise procedures of calculation of with method of finite elements. Than are verified fatigue properties of material and long-term strength of full scale axles.

Fig.1 August Wöhler (* 22. June 1819 in Soltau; † 21. March 1914 in Hannover)

It shows that this method are sufficient for rolling material used till 120 km/h, but for higher speeds and daily mileages is evidently insufficient. Information about service load and statistical data about checking and inspections in service is very limited and in many cases for producer simply inaccessible. For verification of design there are tests of used parameters very important, not saying about improving of proposal process.

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2. Steel for railway axles in accordance with standard EN 13261

Table 1. Mechanical properties and fatigue limits reduced test pieces with diameter Ø 10 mm from steel grade EA1N and EA4T

Steel grade	Chemical composition [%]			Rm [MPa]	RfL [MPa]	RfE [MPa]	q = RfL/RfE
	C	Si	Mn				
EA1N	Max. 0,40	Max. 0,50	Max. 1,2	550 - 650	≥250	≥170	≤1,47
EA4T	0,22 - 0,29	0,15 - 0,40	0,5 - 0,8	650 - 800	≥350	≥215	≤1,63

Where: Rm … Ultimate strength
RfL ... Fatigue limit of steel loaded by rotating bending moment on reduced test specimen with smooth surface.
RfE ... Fatigue limit of steel loaded by rotating bending moment on reduced test specimen with notch. Notch on the surface with depth 0,1 mm, and angle 30° and radius on the notch root R = 0,1 mm.
q ... notch sensitivity.

Table 2. Fatigue limits for full scale test piece

Steel grade	In accordance with EN 13261	In accordance with EN 13260 (for solid axle)	In accordance with EN 13260 (for hollow axle)
	F1 [MPa]	F3 [MPa]	F4 [MPa]
EA1N	≥200	≥120	≥110
EA4T	≥240	≥144	≥132

Where: F1 ... Fatigue limit on free surface of the axle
F3 ... Fatigue limit on the seat in press fitting for solid axle
F4 ... Fatigue limit on the seat in press fitting for hollow axle

3. Load on the axle

In service there is axle loaded by bending moment. Stresses evoked by bending moment are checked in various cross sections of the axle by calculation method. Than is by test verified maximal permissible values of stresses in particular cross sections:

$$\sigma = \frac{M}{W} \text{ [MPa]} \tag{1}$$

Where: σ ... bending stress [MPa]
M ... bending moment [Nm]
W ... section modulus. [m^3]

Test stresses in accordance with standards EN 13261 and event EN 13262 in particular cross sections had not to initiate surface cracks after 10 millions cycles.

Table 3. Roughness of the axle surface in accordance with EN 13261

Part of the axle	Journal	Wheel seat	Transition part seat / shaft	Shaft
Roughness of the surface in micrometers	0,8	0,8 – 1,6	1,6	3,2

4. Cracks of the axles and derailments of railway wagons

During railway history there are known a lot of cases of axle break or initiation of cracks. From beginning of railway history engineers endeavour to ensure the safety and best properties of railway axles. In spite of this effort there are found small cracks during inspections of railway axles or even come about to crack of railway axle in service. Such disaster entails large material damage or even lost of lives, that evoke discussion if used calculation methods are enough precise and procedure of dimensioning of axles is sufficient.

Only in recent years there were several accidents with broken axles. For instance last of this very serious accidents was in Viareggio on 29th June2009, where it comes to fracture of the axle in the area of dust guard of tank wagon. Another accident took place at Köln am Rhein where it comes to fracture of axle of high speed ICE3 train. On 26th July 2006 in Brigg in entrance to Simplon tunnel came to fracture of the axle of freight wagon as a result of corrosion after damage of painting on the free part of the axle shaft. On the 11th February 2001 at Drummondville in Canada came to fracture of the axle as a result of corrosion in the area of dust guard.

From Wöhler-times dimensioning of the railway axles has been developed more than hundred years and is more precise. On one side producer must forecast durability of the axle up to every detail but return information about load spectra, mileage and rejection from service are to disposition only very rarely. From time to time designer obtain information about inspections in railway repair workshops. For instance in America AAR in the years from 1991 to 2000 was found number of cracks given in the table 4.

Table 4. Railway axles AAR with failures [5]

Data about failure of axles AAR in years 1991 -2000										
Year of failure	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Number of failures	3	5	5	4	5	5	6	2	4	2

Also in former Czechoslovakia there were made careful inspections and statistic evaluation of railway axle failures. [3]:

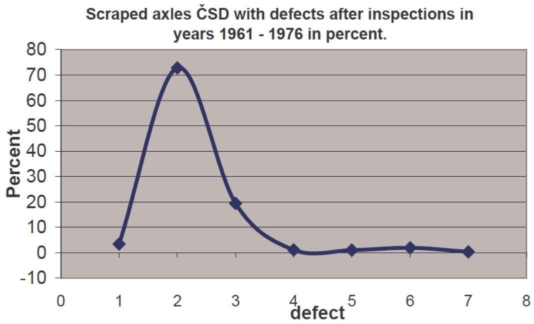


Fig. 2. Rejected axles with defects after ultrasonic checking – Number of failures in percent in accordance with area of occurrence.

Defects:
1. Defect on the dust guard - 3,41 %
2. Defect on the wheel seat - 72,78 %
3. Defect of the journal - 19,44 %
4. Seized journal - 1,07 %
5. Fatigue crack on the axle shaft 1,03 %
6. Material defect -1,9 %
7. Ring on the bearing ring - 0,36 %

From displayed data there is clear that defects on the axles are initiated mostly in critical areas and that area are on the wheel seat and in transition part from seat to the shaft in accordance with ratio of wheel seat diameter and shaft diameter.

There is necessary to ensure the best possible properties or railway axle for its whole life time. It concerned about:

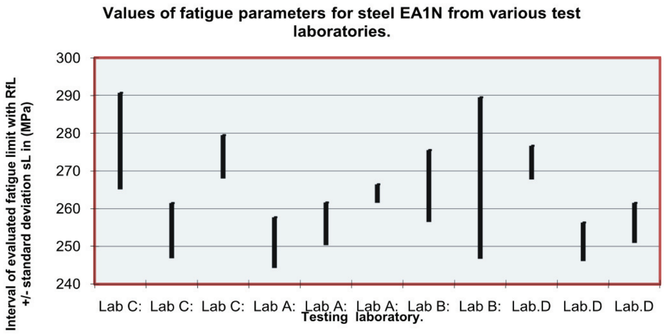
- Chemical and mechanical properties of material. This properties are checked in accordance with demands of EN 13261,
- Fatigue properties of steel,
- Long-life strength of the axle ,
- Improve properties in critical areas,
- Take account of specific conditions in production and in service.

This entire properties shall be carefully checked and tested in accordance with standards and instructions. Because tests and especially fatigue tests are very time consuming and therefore very expensive, there is not possible make test with large numbers of test pieces and from this reason all fatigue tests must be precisely prepared, evaluated and compared with other ones.

5. Fatigue test of steel of the axles

Tests on reduced test pieces with shape not depending on geometry of full scale axle are made with regard to properties of steel grade.

Procedure of tests is well-known and results reached in various test laboratories can be good compared. But there is very important workmanship of test specimen and exact shape of notch with depth 0,1 mm and tip radius 0,04 mm. When the notch has not exact shape than test results show large scatter of values and we obtain devaluate results. For instance when result of test is fatigue limit for test specimen with notch RfE = 197 MPa and standard deviation σE = 29,24 MPa , it shows that during test was something wrong.



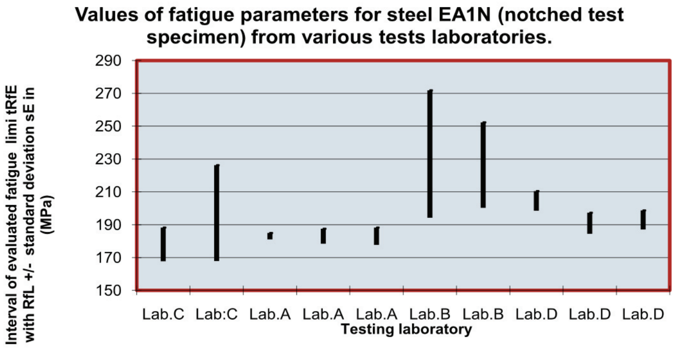


Fig. 3. Results of fatigue limit of steel EA1N on reduced test pieces made in various test laboratories.

6. Tests of full scale axles

Table 5. Criteria of fatigue properties for various cross sections of railway axle that are given by standards EN 13261 a 13260.

Cross section / Standard	F1 EN 13261	F2 EN 13261	F3 EN 13260	F4 EN 13260	F5 EN 13260
Limit value (MPa)	≥200	≥80	≥120	≥110	≥94

Where: - Fatigue limit *F*1 on body surface or railway axle
- Fatigue limit *F*2 on the bore surface of a hollow axle
- Fatigue limit *F*3 under the fitting area
- Fatigue limit *F*4 under the fitted parts, excerpt for journals of a hollow axle
- Fatigue limit *F*5 under the fitted parts of the journals of a hollow axle

The values defined for full scale specimen are used for the calculation of the maximum permissible stresses that are referred to in design rules in EN 13103 and

EN 13104. Dimensions and manufacture of full scale test pieces are similar to the final product.

From this point of view requirement for evaluating of fatigue limit on bore surface of hollow axle has hardly some sense, because test of bore surface is scarcely possible. Firstly because bending stresses on the bore surface are in every case much smaller than stresses on the outer surface and secondly that manufacturing of the notch in the centre of bore is extremely complicated. And test of full scale axle with notch on the outer surface has hardly some sense.

The tests shall be performed with machines that induce rotating bending stresses in the area where the cracks could initiate. For each limit F1, it shall be verified that for three test pieces there is no crack after 10^7 cycles of load that generates a surface stress level equal to F1.

In the standard EN 13261 in chapter 3.2.3.4. is written:
„The values of the stresses are calculated by classical beam theory where it may be applied. If not, the stresses shall be measured by strain gauges in the areas where the fatigue cracks initiate.“

This ambiguous definition enabled tests on two completely different loading values. There were made more tests on both levels of loading and difference between measured and calculated values of test stress level are displayed in picture 4. The difference between these two different loading levels makes about 12%.

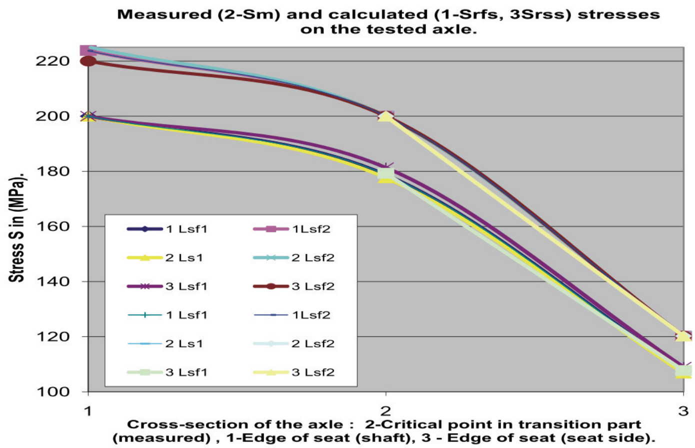


Fig. 4. Measured (2) and calculated (1) values of stresses on the axle.

In accordance with values (1) and (2) stall be evaluated fatigue strength of the axle on the free surface and in accordance with value (3) fatigue strength on seat surface in press fitting. The values (1) and (2) for pre- set of full scale test on the free surface are different about 12%, but both methods of pre- setting of test are recommended by EN 13261.

Table 6. Maximal values of stresses for pre setting of full scale test of the axle that corresponds with chapter 3.2.3.4. of standard EN 13261

Loading level	σ_{max} – transition part [MPa]. (Measured by stress gauges on the free surface)	σ_{nen} seat edge [MPa] (nominal value of stress calculated for free surface of shaft on the seat edge)	σ_{seat} [MPa] (nominal value of stress calculated for seat surface on the seat edge)
1	200	179	107,4
2	223	200	120

Loading on the level one lasts all axles from steel EA1N without cracks. When axles are loaded by level two on some tested axles appeared cracks in transition part from seat to shaft. When axle was tested in area of the seat (3) in accordance with EN 13260, than on the mentioned stress levels was no cracks on seat surface.

Scatter of test results in accordance to calculated values of stresses in wheel seat area is in cases of tests on the free surface large and gives not exact information about maximal stresses in critical area on free surface of the axle. During tests is necessary evaluate stresses in critical area of the axle and from this reason is necessary that test specimen has same shape, dimensions, surface roughness and also same type of heat treatment and machining as the axle delivered to railway service, not saying about as precise as possible measuring of stresses.

For evaluating of axle lifetime is also very important evaluating of strength in press fitting part. European standards EN 13261 and EN 13260 suppose that value of fatigue strength in press fitted part is equal to 60 percent of fatigue strength on free surface of the axle. However during full scale tests was discovered that in lot cases the fatigue strength in press fitted parts is lower than 60 percent of fatigue limit on smooth specimen. It depends on a lot of parameters, for instance alloys in steel, shape and stresses in press fit, diameter ratio, amplitude of relative motion of fitting parts, and so on. Very subjective is also evaluation of eventual damage on seat surface after test, when on the surface are initiated small pits and debris from fretting corrosion, from that after some time initiates small cracks. When this small cracks connects each other and when reach certain size became growth as fatigue cracks but when small fretting cracks changes into fatigue cracks that became growth is hardly determinable.

Some results relating to fatigue strength in press fitted parts with relation to alloying steel and value of fitting press were published already by Serensen [14], page 233.

Table 7. Decline of fatigue properties in press fitted part in accordance with Serensen [4]

Steel			Fatigue limit [MPa]	(%)
0.57 % C	Smooth test piece		290	100
	Press fit assembly	- p = 65 MPa	160	55
	Press fit assembly	- p = 120MPa	160	55
	Press fit assembly	- p = 210 MPa	155	53
0.42 % C	Smooth test piece		224	100
	Press fit assembly	- p = 64 MPa	155	69
	Press fit assembly	- p = 113 MPa	112	50
12XH3A	Smooth test piece		355	100
	Press fit assembly	- p = 0 MPa	140	39.4
	Press fit assembly	- p = 50 MPa	128	36

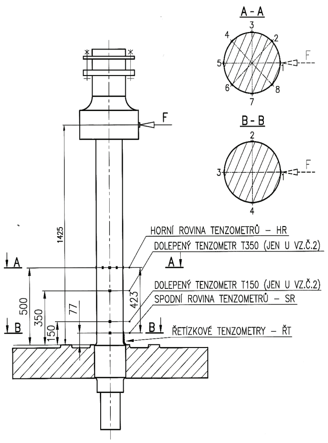


Fig. 5. Lay – out of the axle for full scale fatigue test.

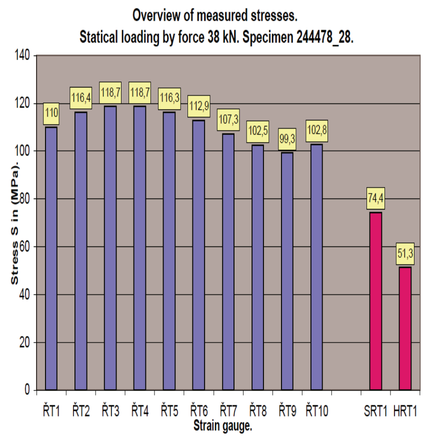


Fig. 6. Overview of measured values of stresses in the transition area from shaft to seat (left) and on the free surface (right) of the axle.

7. Conclusion

For ensure of service safety was made a lot number of full scale tests of railway axles for long – time strength. Some test defined by European standards are unambiguous and can be good comparable. But some of these full scale tests are different each other not only from reason of testing facilities but also with different interpretation of demands prescribed in standards.

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