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# Measurement on Scale-Induced Fatigue Behaviour for Railway Axle

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**Keywords:** Fatigue; Material; Structure; Probability; S-N curve.

**Abstract.** Transferring of fatigue behavior is investigated from material to structure for Chinese railway LZ50 axle carbon steel. *S-N* data in mid-fatigue life range and fatigue limit data of smooth small specimens are applied for material fatigue behavior. Real axles and similar smooth bigger specimens were tested with respect to fatigue limits. The data of real axles reveal the difference between material and a special structure. And the data of similar specimens play a role of bridge to connect material and material structures. Probabilistic transferring relations are deduced by the data from material, to similar specimens, and then to structures at the fatigue limit phase. Structural probabilistic *S-N* curves are obtained by the material fatigue behavior to extend the transferring relations to entire fatigue life range. Determinations of the fatigue behavior of the groove of LZ50 steel axle indicate availability of the present investigation.

## Introduction

Due to the differences of size, geometry, surface quality, or service environment, fatigue behavior of engineering structures is generally different from that of material samples. Appropriate modification is an important phase of making reasonably fatigue reliability analysis.

Some efforts have been made in two categories [1-3]. One is independent element method by Cerensen [1]. Four coefficients relative to structural size, geometry, surface quality, and service environment are separately measured through independent experiments. And then an integrated formulation is applied to consider the concurrent actions of the multi-affecting factors. Zhao *et al.* [2] recognized that the Cerensen's formulation should be applied using a concept of relative coefficients. Another is collective element method. Similar or real structural specimens concluding the partial or entire affecting factors [3] are fatigued. A collective affecting factor or affecting regularity is determined by comparing the test data from similar or real structural specimens to material specimens.

Fatigue failure of railway axle is relative to train service safety. More details on the fatigue properties between the material and real structures are expected to be known. Present work investigates the approach of obtaining structural fatigue behavior by material test data. A policy is applied through comparing the fatigue limits of similar specimens and real axles.

## Material and Experiments

**Material and Specimens.** The material used for present study is LZ50 carbon steel. Chemical composition and mechanical properties of this material is given respectively in Tables 1 and 2.

As shown in Figs.1 and 2, three categories are applied for the specimens of present study. They are material smooth round bar specimen with 7.5 mm diameter, similar smooth round bar with 9.5 mm diameter, and real half railway axle with a 172 mm diameter test section.

Table 1 Chemical composition of the LZ50 axle steel [Mass percentage %]

| C | Si | Mn | Cr | Ni | Cu | Al | P | S | Residual |
|---|---|---|---|---|---|---|---|---|---|
| 0.47 | 0.26 | 0.78 | 0.02 | 0.028 | 0.15 | 0.021 | <0.014 | <0.007 | Fe |

**Experiments.** Eight real axles are fatigued on the rotational bending test plate under a loading frequency of 800 Hz. Objective is to obtain fatigue limit of the real axle. The tests were stopped when the life is over $10^7$ cycles.

Four groups, total thirty one, of material specimens are tested at different load levels on a rotational material test machine at a frequency of 50 Hz. Under the same test condition, fifteen material specimens are fatigued using the small sampling up-and-down (staircase) test method to obtain the fatigue limits with respect to a fatigue life of $10^7$ cycles [4]. Results of the group tests and the fatigue limits test are shown in Fig. 4.

Twelve similar specimens are fatigue under the same test conditions to the material specimens using the staircase test method. The objective aims also to the fatigue limits.

Totally, 4 pairs of "failure" vs "survival" data for real axle specimens, 7 pairs of the data for material specimens, 6 pairs of the data for similar specimens, 31 pairs of *S-N* data for material specimens are obtained for the present study. The "failure" vs "survival" data are given in Table 3.

Table 2 Mechanical properties of LZ50 axle steel [5]

| Parameter | Young's modulus $E$ [GPa] | Yielding strength $\sigma_s$ [MPa] | Ultimate tensional strength $\sigma_b$ [MPa] | Elongation $\delta_5$ [%] | Reduction of area $\Psi$ [%] |
|---|---|---|---|---|---|
| $P_{av}^{*}$ | 209.75 | 329.94 | 628.96 | 24.41 | 41.92 |
| $P_{sd}^{**}$ | 13.1111 | 4.7277 | 5.4559 | 0.7397 | 0.9963 |
| $P_{cv}^{***}$ | 0.0625 | 0.0143 | 0.0087 | 0.0303 | 0.0238 |

*$P_{av}$ is average value; **$P_{sd}$ is standard deviation, and ***$P_{cv}$ is coefficients of variations.

Fig.1 Real half axle for present study

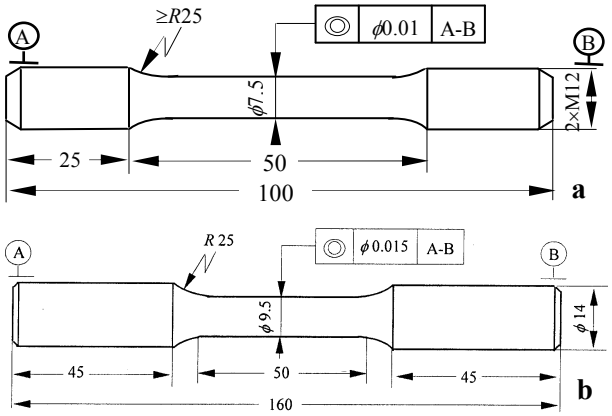


Fig. 2 Material specimen and similar specimen

Fig.3 Rotational bending test plate for real half axle

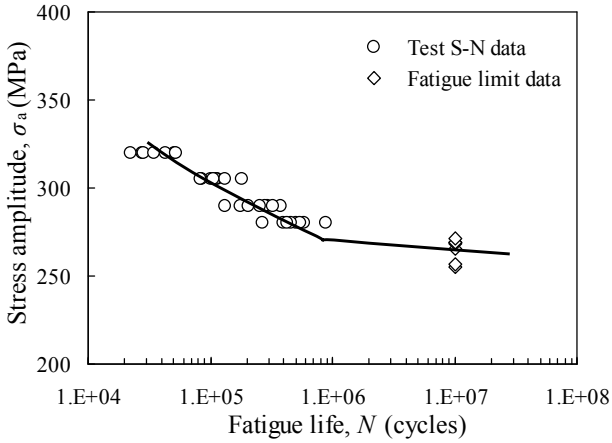


Fig. 4 Test results of material specimens

## Assessment

By the present test results, the fatigue behavior from material to structures should be assessed by comparing the fatigue limits. The data of real axles have a collective effect to assess the differences of

Table 3 Fatigue limit data using staircase test method for real axles, material, and similar specimens

| Specimen type | Ordinal | $\sigma_a$ [MPa] | $N$ [cycles] | Ordinal | $\sigma_a$ [MPa] | $N$ [cycles] |
|---|---|---|---|---|---|---|
| Real axle | 1 | 238 | 246000 | 2 | 218 | $>1.0\times10^7$ |
| | 3 | 228 | 339000 | 4 | 218 | |
| | 5 | 228 | 520000 | 6 | 218 | |
| | 7 | 228 | 530000 | 8 | 218 | |
| Material specimen | 1 | 275 | 246200 | 2 | 265 | $>1.0\times10^7$ |
| | 3 | 275 | 538300 | 4 | 265 | |
| | 5 | 275 | 738200 | 6 | 265 | |
| | 7 | 275 | 802900 | 8 | 265 | |
| | 9 | 275 | 1911900 | 10 | 265 | |
| | 11 | 265 | 618600 | 12 | 255 | |
| | 13 | 265 | 808900 | 14 | 255 | |
| Similar specimen | 1 | 275 | 195000 | 2 | 255 | $>1.0\times10^7$ |
| | 3 | 275 | 249000 | 4 | 255 | |
| | 5 | 255 | 1030000 | 6 | 235 | |
| | 7 | 255 | 1070000 | 8 | 235 | |
| | 9 | 255 | 1760000 | 10 | 235 | |
| | 11 | 255 | 322000 | 12 | 235 | |

sizes and surface qualities between material and real axles. The data of similar specimens have an effect to assess the difference of sizes between the material and similar specimens. They play a role of bridge to connect the material with the structures. According to the test data in Table 3, parameters $n_s$, $\sigma_{-1av}$, and $\sigma_{-1rms}$ of the present study are measured using an improved estimation approach for fatigue limit [6]. Results are given in Table 4. By these parameters, the average relationship and standard deviation of fatigue limits from material to the railway axle can be deduced as

$$\sigma_{-1\mathbf{av}} = C_{\mathbf{av}} A^{m_{\mathbf{av}}} \tag{1}$$

$$\sigma_{-1\mathbf{rms}} = C_{\mathbf{rms}} A^{m_{\mathbf{rms}}} \tag{2}$$

where $\sigma_{-1}$ is fatigue limit; $A$ is effective area; $C$ and $m$ are material constants; subscripts av and rms represent respectively the average value and standard deviations. For the present axle, $C_{av}$, $m_{av}$, $C_{rms}$, and $m_{rms}$ are 285.82, -0.0251, 3.7250, and 0.0825. The transferring effects are shown in Figure 5.

Table 4 Parameters of fatigue limits for the real axles, material specimens, and similar material specimens

| Category | $n_s$ | $\sigma_{-1av}$ [MPa] | $\sigma_{-1rms}$ [MPa] |
|---|---|---|---|
| Real axles | 4 | 222.43 | 8.97 |
| Material specimens | 7 | 264.88 | 4.86 |
| Similar specimens | 6 | 251.61 | 7.11 |

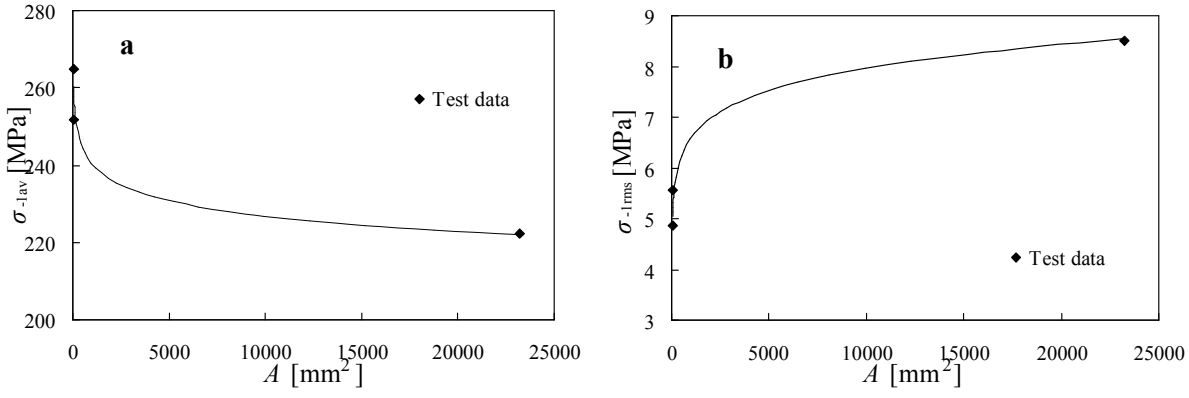


Fig. 5 Changes of average value and standard deviation of fatigue limit from material to axle

Correspondingly, transaction coefficients with respect to the average value and standard deviation of fatigue limits can be established as

$$K_{\mathbf{m,av}} = \frac{\sigma_{-1\mathbf{av}}}{\sigma_{-1\mathbf{oav}}}: \qquad K_{\mathbf{m,av}} = D_{\mathbf{av}}\left(\frac{A}{A_{\mathbf{o}}}\right)^{w_{\mathbf{av}}} \tag{3}$$

$$K_{\mathbf{m,rms}} = \sqrt{\frac{\sigma^2_{-1\mathbf{rms}}}{\sigma^2_{-10\mathbf{av}}} + \frac{\sigma^2_{-1\mathbf{av}}\sigma^2_{-10\mathbf{rms}}}{\sigma^4_{-10\mathbf{av}}}}: \quad K_{\mathbf{m,rms}} = D_{\mathbf{rms}}\left(\frac{A}{A_{\mathbf{o}}}\right)^{w_{\mathbf{rms}}} \tag{4}$$

where $A$ and $A_o$ are effective areas of material specimen and structure, respectively. For the present work, $D_{av}$, $w_{av}$, $D_{rms}$, and $w_{rms}$ are 0.9812, -0.0251, 0.0263, and 0.0486, respectively. The fit effects are exhibited in Figure 6.

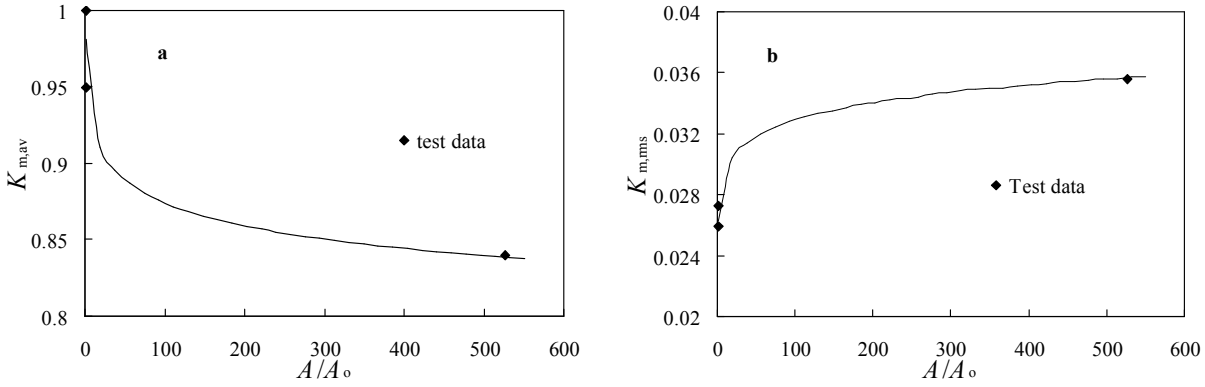


Fig. 6 Changes of average value and standard deviation of affect coefficients from material to axle

From a statistical viewpoint and assuming the fatigue limits following normal distribution, there is a probabilistic modification factor $K_m$ from material to a real axle

$$K_{\mathbf{m}P-C} = K_{\mathbf{m,av}} - \left[t_{1-C}\left(n_{\mathbf{so}} - 1\right) + Z_P\right]K_{\mathbf{m,rms}} \tag{5}$$

where $P$-$C$ are survival probability and confidence; $n_{so}$ and $t_{1\text{-}C}(n_{so}\text{-}1)$ are sampling size of material specimens and t-distribution function with degree-of-freedom of $n_{so}$-1 at a significance of 1-$C$, and $Z_P$ is percentage of normal distribution with probability of $P$.

## Structural Behavior

If extrapolate this modification into entire fatigue life range and consider the independency of material tests and structural tests, for a material holding the following behavior [7]

$$\lg N_{P-C} = A_{P-C} + B_{P-C}\lg\left(s_{-1\mathbf{a}}\right) \quad (N<N_T) \tag{6}$$

$$\lg N_{P-C} = F_{P-C} + G_{P-C}\lg\left(s_{-1\mathbf{a}}\right) \quad (N>N_T) \tag{7}$$

and the structural behavior can be similarly described as

$$\lg N_{P-C} = A_{P-C} + B_{P-C}\lg\left(\frac{S_{-1\mathbf{a}}}{K_{\mathbf{m}P-C}}\right) = Q_{P-C} + T_{P-C}\lg S_{-1\mathbf{a}} \quad (N<N_T) \tag{6}$$

$$\lg N_{P-C} = F_{P-C} + G_{P-C}\lg\left(\frac{S_{-1\mathbf{a}}}{K_{\mathbf{m},P-C}}\right) = U_{P-C} + V_{P-C}\lg S_{-1\mathbf{a}} \quad (N>N_T) \tag{7}$$

**For Example**. The groove of RD2 type axle between wheel seat and bearing for Chinese railway freight car has diameter of 165 mm. This section was verified to be a key position affecting fatigue safety [8-10]. According to Eqs. (3) and (4), the average value and standard deviation of modification factors are 0.8402 and 0.0355. Probabilistic affecting factors for the groove section are estimated and given in Table 5. Parameters of the structural probabilistic *S-N* curves at the groove of axle are obtained and shown in Table 6. Probabilistic curves at *C*=50% for the material and the groove section of axle are shown in Figure 7. These curves seem to have much conservative.

Table 5 Probabilistic modification factors at groove section of RD2 type of railway axle

| $P$ | $C$ [%] | $K_m$ | $P$ | $C$ [%] | $K_m$ |
|---|---|---|---|---|---|
| 0.5 | 50 | 0.8402 | 0.5 | 95 | 0.7712 |
| 0.9 | | 0.7947 | 0.9 | | 0.7256 |
| 0.95 | | 0.7818 | 0.95 | | 0.7127 |
| 0.99 | | 0.7575 | 0.99 | | 0.6885 |
| 0.999 | | 0.7304 | 0.999 | | 0.6614 |
| 0.9999 | | 0.7081 | 0.9999 | | 0.6391 |
| 0.5 | 90 | 0.7890 | 0.5 | 99 | 0.7286 |
| 0.9 | | 0.7435 | 0.9 | | 0.6830 |
| 0.95 | | 0.7306 | 0.95 | | 0.6701 |
| 0.99 | | 0.7064 | 0.99 | | 0.6459 |
| 0.999 | | 0.6793 | 0.999 | | 0.6188 |
| 0.9999 | | 0.6569 | 0.9999 | | 0.5965 |

Table 6 Parameters of the probabilistic *S-N* curves at groove section of RD2 type of railway axle

| $P$ | $C$ [%] | $Q$ | $T$ | $\sigma_T$ [MPa] | $U$ | $V$ |
|---|---|---|---|---|---|---|
| 0.5 | 50 | 50.7967 | -19.0190 | 228.93 | 216.089 | -89.0668 |
| 0.9 | | 48.8810 | -18.5137 | 209.23 | 207.117 | -86.7007 |
| 0.95 | | 48.3377 | -18.3705 | 203.77 | 204.573 | -86.0300 |
| 0.99 | | 47.3183 | -18.1018 | 193.69 | 199.799 | -84.7717 |
| 0.999 | | 46.1749 | -17.8007 | 182.63 | 194.445 | -83.3614 |
| 0.9999 | | 45.2332 | -17.5528 | 173.72 | 190.034 | -82.2005 |
| 0.5 | 90 | 50.0941 | -19.0190 | 210.26 | 212.798 | -89.0668 |
| 0.9 | | 48.1623 | -18.5137 | 191.34 | 203.752 | -86.7007 |
| 0.95 | | 47.6141 | -18.3705 | 186.10 | 201.184 | -86.0300 |
| 0.99 | | 46.5849 | -18.1018 | 176.44 | 196.365 | -84.7717 |
| 0.999 | | 45.4299 | -17.8007 | 165.85 | 190.956 | -83.3614 |
| 0.9999 | | 44.4778 | -17.5528 | 157.33 | 186.497 | -82.2005 |
| 0.5 | 95 | 49.8504 | -19.0190 | 204.15 | 211.657 | -89.0668 |
| 0.9 | | 47.9122 | -18.5137 | 185.48 | 202.580 | -86.7007 |
| 0.95 | | 47.3620 | -18.3705 | 180.32 | 200.004 | -86.0300 |
| 0.99 | | 46.3290 | -18.1018 | 170.79 | 195.166 | -84.7717 |
| 0.999 | | 45.1693 | -17.8007 | 160.35 | 189.735 | -83.3614 |
| 0.9999 | | 44.2131 | -17.5528 | 151.96 | 185.257 | -82.2005 |
| 0.5 | 99 | 49.2740 | -19.0190 | 190.39 | 208.958 | -89.0668 |
| 0.9 | | 47.3187 | -18.5137 | 172.28 | 199.801 | -86.7007 |
| 0.95 | | 46.7633 | -18.3705 | 167.28 | 197.200 | -86.0300 |
| 0.99 | | 45.7199 | -18.1018 | 158.05 | 192.314 | -84.7717 |
| 0.999 | | 44.5476 | -17.8007 | 147.96 | 186.824 | -83.3614 |
| 0.9999 | | 43.5802 | -17.5528 | 139.85 | 182.293 | -82.2005 |

## Summary

1. Transferring of fatigue behavior is investigated from material to structure for Chinese railway LZ50 axle carbon steel. *S-N* data in mid-fatigue life range and fatigue limit data of smooth small specimens are applied for material fatigue behavior. The data of real axles reveal the difference

between material and a special structure. And the data of similar specimens play a role of bridge to connect material and material structures.

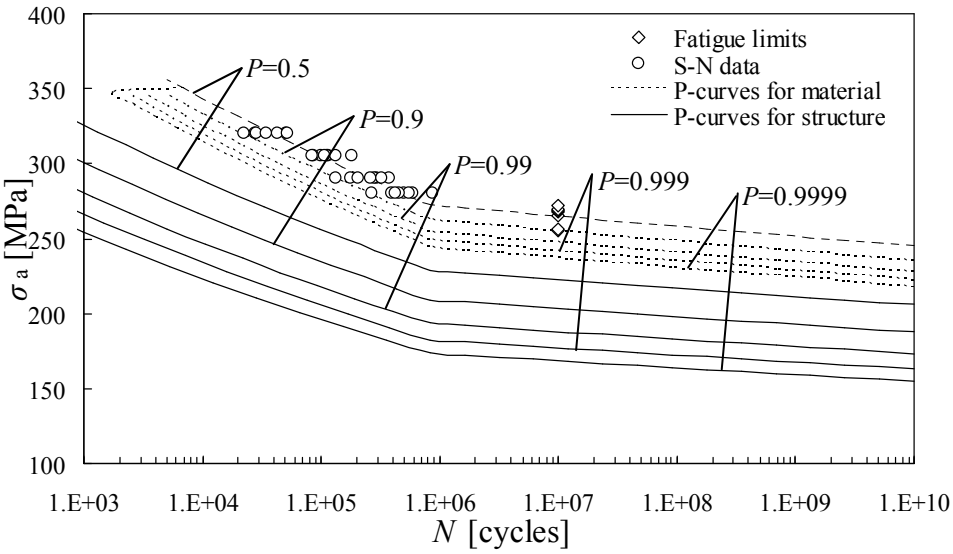


Fig. 7 Probabilistic *S-N* curves at *C*=50% of material and groove section of the RD2 type of railway axle

2. Probabilistic transferring relations are deduced by the data from material, to similar specimens, and then to structures at the fatigue limit phase.
3. Structural probabilistic *S-N* curves are obtained by the material fatigue behavior to extend the transferring relations to entire fatigue life range.

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