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The mean stress influence of rope wires stressed by tension-tension

In tension-tension tests the amplitude stress as well as the mean stress can be adjusted to any desired level. For a common evaluation of all tension-tension tests amplitude and mean stresses should be substituted by an equivalent amplitude stress. For determination of these equivalent stress the so called mean stress influence hast to be known. In the following, suitable models will be presented which allow a common evaluation of all tension-tension tests and also a general description of rope wire fatigue behavior.

1 Introduction

The fatigue behaviour of steel rope wires can tested with help of rotary bending tests and tension-tension tests. They will described in the following two chapters. Fig. 1 shows wire arrangements of mentioned fatigue tests, zones of maximum stress amplitude in wire cross-section, amplitude stresses and mean stresses.

In rotary bending tests tension-tension tests the maximum wire stress occurs at the wire surface and decreases linearly form outside of the wire to the wire axis. In opposite to that, in tension-tension tests the wire stress is constant over the whole cross-section. The theory of stress gradient means that the outer highly stressed part can be supported by the less stressed part below. It follows that that the fatigue strength amplitude (endurance limit) of wires in rotary bending tests should be much higher than the once in tension-tension tests. However this was not detected for rope wires. Therefore Unterberg [1] stated that the stress gradient effect does not exist for rope wires. Therefore it is allowed to evaluate results of rotary bending tests and tension-tension tests together.

	rotary bending test	tension-tension test
wire arrangements for testing		
zone of maximum fluctuating stress		
amplitude stress	$\sigma_a = \sigma_b$	$\sigma_a = \sigma_{t,a}$
mean stress	$\sigma_m = 0$	$\sigma_m = \sigma_{t,m}$

Fig. 1: Wire arrangement for fatigue tests, zones of maximum stress amplitude in wire cross-section, amplitude stresses and mean stresses

2 Rotary bending test

In a rotary bending test, the wire is bent in a free bow around its own axis and will be rotated araound its own axis. This creates an alternating bending stress The mean stress is zero. The most common test machine is the rotary test machine of type IFT Stuttgart. Test arrangement and way of operation are described in detail be Wolf [2] and Feyrer [3]. The author [4] has done a voluminous investigation of fatigue behavior of wires. Fig. 2 shows a typical shape of curve of the achieved number of rotary bending cycles in dependence of the adjusted bending stress.

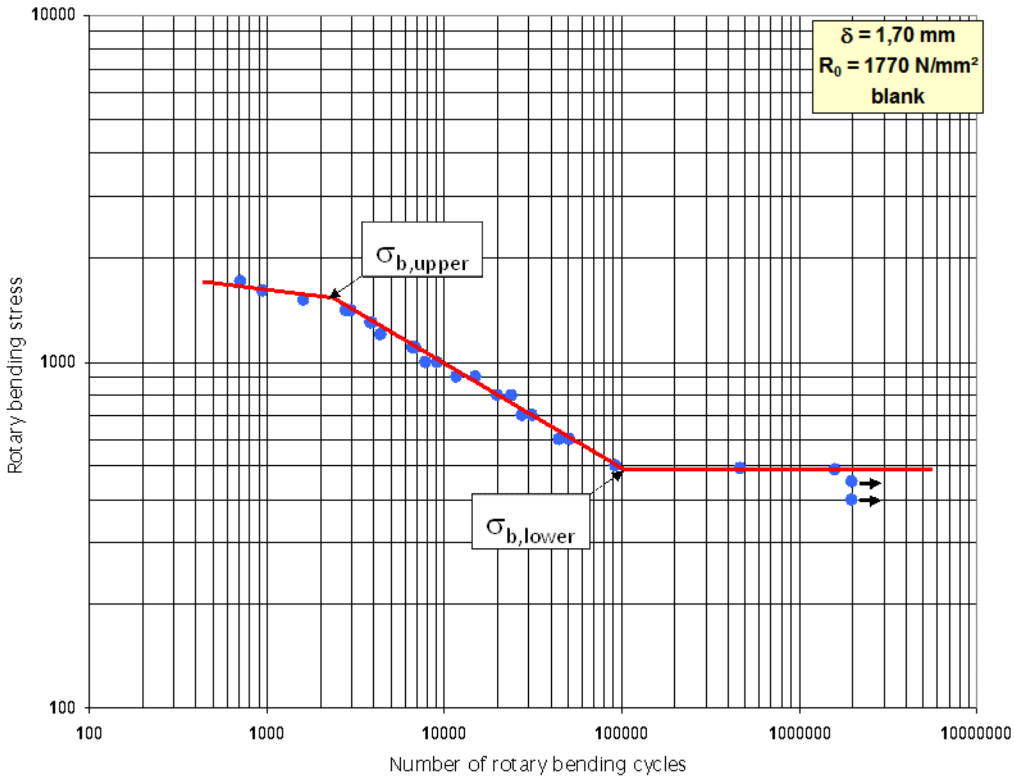

Fig. 2: Typical Woehler line of a rope wire stressed by rotary bending stress [4]

In average the fatigue life area (low cycle fatigue area) is limited by the bending stress amplitudes $\sigma_{b,lower} = 0.31 \cdot R_m$ and $\sigma_{b,upper} = 0.77 \cdot R_m$. The expected number of rotary bending cycles the mentioned load area could be described for bright wires with the endurance equation

$$\lg N = 13.74 - 3.243 \cdot \lg \sigma_b - 0.30 \cdot \lg \delta - 0.74 \cdot \lg \frac{R_0}{1770}. \qquad (1)$$

with the bending stress σ_b, the wire diameter δ and the nominal tensile grade R_0. Galvanized wires have 19% less of endurance [4].

Ziegler, Vogel and Wehking [5] found an endurance equation similar to Equation (1). Also they found that results of rotary bending tests correlate with bending fatigue of ropes which were manufactured of these wires.

3 Tension-tension test

In a tension-tension test the wire is stressed by pulsating load. An endurance equation for rope wires does not exist. Unterberg [1] has investigated the transition area to the endurance limit and has summarized the results in Fig. 3.

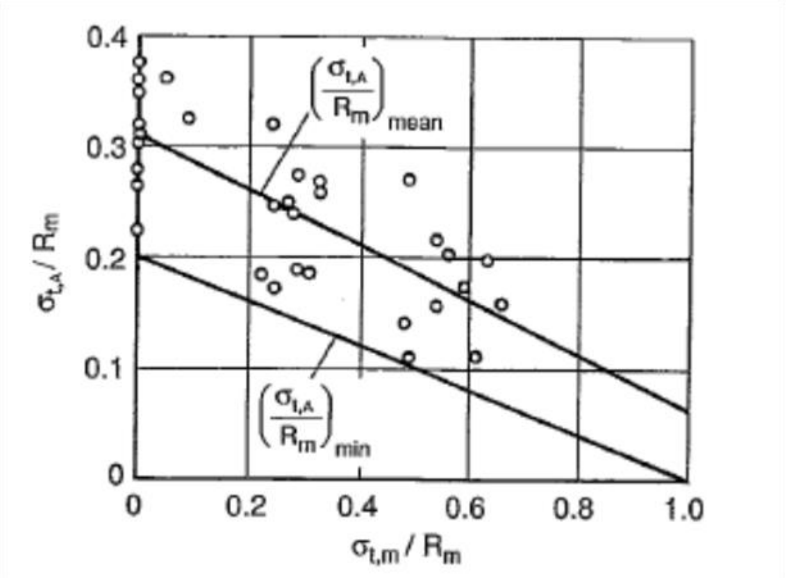

Fig. 3: Relative fatigue strength amplitude and corresponding relative mean stress [1]

For mean stress of zero the amplitude stress is $\sigma_{z,A}(\sigma_{z,m} = 0) = 0{,}313 \cdot R_m$ which corresponds with the bending stress $\sigma_{b,min}$ in the rotary bending test. Unterberg concludes that stress gradient effect does not exist for steel rope wires.

With the following proposed mean stress influence it will be possible to calculate the expected number of tension-tension cycles out of the load parameters amplitude and mean stress.

4 Mean stress influence

It exists a number of models to describe the mean stress influence on the fatigue behaviour of metals. All models substitute the amplitude stress σa and the mean stress σm by an equivalent amplitude stress σq and a mean stress σm of zero. σq and σm of zero lead to the same fatigue life as the combination of the substituted stresses σa and σm. Out of literature ten models will be presented and discussed.

Gerber (1874), [6] $$\frac{\sigma_a}{\sigma_q} + \left(\frac{\sigma_m}{R_m}\right)^2 = 1 \qquad (2)$$

With the tensile strength R_m. Gerber´s model is suitable for ductile materials. For compressive loads and brittle materials in particular it is less suitable.

Goodman (1930), [7]
$$\frac{\sigma_a}{\sigma_q} + \frac{\sigma_m}{R_m} = 1 \qquad (3)$$

Goodman´s model is more suitable for brittle materials.

Soderberg (1930), [8]
$$\frac{\sigma_a}{\sigma_q} + \frac{\sigma_m}{R_e} = 1 \qquad (4)$$

In opposite to Goodman Soderberg uses the yield strength R_e insteas of tensile strength R_m.

Morrow (1968), [9]
$$\frac{\sigma_a}{\sigma_q} + \frac{\sigma_m}{\sigma_f} = 1 \qquad (5)$$

In opposite to Goodman Morrow uses the actual breaking strength σ_f instead of (nominal) tensile strength R_m. In case of rope wires there is no difference between both values, because rope wires are classified by the rough nominal tensile grade instead R_0 and not by a (nominal) tensile strength R_m.

Dowling (1972), [10]
$$\frac{\sigma_a}{\sigma_q} + \frac{\sigma_m}{\sigma_f'} = 1 \qquad (6)$$

In opposite to Goodman Dowling uses a special strength $\sigma_{f'}$ instead of tensile strength Rm, where $\sigma_{f'}$ is determined by expanding the low cycle segment of Woehler line up to N = 1.

Smith, Watson, Topper (1970), [11]
$$\sigma_q = \sqrt{(\sigma_m + \sigma_a) \cdot \sigma_a} \qquad (7)$$

This model (short form SWT) differs from the previous models. It uses load characteristics only and no material characteristics.

Walker (1979), [12]
$$\sigma_q = (\sigma_m + \sigma_a)^{1-\gamma} \cdot \sigma_a{}^{\gamma} \qquad (8)$$

Walker´s model is the generalized version of SWT model. The sum of the exponents is one. γ has to be determined by evaluating of test results.

The next two models were proposed to evaluate tension-tension test results of wire ropes. The equivalent stress corresponds here with the pulsating fatigue strength instead of the alternating fatigue strength in the previous models.

Yeung and Walton (1985), [13]
$$\frac{2 \cdot \sigma_a}{\sigma_q} + \frac{\sigma_m - \sigma_a}{R_0} = 1 \qquad (9)$$

Yeung and Walton´s model uses forces instead of strains. For better comparison their equation is changed into the type of Goodman´s model (Equation (5)). For using this model to evaluate tension-tension test results of rope wires, rope minimum breaking load (used by Yeung and Walton) is changed into nominal tensile grade R_0.

Matzukawa et al (1985), [14]
$$\frac{2 \cdot \sigma_a}{\sigma_q} + \frac{\sigma_m - \sigma_a}{R_m} = 1 \qquad (10)$$

In opposite to Yeung and Walton Matzukawa et al use the actual breaking strength R_m instead of the minimum breaking load (changed into nominal tensile grade R_0).

A complete different approach uses an exponential equation.

Kwofie (2001), [15]
$$\frac{\sigma_a}{\sigma_q} = e^{\left(-\alpha \cdot \frac{\sigma_m}{R_m}\right)} \qquad (11)$$

Parameter α has to be determined by evaluating of test results. For small numbers of α the original function can be developed into a Taylor series. The approximated formula is

$$\frac{\sigma_a}{\sigma_q} + \alpha \cdot \frac{\sigma_m}{R_m} = 1. \qquad (11a)$$

Equation (11a) shows that for choosing $\alpha = 1$ it leads to Goodman´s model and for $\alpha = \sigma_m/R_m$ to Gerber´s model. With choosing $\alpha = 1$ and R_e, σ_f or σ_f' instead of R_m it leads to Soderberg´s, Morrow´s or Dowling´s model.

Gerber´s, Goodman´s, Soderberg´s, Morrow´s, Dowling´s and Kwofie´s models could be drawn in a Figure similar to Fig. 3 with the axes σ_m/R_m and σ_a/σ_q. Fig. 4 shows the comparison. Gerber´s model leads to a parabola. Goodman´s, Soderberg´s, Morrow´s and Dowling´s models lead to straight lines. Kwofie´s exponential curve is drawn by way of example for $\alpha = 0.5$. The equations of the other four models cannot be solved for σ_a/σ_q.

Due to the fact that for rope wires no difference between Goodman´s and Morrow´s model exists, both straight lines has been drawn by way of example with a slight difference only, Fig. 4.

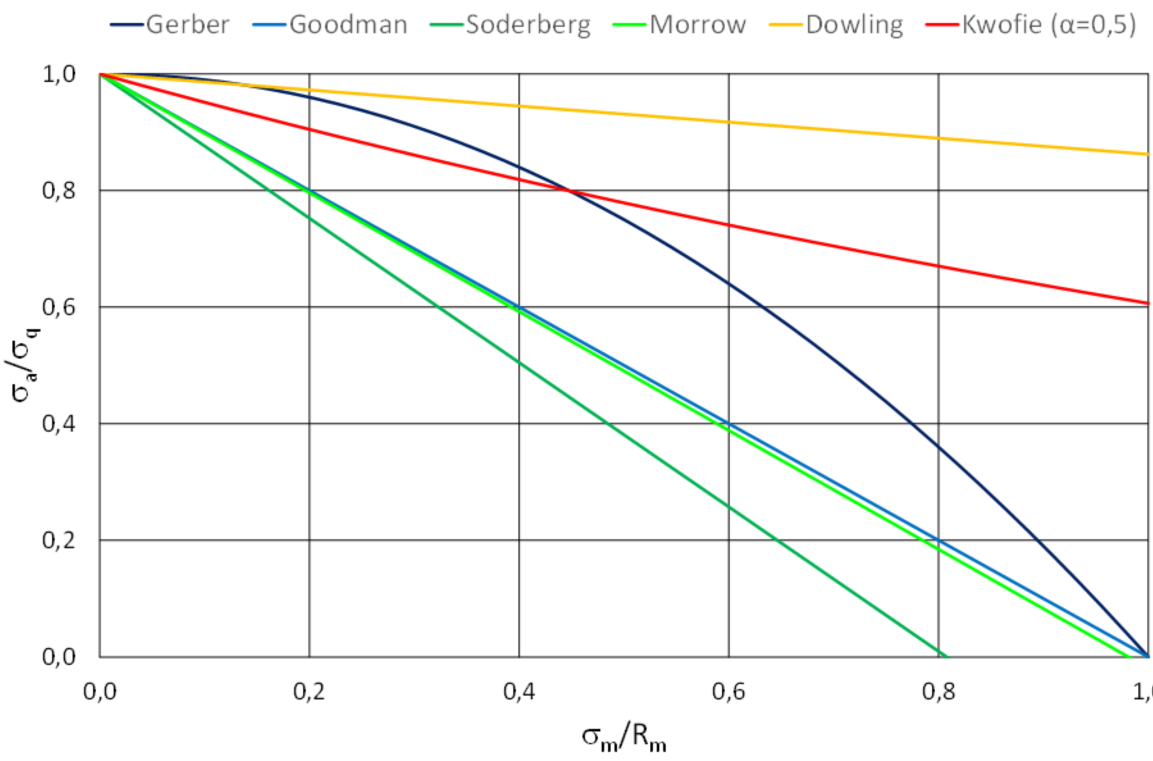

Fig. 4: Various models to describe the mean stress influence

5 Tests and evaluation

The tests were carried out with samples of two wires, one galvanized wire and one bright wire. Each of both wires had a diameter δ = 1.00 mm and actual tensile strengths of R_m = 2273 N/mm² for the galvanized wire and R_m = 2196 N/mm² for the bright wire. With both wires 61 rotary bending tests and 20 tension-tension tests were carried out [16, 17 and 18].

Due to the fact, that in rotary bending tests mean stress is zero, the corresponding bending stress for an achieved number of tension-tension cycles is the equivalent stress σ_q and can be calculated out of Equation (1). That means that tension-tension tests will be traced back to rotary bending tests. By that, a limited area for mean stress and amplitude stresses are possible only. In order to be in each case within the fatigue life area (detected by rotary bending tests) stress configurations of performed tension-tension tests were selected in the range between $\sigma_m = 0.45\ R_m$ / $\sigma_a = 0.27\ R_m$ and $\sigma_m = 0.59\ R_m$ / $\sigma_a = 0.23\ R_m$. The subsequently possible lower und upper tensions are $\sigma_{lower} = 0{,}18\ R_m$ und $\sigma_{upper} = 0{,}82\ R_m$. These area is drawn by help of limitation lines in Fig. 5. A trace back of tension-tension tests to rotary bending tests seems to be possible.

The results of rotary bending tests (mean stress zero) and tension-tension tests (means stress between the limitation lines) are drawn in Fig. 5 too. Gerber-Parable and Goodman straight line, which are drawn in Fig. 5 too show that test results can be described with an approach which is similar to Gerber´s and Goodman´s one. The exponent of the breaking strength related mean stress has to be within 1 and 2. By regression calculation the exponent is calculated to x = 1.58 and the standard deviation to s(x) = 0.16. The standard deviation of $s(\sigma_a/\sigma_q)$ is calculated to 0.039. With the standard deviation of x and with an assumed normal deviation of x Goodman´s curve can be interpreted as the statistical 0.01%-curve and Gerber´s curve as the statistical 99.6%-curve. For tension-tension tests with rope wires the equivalent stress σ_q can be calculated with Equation (12).

$$\sigma_q = \frac{\sigma_a}{1-\left(\frac{\sigma_m}{R_m}\right)^{1.58}} \tag{12}$$

As a second approach the exponential approach of Kwofie will be investigated. For each tension-tension test a factor α via Equation (11) can be calculated. The calculated factors α for all 20 tension-tension tests have the mean value α = 0.85 and the standard deviation $s(\alpha)$ = 0.074. The standard deviation $s(\sigma_a/\sigma_q)$ is calculated to 0.030. For tension-tension tests with rope wires the equivalent stress σ_q can also be calculated with Equation (13).

$$\sigma_q = \sigma_a \cdot e^{\left(\alpha \cdot \frac{\sigma_m}{R_m}\right)} \tag{13}$$

Both regression curves are drawn in Fig. 5 too. Both equations describe the test results very well, Equation (13) even a little better. With the equivalent stress σ_q calculated by Equation (12) or Equation (13) the number of expected number of tension-tension cycles can be calculated with Equation (1).

Rope wires can be treated as solid rods. Because of the helical nature of wire ropes formed of many individual wires and their ability to slide over each other, fatigue test results of wires especially results of tension-tension tests with wires cannot be adapted to wire ropes. Tension-tension behaviour of wire ropes have been described in a very extensive literature. [19], [20] and [21] are given exemplarily.

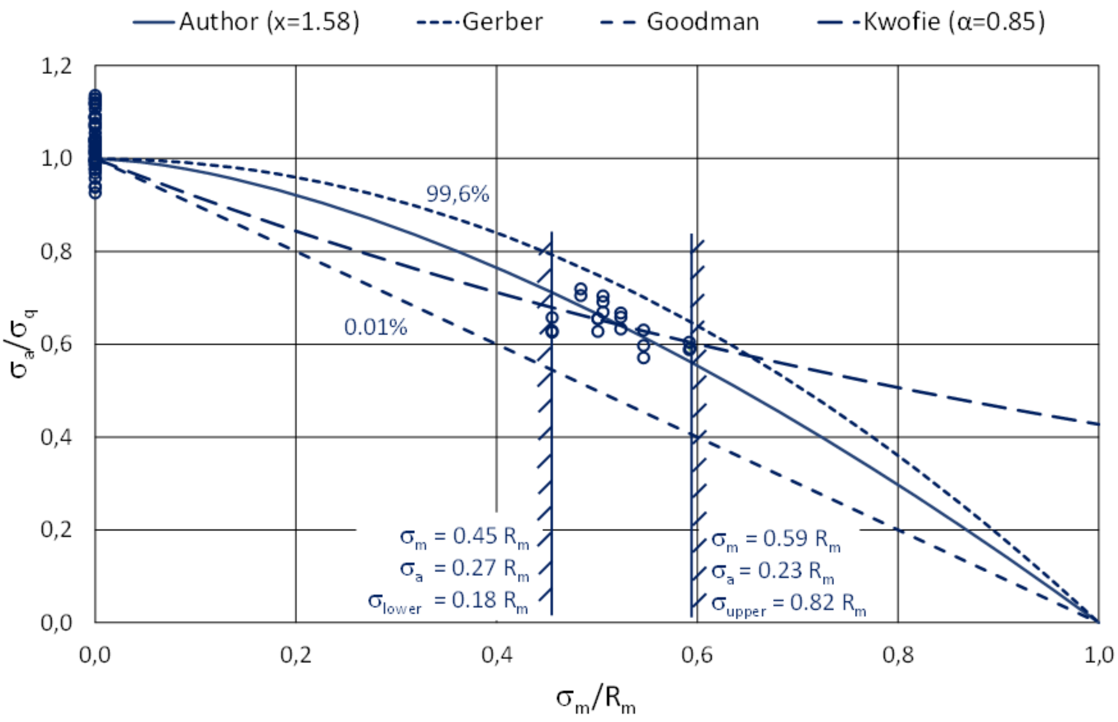

Fig. 5: Area of selected mean stresses, test results and regression curve of Author and influence curves of Gerber, Goodman and Kwofie

6 Conclusion

For describing the mean stress influence of rope wires two models have been investigated, a modified model similar to Gerber´s and Goodman´s models and Kwofie´s model adapted to rope wires. Both models describe the test results very well. With help of these models and with the lifetime equation of rotary bending tests the expected number of tension-tension cycles can be reliable estimated for the very first time.

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