Evaluation of fatigue strength criteria for thick-walled nodular cast iron components from EN-GJS-400 under multiaxial load

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Abstract. This paper discusses the quality of common methods for estimating the fatigue strength of EN-GJS-400-18-LT specimens under multiaxial stress. This is particularly important for the lightweight design of wind turbines. Experimental fatigue tests with axial, torsional and combined loads with a load ratio of R = -1 were performed. The results of these fatigue tests are used to validate commonly used multi-axial stress hypotheses. The investigated methods are the von Mises hypothesis, the Findley-criterion, the modified Gough-Pollard method and the critical plane nominal stress hypothesis.

1 Introduction

Due to the growing demand for regenerative energy production, developments in wind energy technology are leading to more powerful wind turbines and thus increasing turbine sizes [1]. For their realization, an improved utilization of the lightweight design potential is essential, taking into account the required component strength and reliability. Since for cyclically loaded large components an experimental fatigue strength verification can only be performed with economically unacceptable effort, the calculated fatigue life estimation based on available or easy to determine methods is of central importance. The accuracy of the methods used here is crucial for the reliability of the calculation results. The methods used so far, in particular for assessing the fatigue strength, have not been verified for thick-walled cast parts, such as those found in wind turbines, and can therefore only be used with high safety factors. The fatigue life under combined loads depends to a great extent on the locally available material properties, especially the toughness. However, it is not known how the ductile EN-GJS-400, which is widely used in wind turbine construction, will behave under non-proportional multiaxial stresses.

In the first part of this paper, the experimental fatigue strength of EN-GJS-400-18-LT specimens under axial, torsional and combined loading is presented. For combined loading, experiments with a phase shift of 0° and 90° between the axial and torsional loads are carried out. In the second part, a number of fatigue strength criteria for multiaxial loading is validated. In addition to the criteria given in commonly used recommendations (Eurocode 3, DNV GL), two methods from the literature (v.Mises equivalent stress hypothesis, Findley

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hypothesis) are examined. The required characteristic values are determined on the basis of the fatigue tests from part one. The results of the individual methods are then validated using the results of the fatigue tests with combined loading.

2 Experiments

2.1 Material and specimen geometry

The tests were carried out with slightly notched cylindrical specimens ($K_{t,tension}$ = 1.27, $K_{t,torsion}$ = 1.13 using von Mises stress) made out of nodular cast iron EN-GJS-400-18-LT. The specimens have a diameter of 20 mm in the cross section, **Fig. 1**. They were taken from Y blocks, which measure 260 mm x 500 mm x 260 mm at the point where the samples were taken.

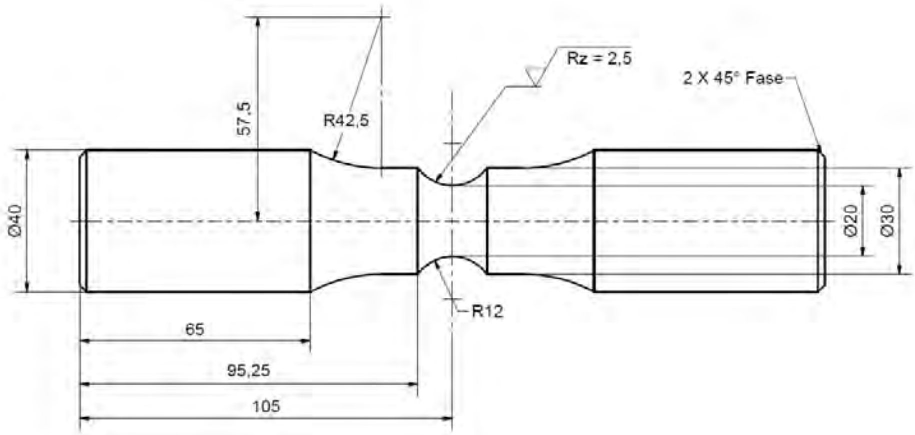


Fig. 1. Geometry of the specimen.

Static tensile tests were carried out on 25 Specimens to evaluate the mechanical properties of the material. The results are given in **Table 1.** The chemical composition was also analysed and is shown in **Table 2.**

Table 1. Mechanical properties of the analysed cast iron EN-GJS-400-18-LT

Tensile strength	0.2% proof strength ($R_{p,0.2}$)	Elongation at fracture	Necking	Impact energy 20°C
361 MPa	229 MPa	15.5 %	10.6 %	11.77 J

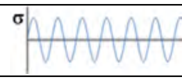
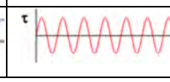
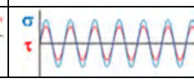
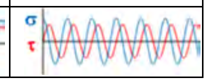
Table 2. Chemical composition in % by mass for EN-GJS-400-18-LT

Element	C	Si	Mn	P	S	Mg	Cr
% by mass	3.740	2.120	0.240	0.013	0.005	0.040	0.030

2.2 Testing and experimental results

The results presented here cover four test series. Pure tension and torsion tests were carried out for a load ratio of R = -1. Tests with combined loads were carried out with a phase shift of φ = 0° and φ = 90° and a load ratio of R = -1. Based on the results of the uniaxial fatigue tests, the ratio of the load by a torsional moment to that of the axial force used for the combined tests was chosen in such a way that the specimens are equally damaged by both loads ($M_T/F = 5.25$). **Table 3** shows the tests presented in this work:

Table 3. Test series carried out

Load ratio	Pure tension	Pure torsion	Combined load	
			φ = 0°	φ = 90°
R = -1				

Three different machines were used to carry out the tests presented below:

- Pure tension: resonance pulser, load cell: F = 100 kN, frequency f ≈ 125 Hz
- Pure torsion: servo hydraulic, load cell: M_T = 5000 Nm, frequency f = 30 Hz
- Combined load: servo hydraulic, load cell: M_T = 5000 Nm, F = 100 kN, frequency f = 15 Hz

In order to identify a possible influence of the frequency of the individual testing machines on the fatigue strength, specimens from the test series "pure tension" and "pure torsion" were carried out using the testing machine for combined tests. The results were within the scatter band of the remaining tests. For this reason, the influence of frequency on the test results was considered negligible.
All tests have been performed under load control in the range $10^4 \leq N \leq 10^7$. The failure criterion was defined as 2 % drop in stiffness for the servo-hydraulic machines and 0.1 % drop in frequency for the resonance pulser. The SN-curve parameters determined by statistical analysis from the experiments are given in **Table 4.** With the exception of k*, all parameters were derived from the test results. Due to the weak data situation in the area of very high numbers of cycles, the slope k* after the break point was chosen according to the recommendation of [2].

Table 4. SN-curve parameters based on the fatigue tests carried out.

Load	No spec.	N_k	F_a	M_a	k	k*	$1/T_S$
Pure tension	17	$6.3 \cdot 10^6$	35.65 kN	-	7.57	45	1.15
Pure torsion	14	$7.9 \cdot 10^6$	-	209 Nm	10.8	45	1.10
Comb. load, $\varphi = 0$	12	$3.2 \cdot 10^6$	24.76 kN	123 Nm	8.03	45	1.14
Comb. load, $\varphi = 90$	13	$4.0 \cdot 10^6$	28.58 kN	150 Nm	9.14	45	1.06

Based on the test results, SN-curves for a survival probability of 50% were estimated, see **Fig. 2**. It can be seen that a pure torsional load results in a slightly higher slope k than a pure axial load. The SN-curves for combined loading have a similar slope, which lies between that for pure axial and torsion loads. For combined loads, a phase shift of φ = 90° compared to φ = 0° results in a slightly longer fatigue life. This characteristic is usually observed for brittle materials [3], but has also been observed in the past for the semi ductile material EN-GJS-400 [4, 5]. In the experimental results, this effect can be identified primarily for high numbers of cycles. For lower number of cycles the influence of the phase shift on the fatigue life diminishes.

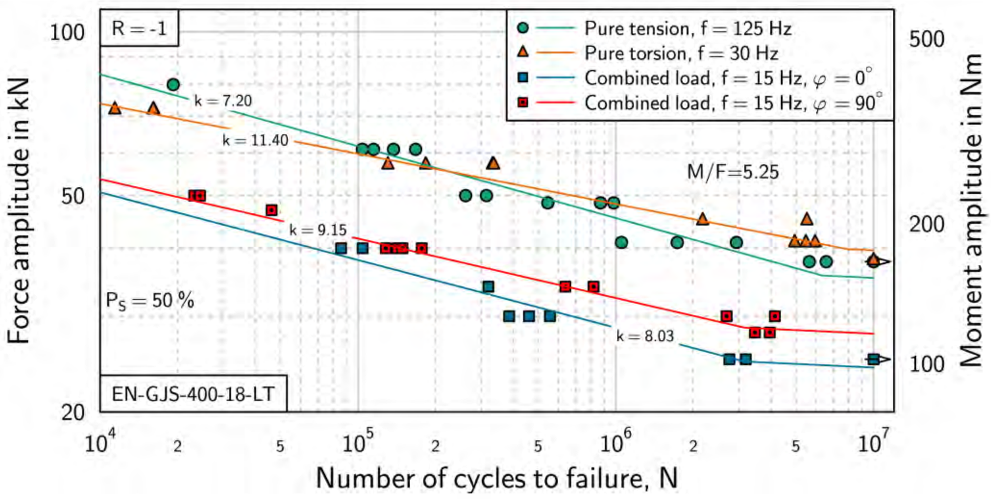


Fig. 2. Experimental results for pure tension, pure torsion and combined loading with and without phase shift. The ratio of force to moment amplitude is 1:5.25 at all times.

3 Fatigue life hypothesises

In this paper, the following stress-based multiaxial methods are investigated: The von Mises hypothesis, the Findley criterion [6], as well as the modified Gough-Pollard method recommended in Eurocode 3 [7] and the critical plane normal stress hypothesis referred to in DNV GL [8] for the given material EN-GJS-400-18-LT. The four methods mentioned are briefly presented in the following for the here considered case of a load ratio of R = -1 and constant amplitudes. For a more detailed explanation, we refer to the literature at this point.

3.1 Von Mises hypothesis

The von Mises hypothesis is the simplest of the methods presented here. The time history of the von Mises comparative stress is calculated according to the following formula

$$\sigma_{vM}(t) = \operatorname{sign}(\max(|\sigma_1(t)|, |\sigma_2(t)|)) \cdot \sqrt{\sigma_x(t)^2 + \sigma_y(t)^2 - \sigma_x(t) \cdot \sigma_y(t) + 3 \cdot \tau_{xy}(t)^2} \quad (1)$$

where the sign is determined by the principal stresses σ_1 and σ_2. The mean stress $\sigma_{vM,m}$ and the amplitude $\sigma_{vM,a}$ can be derived from $\sigma_{vM}(t)$. The equivalent stress amplitude is considered crucial for the fatigue strength.

3.4 Critical plane normal stress hypothesis (CPNS)

For the critical plane nominal stress hypothesis the normal stress σ_i(t) is calculated for each plane i. Based on this, the normal stress amplitude $\sigma_{a,i}$ and the mean stress $\sigma_{m,i}$ can be determined. The greatest stress amplitude of all planes is considered as relevant for the fatigue life, see Eq. (2). The respective plane is called the critical plane:

$$\sigma_{CPNH,a} = \max_{plane\ i} (\sigma_{a,i}) \quad (2)$$

3.2 Findley-criterion (FIN2)

The Finley-criterion is also a critical plane method, i.e. the criterion is applied to a number of cutting planes. Since the failure starts from the surface where a plane state of stress is present, the critical plane method is used for the 2D case. The plane at which value of f_{fin} reaches its maximum is assumed to be critical:

$$f_{fin} = \max_{plane\ i} (\tau_{a,i} + k_{fin} \cdot \sigma_{n,max,i}) \quad (3)$$

In Eq. (3) $\tau_{a,i}$ denotes the shear stress amplitude in plane i, $\sigma_{n,max,i}$ the maximum normal stress in plane i and k_{fin} a material parameter, which is obtained using the experimental fatigue life data for pure axial and pure torsion loadings from chapter 2.

3.3 Modified Gough-Pollard method (EC3)

The basis for the fatigue life evaluation under combined loading according to Eurocode 3 design code is a modified form of the Gough-Pollard criterion [9]. This criterion is given in Eq. (4).

$$\left(\frac{\sigma_{a,comb}}{\sigma_{a,pure\ axial}(N)}\right)^3 + \left(\frac{\tau_{a,comb}}{\tau_{a,pure\ torsion}(N)}\right)^5 \leq 1 \quad (4)$$

$\sigma_{a,comb}$ and $\tau_{a,comb}$ represent the local normal and shear stress and $\sigma_{a,pure\ axial}(N)$ and $\tau_{a,pure\ torsin}(N)$ the tolerable normal and shear stress respectively in the uniaxial case for the number of cycles N. The modification of this method consists in the exponents that were originally set to exp = 2.

4 Fatigue life evaluation

For the application of the different multiaxiality methods, the local stress components in the notch are required. To determine these, a finite element model of the specimen was created. The specimen was set up as a 2D model under utilization of the rotational symmetry. The boundary conditions of the finite element model are shown in **Fig. 3.**

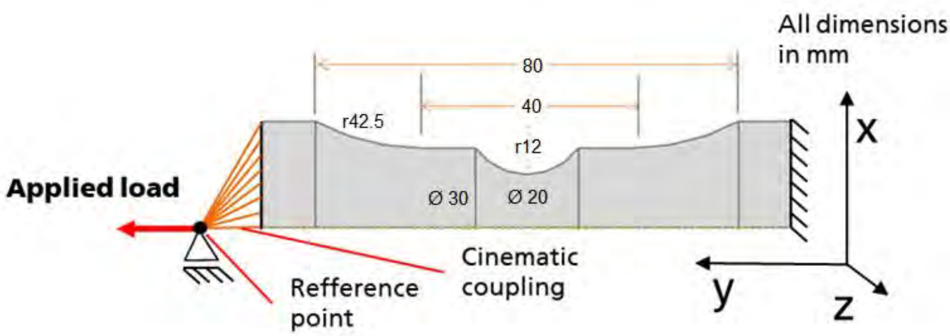


Fig. 3. Boundary conditions used in the FE-model

In **Table 5,** the stress components in the notch are given, which result from a load of F = 1 kN for pure tension and M_T = 1 Nm for pure torsion respectively. The stress components for combined load were determined by superposition of the two load cases mentioned above.

Table 5. Notch stress components calculated by the finite element method in the notch

Load	σ_y	σ_z	τ_{yz}
Pure Tension	4.352	0.682	-
Pure Torsion	-	-	0.717

This results in a stress ratio of normal to shear stress of 1:1.16 for the combined tests for the given force-to-torsion ratio of 1:5.25.

After determination of the local stress components the calculation of individual component SN-curves according to the individual methods was carried out. The results are shown in **Fig. 4. – 7.** along with the results of the experimental fatigue tests. In the figures, the external load is plotted over the number of cycles to failure (N).

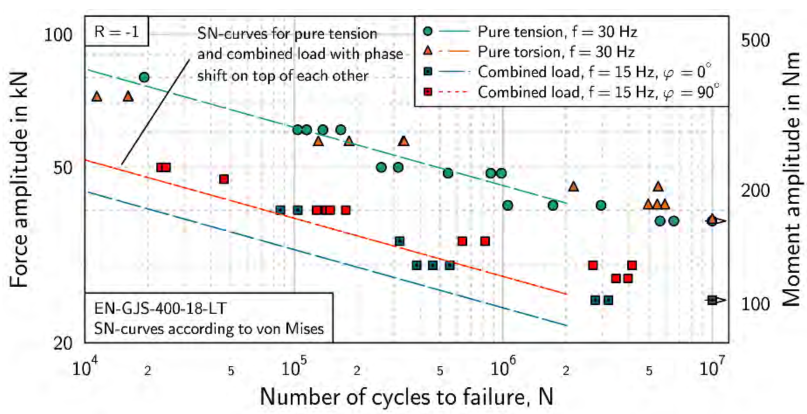


Fig. 4 Numerically derived component SN-curves according to the von Mises criterion in comparison with the experimental results.

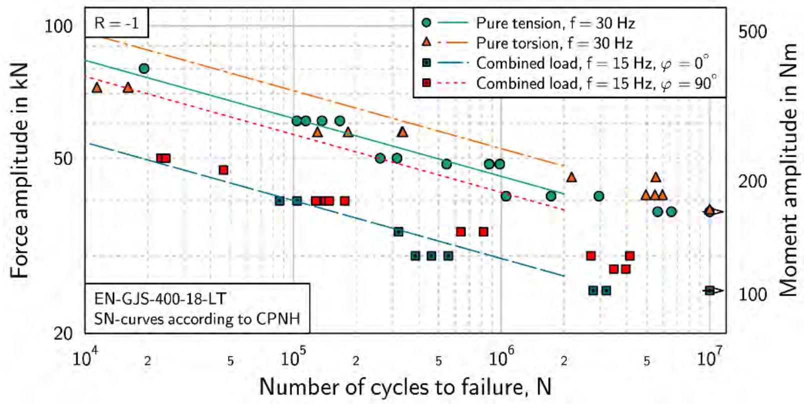


Fig. 5. Numerically derived component SN-curves according to the critical plane nominal stress hypothesis in comparison with the experimental results.

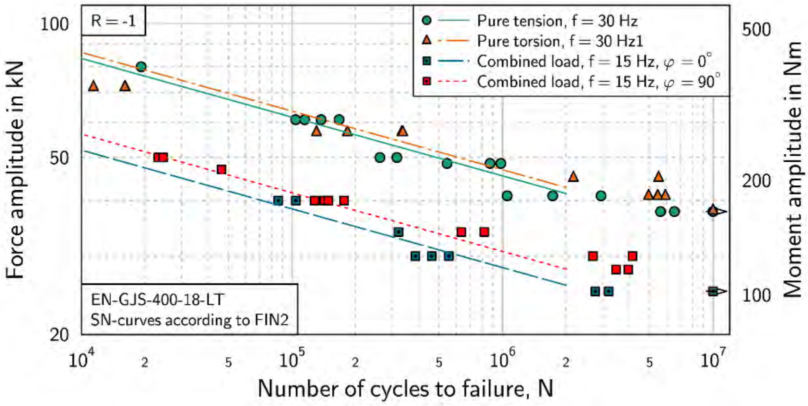


Fig. 6. Numerically derived component SN-curves according to the Findley hypothesis in comparison with the experimental results.

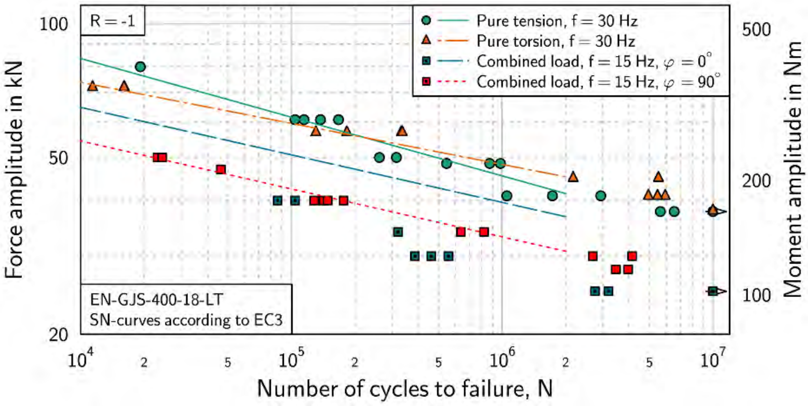


Fig. 7. Numerically derived component SN-curves according to the Eurocode 3 recommendation in comparison with the experimental results.

5 Conclusions

Four different stress based multi-axis hypotheses were validated. The von Mises criterion, the critical plane normal stress hypothesis according to the DNV GL recommendation, the Findley hypothesis and a modified version of the Gough-Pollard criterion according to the Eurocode 3 recommendation were evaluated. The validation was based on the results of experimental fatigue tests on slightly notched cast iron EN-GJS-400-18-LT cylindrical samples. The following load cases were investigated: pure tension, pure torsion and combined loads with a phase shift of 0° and 90°. All tests were performed with a load ratio of R = -1. The following results were obtained:

- Von Mises hypothesis: A strongly conservative estimation for pure torsion results. Combined tests also yield conservative results. The influence of the phase shift on the fatigue strength is accurately reflected.
- DNV GL: For the critical plane normal stress hypothesis non-conservative results are obtained for pure torsion and combined load with phase shift. For combined tests without phase shift, the test results are well represented. Although the method correctly predicts a higher number of cycles for tests with phase shift, the effect is strongly overestimated.
- Findley Hypothesis: This is the best estimate of all investigated methods. The test results can be well represented for pure torsion as well as for combined loads with and without phase shift. The influence of the phase shift is represented correctly.
- Eurocode 3: The modified Gough Pollard criterion is able to accurately model the test results for pure torsion and combined load with phase shift, but for combined load without phase shift there are strongly non-conservative results. In contrast to the methods described above, a lower tolerable number of cycles is obtained for combined tests with phase shift than for those without phase shift.

A comparison of the 4 applied methods shows that the Findley hypothesis is best able to estimate the test results. For a more general statement, however, further study is needed. In order to implement this, a load ratio of R = 0, variable amplitude loading as well as a number of more complex multi-axis methods are being investigated in current investigations.

6 Acknowledgement

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