FATIGUE LIFE OF CAST IRONS GGG40, GGG60 AND GTS45 UNDER COMBINED RANDOM TENSION WITH TORSION

T. Łagoda[1], E. Macha[1], A. Niesłony[1] and A. Müller[2]

[1]Technical University of Opole, Department of Mechanics and Machine Design
ul. Mikołajczyka 5, 45-271 Opole, Poland
[2]Fraunhofer-Institut für Betriebsfestigkeit Darmstadt,
now: BMW AG, EG-542, D-80788 München, Germany

ABSTRACT

The paper contains the fatigue tests results for specimens made of three cast irons under proportional and non-proportional random tension with torsion. The experimental data for long fatigue life have been compared with those calculated according to the algorithm with use of the modified criterion of the maximum normal stress in the critical plane. In the considered algorithm the Palmgren-Miner hypothesis of damage cumulation seems to be useless whereas the Serensen-Kogayev hypothesis gives satisfactory results.

INTRODUCTION

The known algorithms of fatigue life estimation in elements of machines and structures under multiaxial random loading are not well supported by the experimental results. Some of those algorithms have been verified for some steels but we do not know if they are also efficient in the case of cast irons [1]. The aim of this paper is to verify one algorithm for three cast irons. The specimens were subjected to combined random tension with torsion.

FATIGUE TESTS

The fatigue tests were done on a stand for tension-compression with torsion, made by Schenck (series 31), in LBF laboratories in Darmstadt, Germany [2, 3, 4]. While the machine operating, the force was controlled. The specimens were made of three materials: spheroidal cast irons GGG40 and GGG60 and malleable cast iron GTS45. On the basis of microscopic examination the materials could be classified of isotropic. The materials are cyclically hardened. The basic strength parameters are shown in Table 1. The details concerning the realized fatigue tests are given in [2, 3, 4]. Cylindrical specimens with solid cores were used in the tests. The specimen dimensions are given in Fig.1. The specimens of GGG40 and GTS45 and of GGG60 were different but they had the same minimal diameter at the bottom of the spherical relief and the notch effect coefficient for tension – compression α_k was 1.05 for specimen a) and 1.04 for specimen b). These differences do not strongly influence the results of experiments and they can be neglected. For further considerations we assume that the applied specimens have the same shape and the notch coefficient α_k is 1, so they are the smooth specimens.

In the case of uniaxial tension-compression and torsion loading was applied with use of a digitally generated standard time series g(t) with zero expected value. The series was suitably scaled for obtaining the required maximum histories of normal stress, σ_{max} and shear stress, τ_{max}. In the case of combined tension-compression with torsion we realized proportional loading with the correlation coefficient of normal and shear stress equal to 1 ($r_{\sigma,\tau} = 1$) and non-proportional loading with the stress correlation coefficient equal to 0 ($r_{\sigma,\tau} \approx 0$). Uncorrelated stress histories were obtained with use of frequency modulation of loading generating normal stress under the standard history g(t) in torsional loading. For both proportional and non-proportional loading relation between the maximum values of tensile stress $\sigma_{xx\ max}$ and torsional stress $\tau_{xy\ max}$ was 1. Frequency of torsion history extrema was constant and frequency of tension-compression history extrema was changing (the normal stress increment between the successive extrema at time was constant).

TABLE 1.
BASIC STRENGTH PARAMETERS OF THE TESTED CAST IRONS

		GGG40	GGG60	GTS45
$R_{0.2}$	MPa	322	427	310
R_m	MPa	440	649	469
A_5	%	10.9	10.6	9.4
Z	%	10.6	9.7	8.1
E	GPa	167	160	167
ν		0.29	0.29	0.27

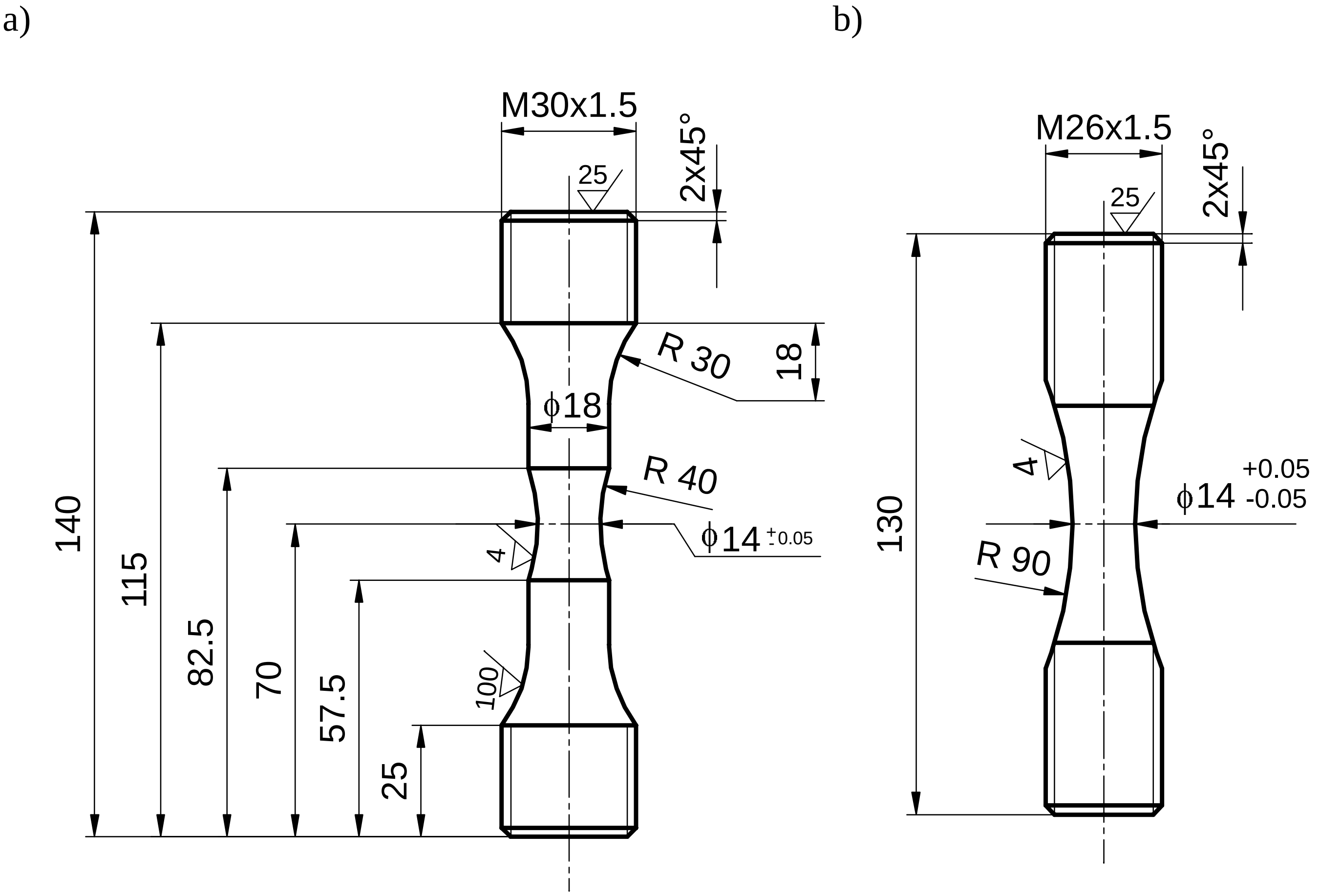


Figure 1: Specimens used in tests a) cast irons GGG40 and GTS45, b) cast iron GGG60

Numbers of cycles up to fracture have large scatters. Thus, it is difficult to verify the proposed calculation models. For example, in the case of GGG40 cast iron under tension-compression and the maximum stress amplitude 300 MPa the minimal life is $1.937 \cdot 10^6$ cycles and the maximum one $19 \cdot 10^6$ cycles, so tenfold scatter is observed. In the case of proportional loading with normal and shear stress correlation coefficient equal to 1 ($r_{\sigma,\tau} = 1$) we can observe a greater life than in the case of non-proportional loading with the stress correlation coefficient equal to 0 ($r_{\sigma,\tau} \approx 0$) for the same maximum stress levels.

ALGORITHM FOR FATIGUE LIFE DETERMINATION

Figure 2 shows a diagram of the algorithm for fatigue life determination under multiaxial random loading. The algorithm was used for analysis of the experimental data.

1	Generation of $\sigma_{ij}(t)$, $(i, j = x, y, z)$
2	Determination of the expected critical plane direction
3	Calculation of the equivalent stress history
4	Cycle counting
5	Calculation of damage degree and fatigue life

Figure 2: Algorithm for fatigue life determination under multiaxial random loading

The stress $\sigma_{ij}(t)$ was generated in the same way as during experiments, by a suitable scaling of the standard history g(t). For determination of the expected direction of the critical plane the damage cumulation method was applied. In this method the fatigue damage is cumulated at many planes; next the plane of the maximum damage is chosen. In such a way we obtain not only a direction of the expected fracture plane but the fatigue life as well [1].

For determination of the equivalent stress the criterion of maximum normal stress in the fracture plane was applied. The criterion was modified, by ratio of the fatigue limits for tension and torsion, i.e.

$$\sigma_{eq}(t) = l_\eta^2 \cdot \sigma(t) + 2 l_\eta m_\eta \frac{\sigma_{af}}{\tau_{af}} \cdot \tau(t) \tag{1}$$

where:
$l_\eta = \cos(\varphi)$, $m_\eta = \sin(\varphi)$,
φ - angle between the longitudinal axis of the specimen and the expected direction of the critical plane $\overline{\eta}(l_\eta, m_\eta)$,
$\sigma(t)$, $\tau(t)$ –histories of the normal and shear stress,
σ_{af}, τ_{af} – fatigue limits for tension and torsion, respectively.

In this paper the rain flow method was used for schematization of random histories. For damage accumulation three hypotheses were applied, i.e:.

- Palmgren-Miner hypothesis

$$S_{PM}(T_0) = \begin{cases} \sum\limits_{i=1}^{j} \dfrac{n_i}{N_0 \left(\dfrac{\sigma_{af}}{\sigma_{ai}} \right)^m} & \text{for } \sigma_{ai} \geq a \cdot \sigma_{af} \\ 0 & \text{for } \sigma_{ai} < a \cdot \sigma_{af} \end{cases} \tag{2}$$

where:
n_i – number of cycles with amplitudes σ_{ai} in T_0,
m – Wöhler curve exponent,
N_0 –number of cycles corresponding to the fatigue limit σ_{af} ,
T_0 – observation time equal to 1 block including 50048 cycles,
a = 0.5 – coefficient including influence of amplitudes less than the limit σ_{af} .

- Corten – Dolan hypothesis

$$S_{CD}(T_0) = \sum_{i=1}^{j} \frac{n_i}{N_1}\left(\frac{\sigma_{ai}}{\sigma_{a1}}\right)^{q_{CD}} \qquad \text{for} \quad \sigma_{ai} \le \sigma_{a1} \tag{3}$$

where :
σ_{a1}, N_1 – maximum cycle amplitude at T_0 and corresponding number of cycles to fracture (from Wöhler's curve),
$q_{CD} = k \cdot m$ – exponent of the secondary calculation Wöhler's curve (Cortan – Dolan curve),
$k = 0.7 \div 1.0$ and it depends on $\sigma_{ai} / \sigma_{af}$.

- Serensen-Kogayev hypothesis

$$S_{SK}(T_0) = \begin{cases} \displaystyle\sum_{i=1}^{j} \frac{n_i}{b\ N_0 \left(\dfrac{\sigma_{af}}{\sigma_{ai}}\right)^m} & \text{for} \quad \sigma_{ai} \ge a \cdot \sigma_{af} \\ 0 & \text{for} \quad \sigma_{ai} < a \cdot \sigma_{af} \end{cases} \tag{4}$$

where:

$$b = \frac{\sum_{i=1}^{k} \sigma_{ai} t_i - a \cdot \sigma_{af}}{\sigma_{a1} - a \cdot \sigma_{af}} \quad \text{for} \quad (b > 0.1) \text{ - Serensen-Kogayev coefficient}$$

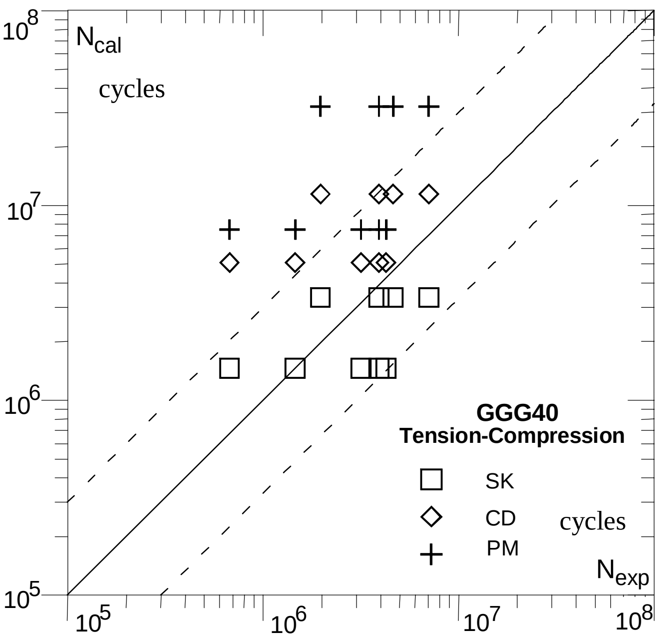
$$t_i = \frac{n_i}{\sum_{i=1}^{k} n_i} \text{ - frequency of occurence of particular levels } \sigma_{a1} \text{ in } T_0$$

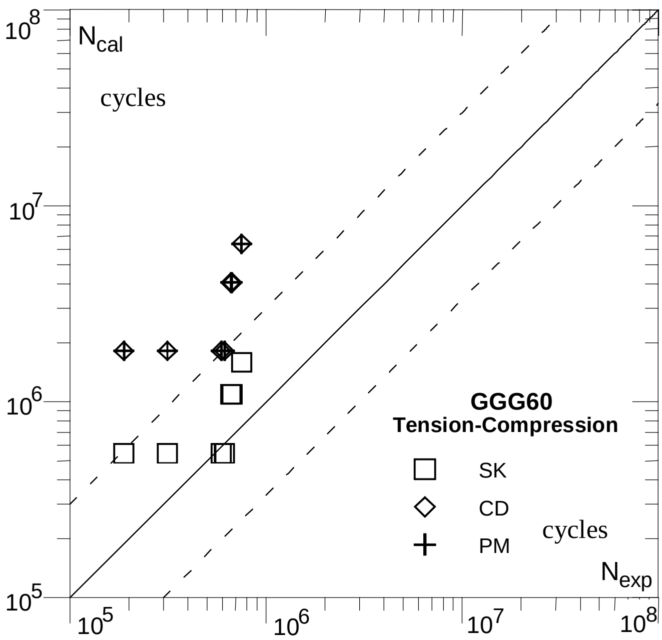
When the damage degree $S(T_0)$ is determined at T_0 according to (2), (3) or (4), we calculate the fatigue life

$$N_{cal} = \frac{T_o}{S(T_o)} \tag{5}$$

COMPARISON OF CALCULATED AND EXPERIMENTAL LIVES

Figure 3 shows comparison of calculated and experimental lives for uniaxial tension-compression according to three considered hypotheses of fatigue damage accululation. Calculations of the fatigue life N_{cal} were done according the algorithm presented in Fig. 2 and with use of relation (5). We can observe that the calculated lives are higher than those obtained while experiments when Palmgren-Miner and Corten-Dolan hypotheses are applied. It could be seen especially under uniaxial loading, where the maxima of the equivalent stress histories are close to the fatigue limit σ_{af} . Applying the Serensen-Kogayev hypothesis, we obtain the best agreement between the calculated and experimental lives. All the results obtained with use of that hypothesis are included in the scatter band with coefficient 3. Only for cast iron GTS45 we obtain greater scatters. Thus, we will use the Serensen-Kogayev hypothesis for further calculations under pure torsion and combined proportional and non-proportional tension-compression with torsion. Figures 4-6 show the calculation results against the experimental data for all the considered cast irons. From the figures it results that most resultes of calculations are included in the scatter band with coefficient 3. Only for cast iron GTS45 greater scatters were obtained, like under uniaxial tension-compression. The calculated directions of the fatigue fracture plane positions for a combination of proportional and non-proportional tension-compression with torsion are included in the range 33-35° and they agree with the experimental directions (~30°) quite well.





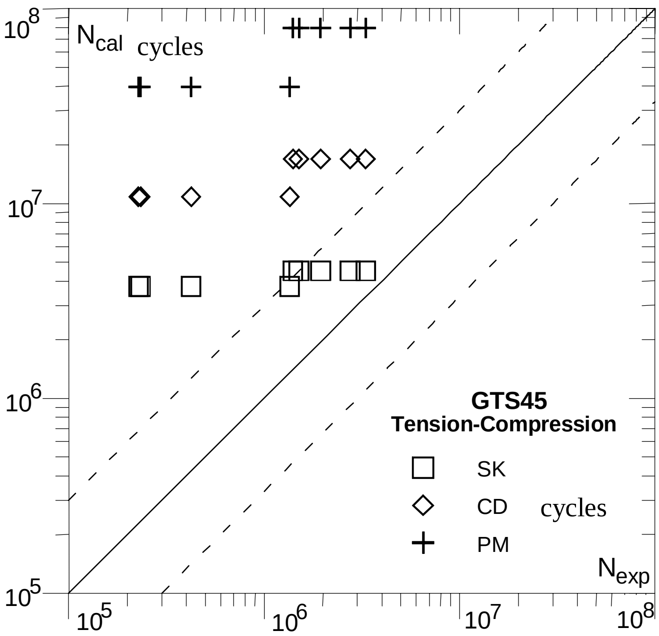


Figure 3: Comparison of the calculated life N_{cal} and the experimental one N_{exp} for three cast irons (GGG40, GGG60 and GTS45) under random tension-compression according to three hypotheses of damage accumulation

CONCLUSIONS

1. From the tests under combined random tension with torsion for three cyclically hardened cast irons it results that non-proportional loading causes fracture more quickly than proportional loading.

2. Fatigue damage summation in the tested cast irons seems to be efficient with use of the Serensen-Kogayev hypothesis. The Palmgren-Miner hypothesis gives unsatisfactory results.

3. The proposed algorithm for fatigue life estimation, based on the modified criterion of maximum normal stress in the critical plane seems to be useful for analysis of the experimental data obtained for the tested cast irons within the long-life time under proportional and non-proportional random loading.

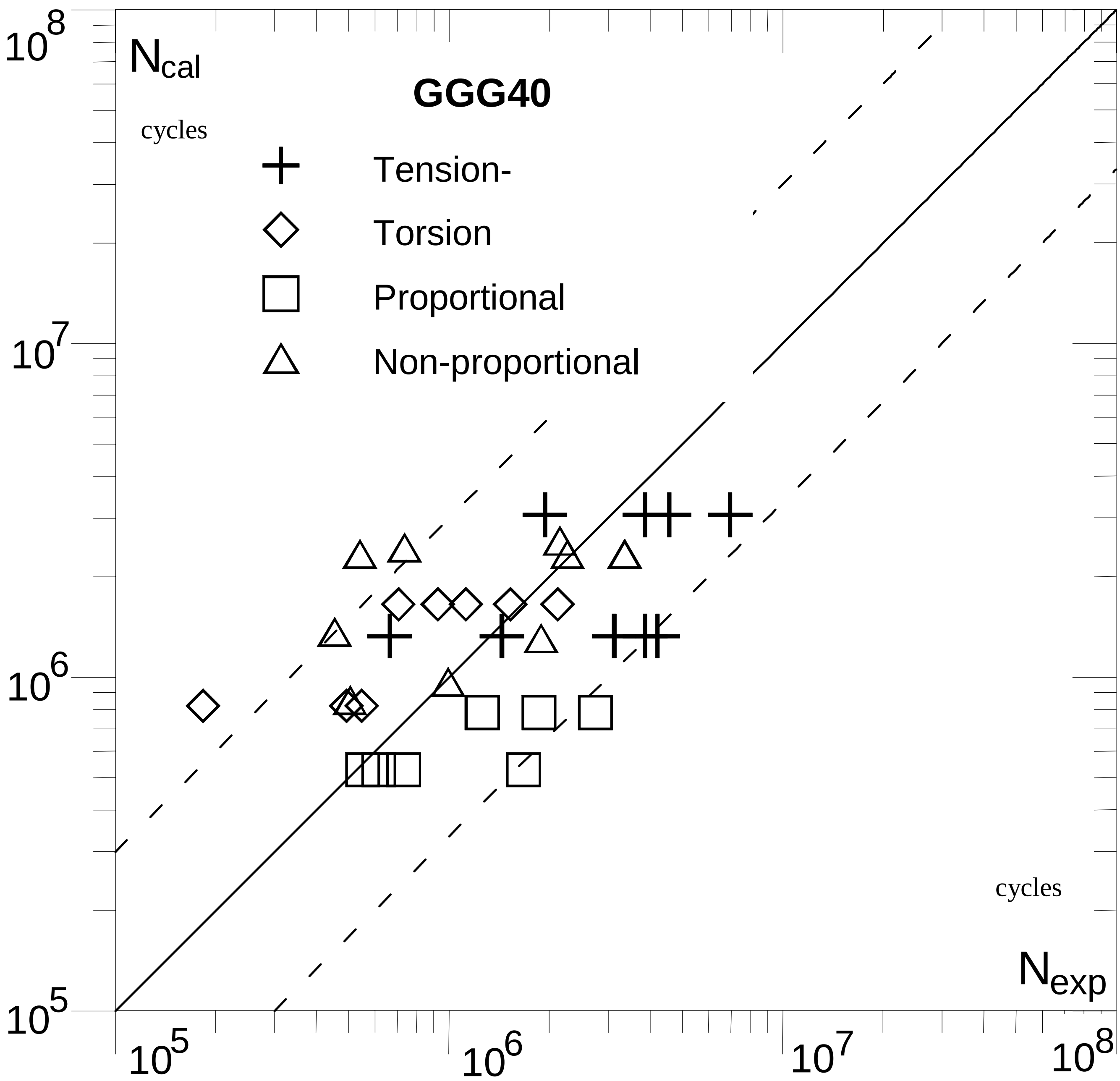


Figure 4: Comparison of the calculated life N_{cal} and the experimental one N_{exp} for GGG40 cast iron under random tension-compression, torsion and proportional and non-proportional tension-compression with torsion according to the Serensen-Kogayev hypothesis

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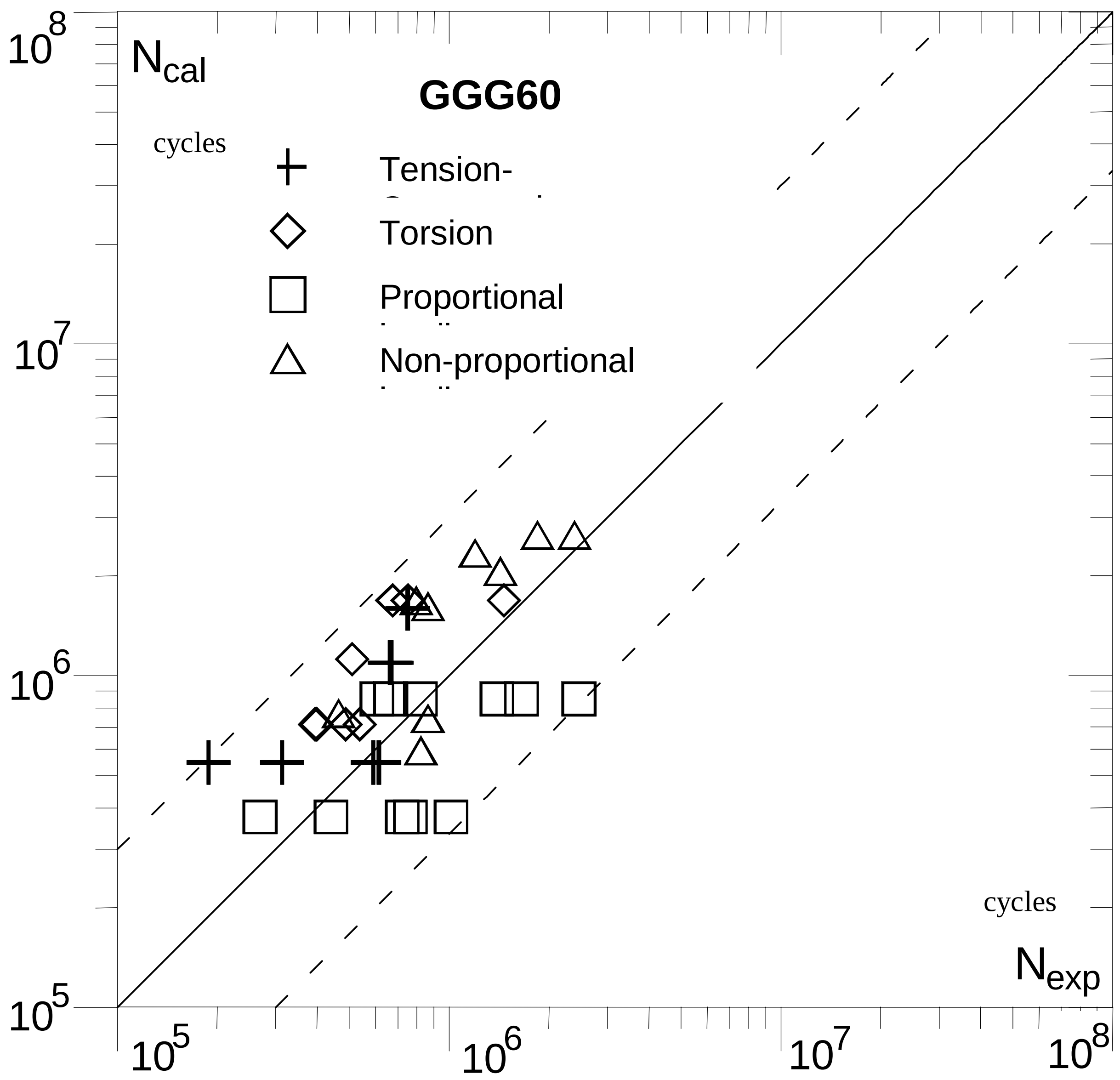

Figure 5: Comparison of the calculated life N_{cal} and the experimental one N_{exp} for GGG60 cast iron under random tension-compression, torsion and proportional and non-proportional -compression with torsion according to the Serensen-Kogayev hypothesis

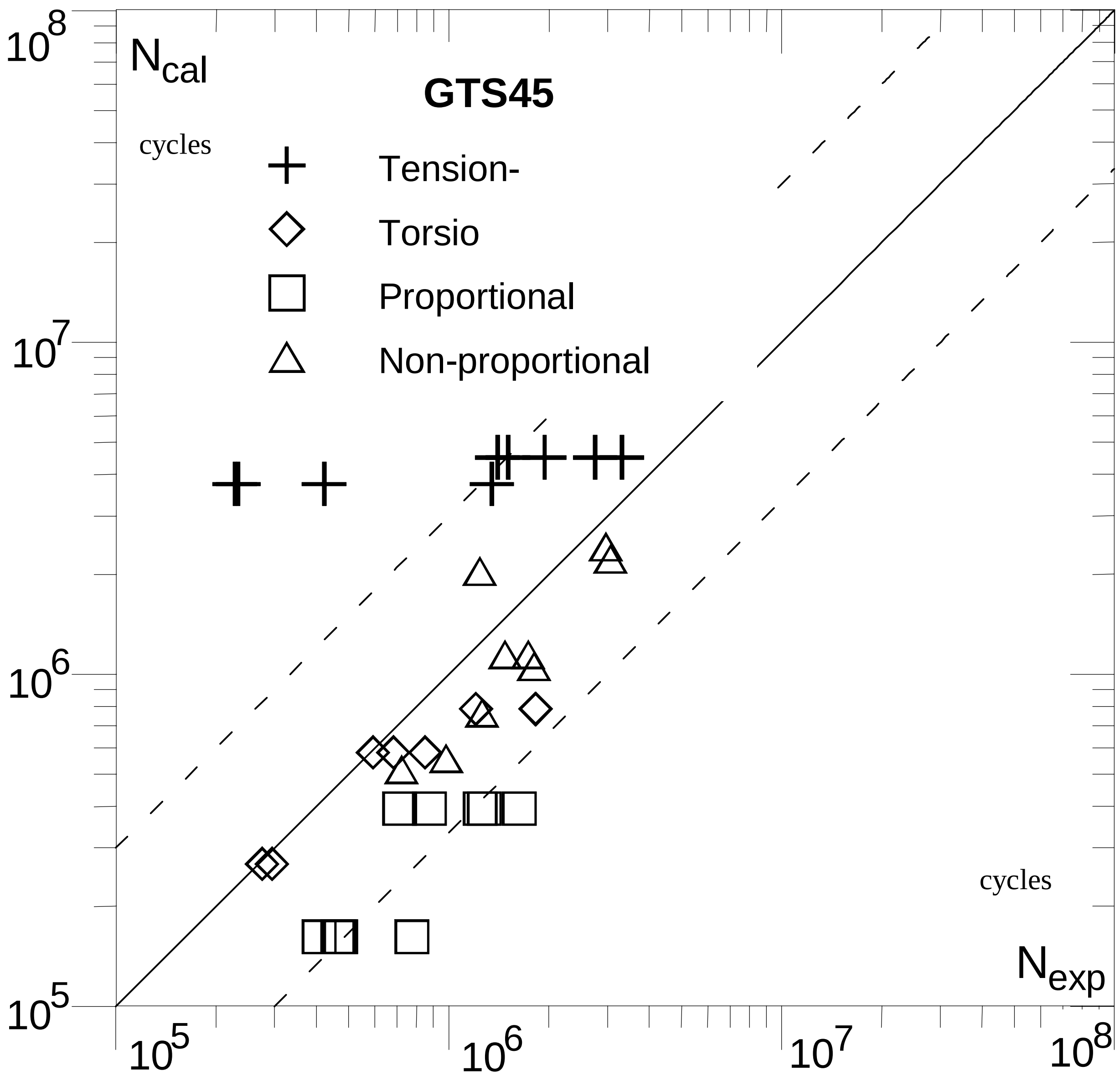

Figure 6: Comparison of the calculated life N_{cal} and the experimental one N_{exp} for GTS45 cast iron under random tension-compression, torsion and proportional and non-proportional -compression with torsion according to the Serensen-Kogayev hypothesis

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