High cycle multiaxial fatigue strength of cast iron: experimental investigation under uniaxial and biaxial loading

R. Tovo[1], P. Lazzarin[2], F. Berto[2], M. Cova[3]

[1] Department of Engineering, University of Ferrara,
Via Saragat 1, 44131 Ferrara, Italy
roberto.tovo@unife.it
[2] Department of Management and Engineering, University of Padova, Stradella San Nicola 3, 36100, Vicenza, Italy
[3] Sacmi Imola S.C. Via Provinciale Selice 17/a, 40026 Imola (BO) Italy

ABSTRACT. *The paper presents new experimental multiaxial fatigue data on cast iron. Several sets of specimens, taken from a real large component, have been tested under uniaxial and biaxial, tensile and torsional loading; in-phase and out-of-phase combined loading have been considered too. Obtained results have been even compared with similar experimental data taken from literature and the tested material showed a high sensibility to mean value of shear stress under torsional loading, as well as the dependence from the mean value of tensile stress under tensile loading. The more suitable fatigue criterion should be related to the larger principal stress variation, but the materials shows even an unusual sensibility to out-phase loading.*

INTRODUCTION

Cast irons have usually good mechanical, physical and manufacturing properties as well as a relatively low production costs. Due to this positive combination of mechanical properties, they had and they will have even in future, several applications, for instance, in the automotive and commercial vehicle industry, as structural material in engines or suspension components or in other structural and non-structural applications as in wind turbines; see [1, 2, 3] among most recent published applied research.

It is well known that fatigue strength of cast iron is related to several parameters and properties, mainly microstructural parameters, ranging from the graphite shape, size and distribution [4], to the matrix ferritic or ferritic-perlitic microstructural properties, as well as defects distribution [5], mainly cavities, porosities and inclusions. One of the main results of this combination of affecting factors is the extreme dependence of fatigue strength from both technological process characteristics and components geometrical peculiarities, mainly size and shape [6], so that cast iron can be investigated regarding a number of different issues.

This paper mainly focuses on multiaxial fatigue behaviour, which is the stress condition frequently occurring in real application [7]. In addition, several contribution states that the multiaxial fatigue criterion and the assessment procedure for defected material is not yet a simple and solved task [8].

The paper mainly presents experimental results obtained on a ductile cast iron under tensile and torsional loading. Then the paper will compare the experimental data with main issues taken from literature considering multiaxial fatigue behaviour of cast iron.

EXPERIMENTAL RESULTS

Fatigue test have been performed on a ductile cast iron EN-GJS-400-18 EN 1563:2011. The considered material was taken from a real large component in order to investigate actual sensitivity to multiaxial fatigue loading of structural components.

Considered specimens are simple cylindrical geometries given in figure 1.

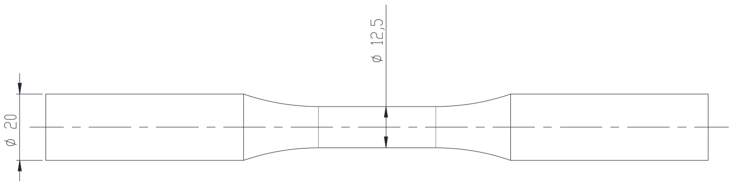

Figure 1: Geometry of specimens

Performed tests considered both uniaxial tensile loading and biaxial loading.

Uniaxial fatigue tests have been carried out on a MTS 810 servo-hydraulic machine with a 250 kN axial load cell; biaxial tests have been carried out on a MTS 809 servo-hydraulic biaxial machine with a 100 kN axial load cell and a torsion load cell of 1100 Nm. All tests have been performed under load control, with a frequency ranging from 1 and 15 Hz, as a function of the load level and multiaxiality.

In uniaxial loading tests have been carried out by changing the stress ratio from positive mean value (R=0) to null o negative mean value (R=-1 ad R=-3).

The biaxial loading has been obtained by combining in the biaxial testing device, torsional and tensile fatigue loading. Simply torsional tests at null and -1 stress ratio have been performed; finally combined “in-phase” and “out-of-phase” tensile and torsional loadings have been investigated too.

Failure criterion was the complete separation of failed specimens; “run-out” tests was interrupted at a number of cycles equal to 3 10^6.

A statistical analysis of obtained results have been done by assuming a log-normal distribution and statistical results are summarised in Table 1. Table 1 shows: the mean values of the nominal stress amplitudes at a reference value of 2 million cycles, the inverse slope k of the SN curves and the scatter indexes. The scatter is assumed constant and the table supplies the logarithmic standard deviation of reference stress σ and the scatter index T, which quantifies the width of the scatter-band included between the 10 and 90% probabilities of survival curves. All failures from 10^4 to 5 10^6 have been processed in the statistical analysis whereas the run-outs were excluded. Results are given as a function of ultimate tensile strength in order to compare sensibility to multiaxial fatigue loading considering irons with different properties.

Figures 2, 3 and 4 show the obtained results in SN curves as well as statistically estimated average behaviour and scatter bands.

From both table 1 and figures, the main outcomes are:

- fatigue strength under tensile and shear loading are quite similar;

- there is a relevant sensibility to mean value of stress so that strength decrease by increasing mean value of tensile stress in uniaxial loading, but also by increasing mean value of shear stress in torsional loading;

-the strength is dependent, in combined loading, from out of phase, compared to in-phase loading.

Table 1. Summary of fatigue strength statistical analysis

Loading	***R***	***Reference strength at 2 10^6***		***k***	***Scatter indexes***	
		T_A/S_{ut}	**σ_A/S_{ut}**		***S***	***T***
Tensile	-1	-	0,376	12.85	0.0298	1,797
Tensile	0	-	0,222	12.4	0.0289	1,769
Tensile	-3	-	0,487	9.4	0.0143	1,353
Torsion	-1	0,364	-	10.07	0.0151	1,375
Torsion	0	0,204	-	5.77	0.0339	1,924
In-phase tensile-tors.	-1	0,225	0,225	7.74	0.0197	1,501
out-phase tensile-tors.	-1	0,259	0,259	8.84	0.0251	1,656

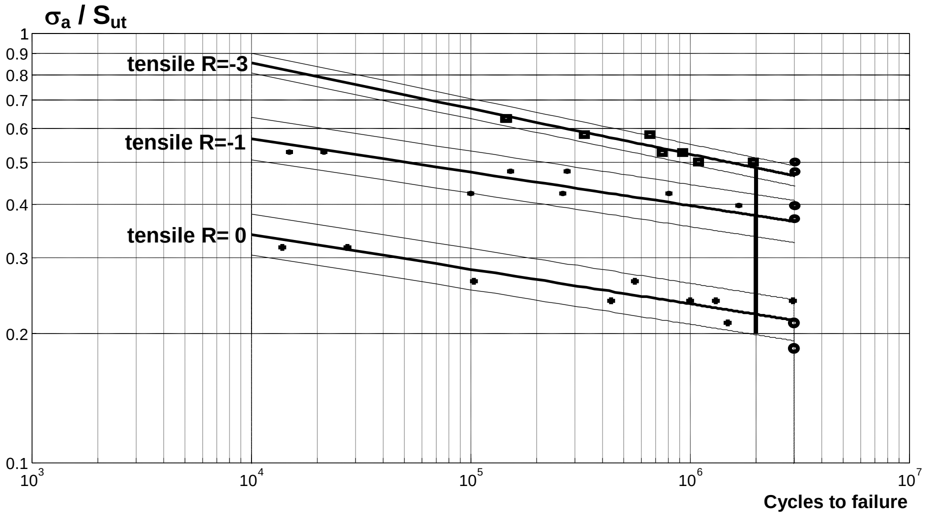

Figure 2: Experimental data of fatigue tests under tensile loading

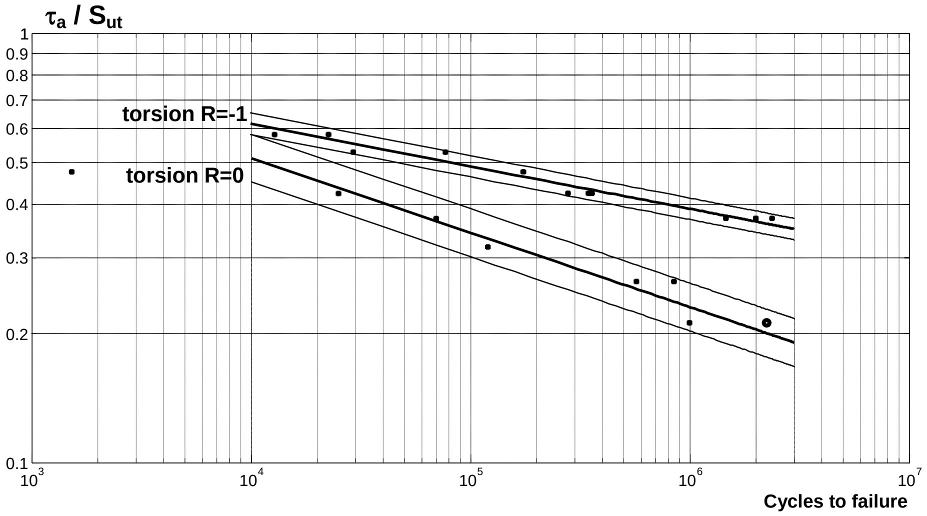

Figure 3: Experimental data of fatigue tests under torsional loading

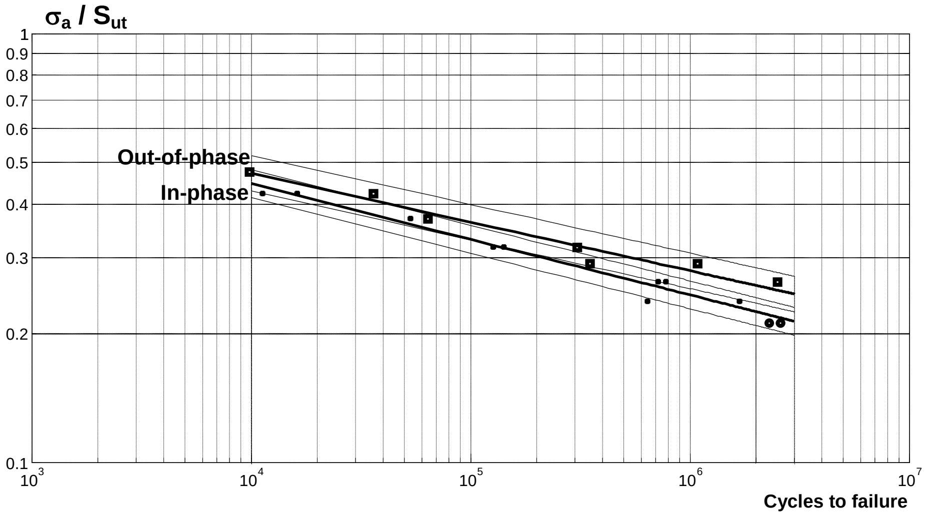

Figure 4: Experimental data of fatigue tests under combined tensile and torsional shear loading

COMPARISON WITH LITERATURE

In order to understand if obtained results can be considered conventional or are somehow original, an initial limited comparison with data taken from literature is here presented. Mainly three references are here considered [9,10,11] reporting similar data about fatigue behaviour of ductile iron. A summary of results is in table 2.

Table 2. Examples of data taken from literature

Ref.	***Loading***	***R***	σ_m/S_{ut}	***Reference strength at 2*** 10^6	
				τ_A/S_{ut}	σ_A/S_{ut}
[9]	Tensile	-1	-	-	0,352
	Tensile	-	0,2912	-	0,216
	Tensile	-	0,416	-	0,168
	Torsion	-1	-	0,290	-
	Torsion	0	-	0,189	-
[10]	Tensile	-1	-	-	0,497
	Tensile	0	-	-	0,351
[11]	Tensile	-1		-	0,411
	Torsion	-1		0,390	-
	Tensile	-1		-	0,346
	Torsion	-1		0,314	-

By comparing tables 1 and 2 it is evident that several experimental outcomes are similar, for instance the dependence of fatigue strength of this kind of material from mean tensile loading, with an absolute value ranging from one half to one third of tensile strength. Obviously, as stated before, this value is strongly dependent from the specific microstructural properties and defect distribution.

However, some peculiarities of the new experimental set of data appear too:

- the ratio of torsional over tensile fatigue strength is, in literature, very high for ductile iron, but is usually close to 0.85 and seldom close to 1. In new data, this ratio is always higher than 0.9 and close to 0.95.
- the tensile sensibility to load ratio (strength at R=0 over strength at R=-1) in literature data is close to 0.7, whilst in proposed data is lower than 0.6. The same holds true for sensibility to stress ratio under torsional loading.
- No similar data have been found for cast iron under combined loading with the same tensile and shear amplitude.

DISCUSSION

It is not the aim of this paper to systematically investigate the applicability to presented data, of existing multiaxial fatigue criteria or even to develop a new multiaxial criterion. The aim of the paper is simply to check if there is any correspondence between main stress parameters and experimental fatigue strength, even considering the connection between experimental direction of fatigue crack propagation and the critical plane orientations. For this purpose, two sets of critical plane parameters has been computed: the critical plane defined as the plane experiencing the maximum normal stress variation (i.e. the main principal stress direction in proportional loading) and the usual critical plane defined as the direction experiencing maximum shear stress amplitude. Results are given in table 3.

Table 2. Critical plane parameters for experimental data

Ref.		***R***	***Max normal stress***			***Max shear stress***		
			ϕ_n [°]	$\sigma_{n,a}/S_{ut}$	$\sigma_{n,m}/S_{ut}$	ϕ_n [°]	$\tau_{n,a}/S_{ut}$	$\sigma_{n,max}/S_{ut}$
New data	Tensile	-1	0,0	0,376	0,000	45,0	0,188	0,188
	Tensile	0	0,0	0,222	0,222	45,0	0,111	0,222
	Tensile	-3	0,0	0,487	-0,243	45,0	0,243	0,061
	Torsion	-1	45,0	0,364	0,000	0,0	0,364	0,000
	Torsion	0	45,0	0,204	0,204	0,0	0,204	0,000
	In-phase tens.-tors.	-1	31,7	0,364	0,000	13,3	0,252	0,113
	out-phase tens.-tors.	-1	31,7	0,297	0,000	0,0	0,259	0,259
[9]	Tensile	-1	0,0	0,352	0,000	45,0	0,176	0,176
	Tensile		0,0	0,216	0,291	45,0	0,108	0,254
	Tensile		0,0	0,168	0,416	45,0	0,084	0,292
	Torsion	-1	45,0	0,290	0,000	0,0	0,290	0,000
	Torsion	0	45,0	0,189	0,189	0,0	0,189	0,000
[10]	Tensile	-1	0,0	0,497	0,000	45,0	0,249	0,249
	Tensile	0	0,0	0,351	0,351	45,0	0,176	0,351
[11]	Tensile	-1	0,0	0,411	0,001	45,0	0,205	0,205
	Torsion	-1	45,0	0,390	0,000	0,0	0,390	0,000
	Tensile	-1	0,0	0,432	0,000	45,0	0,173	0,173
	Torsion	-1	45,0	0,392	0,000	0,0	0,314	0,000

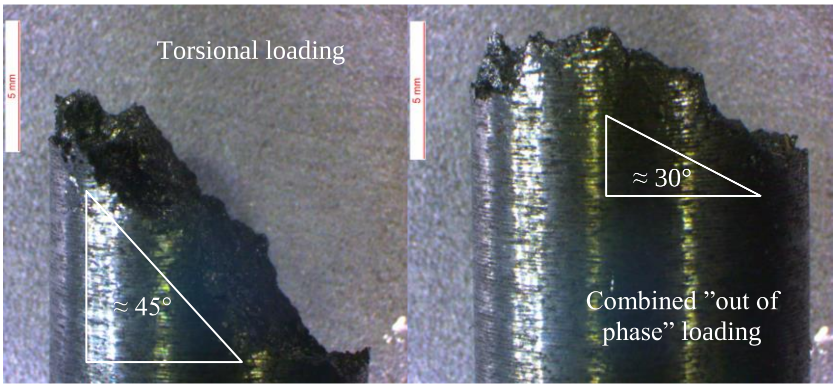

Figure: 5. Example of failures under torsional and combined loading

As a first experimental indication, experimental failures, in new data, have crack path and main failure directions in sound agreement with orientations of maximum normal stress amplitude. Two examples are given on figure 5.

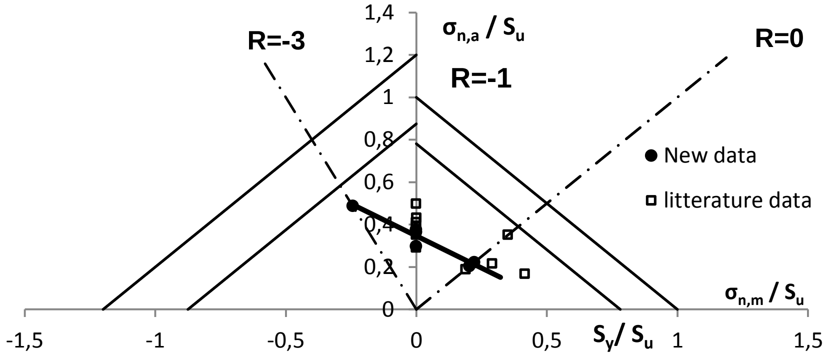

Figure 6: Haigh diagram of experimental data

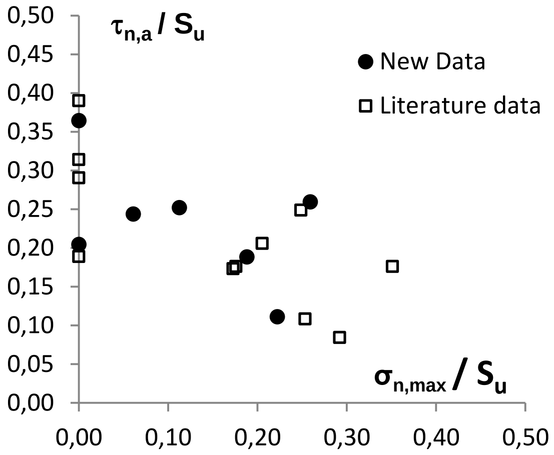

Figure 7: “shear stress” critical plane parameters of experimental data.

If critical plane parameters could be used to define a bi-parametric strength criterion, than for the investigated material, there should exist a univocal relationships between them. To verify this assumption a Haigh diagram (mean value vs amplitude of normal stress) is given in figure 6 and a further diagram showing “shear stress plane” parameter is given in figure 7. Figures 6 and 7 show both new data and the samples of data taken from literature previously presented. Fig. 6 shows even limit stress combination of ultimate and yielding condition, under compression loading those condition are 20% higher.

It is evident that, in these figures, experimental fatigue strength of cast iron is rather scattered, hence generally these parameter are not sufficient to describe fatigue strength.

However, focusing in new experimental data, in the Haigh diagram of figure 6 there is a clear linear dependence between mean value of normal stress and its amplitude; it is possible to argue that for the investigated cast iron, those two parameters are sufficient to depict multiaxial fatigue behaviour. The only one result not accurately estimated by the linear trend given in figure 6 is the out of phase combined loading (having null mean stress) which is lower than linear regression by providing lower experimental strength than expecting according to this tentative criterion.

CONCLUSION

A set of uniaxial and multiaxial fatigue tests on ductile cast iron has been presented. Specimens have been taken from a real large component and tensile, torsional and combine in-phase and out-of-phase loading have been investigated and briefly compared with similar data taken from literature.

Some results agree with data previously published, as well as the relevant sensibility of fatigue strength to mean value of tensile loading. Other influencing factors resulted larger than expected, like the sensibility to mean value of shear stress under torsional loading too.

A first tentative investigation on suitable multiaxial fatigue strength criterion showed that the investigated material seems more sensible to main principal stress variation than stress parameters evaluated on the critical plane defined on max shear stress amplitude.

REFERENCES

[1] Germann H., Starke P., Kerscher E., Eifler D. (2010) *Procedia Engineering* **2**, 1087–1094.
[2] Šamec B., Potrc I., Šraml M. (2011) *Engineering Failure Analysis* **18** 1424–1434.
[3] Hübner P, Schlosser H, Pusch G, Biermann H. (2007) *International Journal of Fatigue* **29**, 1788-1796.
[4] Ferro P., Lazzarin P., Berto F. (2012) *Materials Science and Engineering A* **554,** 122– 128
[5] Costa N., Machado N., Silva F.S. (2010) *International Journal of Fatigue* **32**, 988–995.
[6] Shirani M., G. Härkegård: (2011) *Engineering Failure Analysis* **18**, 12–24
[7] Nadot Y., Denier V. (2004) *Engineering Failure Analysis* 11 485–499
[8] Beretta S. (2003), *Fat.Fract.Engng.Mat.Struct.* **26**, 551-559.
[9] Marquis G., Solin J. (2001) Technical Research Center of Finland, VTT Research Notes 2043, Finland.
[10] Shirani M., Härkegård G. (2011) *Engineering Failure Analysis* **18**, 12-24,
[11] Fukura T, Nisitani H. (2001). In: 6th Int Conf on Biaxial/Multiaxial Fatigue and Fracture p. 285–302, Carpinteri A, de Freitas M, Spagnoli (Ed.), ESIS Publication.