Two scale approach for the fatigue design of automotive suspension components

***Gadouini H.,*Nadot Y. and **A. Ouakka**

** LMPM-ENSMA, 1 Avenue C. Ader, Téléport 2, BP 40 109, 86961 Futuroscope cedex.*
yves.nadot@lmpm.ensma.fr
*** Allevard Rejna Autosuspension, CDRT/CiSM, 201 rue Sin le Noble, 59 500 Douai.*
Abderrahman.ouakka@allevard-rejna.com

***ABSTRACT**: The objective of this paper is to present a method to study the defect tolerance design under multi-axial fatigue loading. The method permits to determine the maximum defect size allowable in a component for a given fatigue life. The idea is to represent the defect by the mean of the stress gradient at the mesoscopic scale using kinematic hardening to represent cyclic effects. At the macroscopic scale, the stress tensor at a given point is applied as boundary conditions to the mesoscopic scale which is the REV containing the defect. The approach is identified on a C35 steel and validated for different multi-axial conditions including mean stress. An application of the method is shown for an industrial automotive suspension spring.*

KEY WORDS: *multi-axial fatigue ; defect ; mean stress effect ; two scale approach ; non-local approach*

1. Introduction

Fatigue behaviour of nodular cast iron or generally flawed materials is mainly governed by defects. Critical defects are located either at the surface or within the bulk. It has been shown that the near surface defects are much more dangerous with regard to the fatigue limit than internal ones [1]. Different approaches considering the defect as a crack or notch exist. However the approaches are often based on 2D description which are limited to uni-axial loading and do not allow to predict fatigue limit evolution under multi-axial conditions. To describe the influence of surface defect geometry on fatigue behaviour, a stress based multi-axial fatigue criterion has been proposed by Nadot and Billaudeau [2]. This model uses Crossland criterion formulation; it considers the amplitude of the second invariant of the stress tensor and the maximum hydrostatic stress as governing variables in the crack initiation process, even for flawed materials [1]. The size of the defect is taken into account through Murakami's parameter $\sqrt{area}$ and the gradient of the hydrostatic stress. This model is identified on a C35 steel containing artificial defects and validated for different fatigue loadings including non-zero mean stress tests. Finally, the proposition is applied to an automotive suspension spring and comparison between experience and computation is presented.

2. Multi-axial fatigue criterion for flawed material

To study crack initiation mechanisms in defect materials, Billaudeau [1] introduces artificial defects at the surface of fatigue samples and observes cracks on these samples after fatigue tests under tension and torsion loading close to the fatigue limit. As shown in Figure 1, the first stage of crack nucleation at the tip of the defect occurs in the maximum shear plane and in the maximum loaded part of the defect under both tension and torsion loading. The stress distribution around defects given by FE simulation gives rise to a high stressed volume located in the plane perpendicularly to the direction of the maximum principal stress. Consequently, the macroscopic crack that leads to failure of the sample propagates in that plane in mode I. Nevertheless, the authors conclude that it seems appropriate to use a multi-axial fatigue criterion based on both normal and shear stress to describe the fatigue limit of a defect material.

Based on the previous experimental observations, a second paper by Nadot and Billaudeau [2] propose a multi-axial fatigue criterion for defective materials.

$$\sigma^{*}_{cr} = \sqrt{J_{2,a}} + \alpha J^{*}_{1\max} \leq \gamma \qquad (1)$$

$$J^{*}_{1\max} = J_{1\max}\left(1 - a\frac{G}{J_{1\max}}\right) \qquad (2)$$

$$G = \frac{J_{1\max}(\text{point}\,A) - J_{1\max}\left(\sqrt{area}\right)}{\sqrt{area}} \qquad (3)$$

$J_{2,a}$: Amplitude of the second invariant of the stress tensor (MPa^2). $J_{1\max}$: Maximum value of the hydrostatic stress (MPa). α and γ are material parameters in Crosland's criterion [3]. a is a material parameter describing defect influence (μm). G is the gradient [2] of hydrostatic stress $J_{1\max}$ based on Papadopoulos work [4]. As shown in equation (3), the gradient is calculated over the size of the defect on the plotting line (see Figure 2).

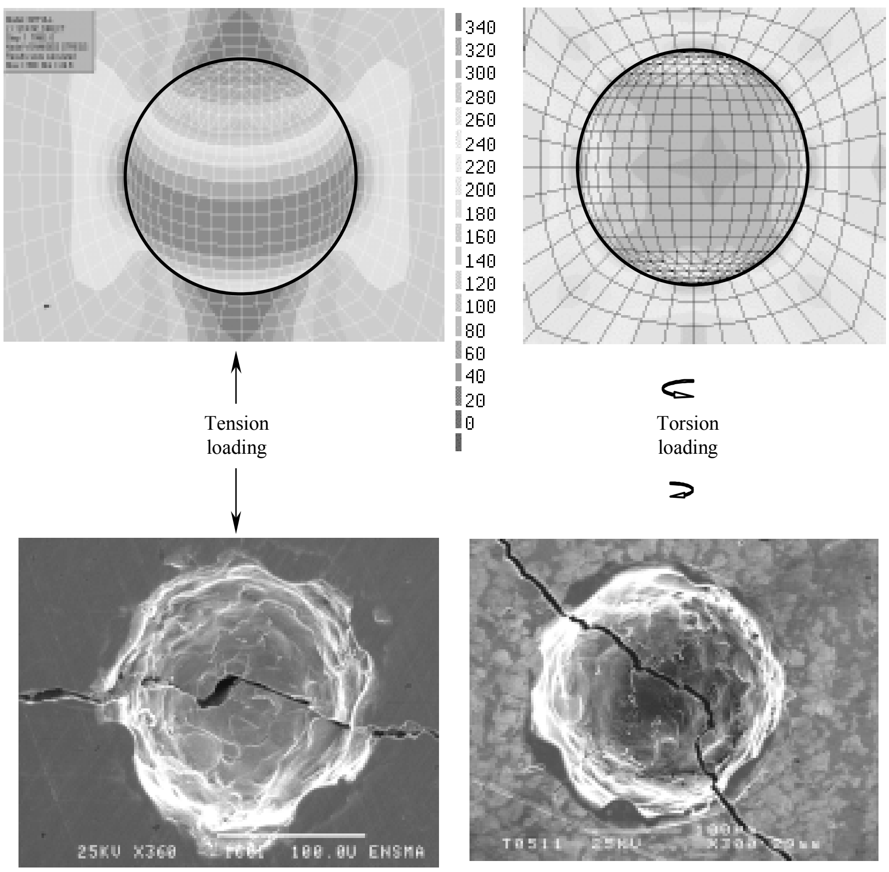

Figure 1. *Stress state (Von Mises equivalent stress) around a spherical defect under tension and torsion and corresponding crack path from SEM pictures.*

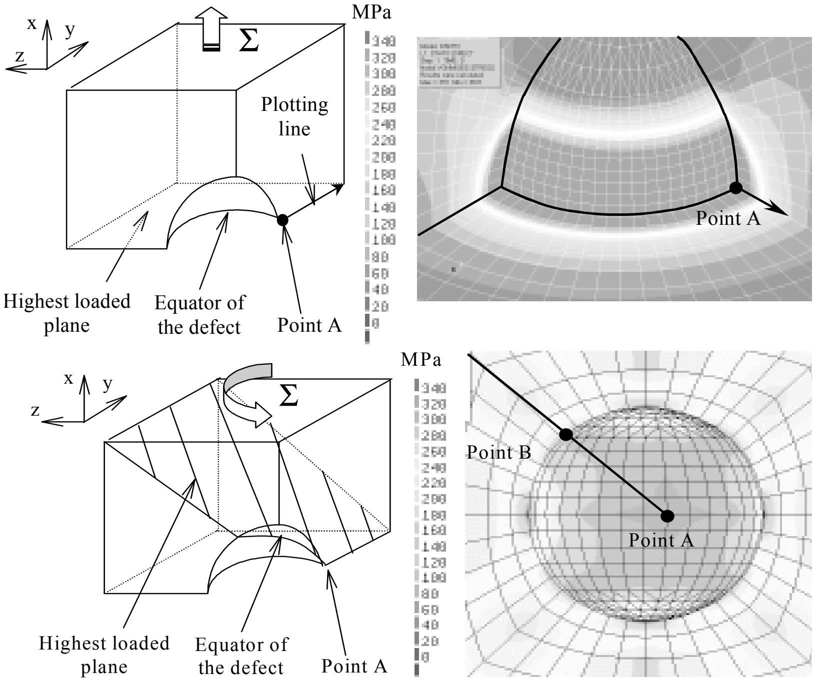

Figure 2. *Details of the geometry and mesh for tension and torsion*

The criterion is limited to surface defects and can be identified by different ways depending on the type of material concerned.

The defect free material exists
It is the case for impacted materials, for in service defect creation (corrosion, damage...) and generally for materials where it is possible to test samples with or without defects (machining surfaces of cast materials). In this case the identification of α and γ needs alternating fatigue limit under tension and torsion for the defect free material. The identification of *a* needs one alternating fatigue limit under tension for a given defect size.

The defect free material does not exists
It is the case of most of industrial casting materials, the identification of α and γ needs alternating fatigue limit under tension and torsion for one given size. The identification of *a* needs one alternating fatigue limit under tension for another given defect size.
The other material data needed is the elastic-plastic cyclic behaviour. A non-linear kinematic hardening law is necessary to describe cyclic plasticity at the mesoscopic scale and particularly relaxation of the mean stress. We use standard 'Chaboche' model [6] in Abaqus software.

3. Validation in the case of non-zero mean stress fatigue tests

In the high cycle fatigue regime, the mean stress under torsion has no influence on the fatigue limit for many metallic materials. In support of this opinion, the classical paper of Sines [7] is frequently cited. Sines reached the conclusion that a superimposed mean static torsion has no effect on the fatigue limit of metal subjected to cyclic torsion. The same conclusion can be drawn from the analysis of Smith's data [8]. The results, in Smith's words, are thus summarised. "The magnitude of any endurance of stress is constant and equal to the magnitude of the endurance range of stress for completely reversed cycles of stress, provided that the maximum stress in the range does not exceed the torsional static yield strength of the steel". For a ductile cast iron, it was found that the shear endurance strength was reduced by about 30% by the applied shear mean stress in R=0 tests, where the maximum shear stress of 365MPa exceeded the shear yield stress of 340MPa for this material [9]. When a tensile stress is applied to a fully reversing torsion loaded specimen, such as under cyclic torsion of a shaft subjected to a mean bending stress, a decrease in fatigue life is often reported [10]. In presence of defects, stress distribution is different than defect free material, therefore the influence of mean stress on high cycle fatigue behaviour may be considered differently. In order to verify this point, experiments have been conducted under non symmetric torsion loading on a C35 steel containing defects. Artificial spherical defects with controlled size ($\sqrt{area}$=400µm) have been introduced by electric discharge machining (EDM) at the surface of fatigue samples. Fatigue limit tests have been conducted under tension and torsion loading. Every tested sample has been tempered (1 hour, 500°C, vacuum). The material's Young modulus is 212 GPa, the cyclic yield stress is 273 MPa, fatigue limits of defect free material under symmetric tension and torsion loading are respectively 236 MPa and 169 MPa. Tension and torsion experiments have been conducted at respectively 125Hz and 45 Hz. The size of the defect is characterised by the $\sqrt{area}$ parameter [5]. Fatigue tests have been performed under tension and torsion loading in order to determine the fatigue limit (see Table 1).

Case number	Loading	σ_{max} MPa	σ_a MPa	σ_{moy} MPa	τ_{max} MPa	τ_a MPa	τ_{moy} MPa
Case7	Tension R=-1	150	150	0	0	0	0
Case13	Tension R=0,1	280	126	154	0	0	0
Case11	Torsion R=-1	0	0	0	145	145	0
Case15	Torsion R=-0,5	0	0	0	173	130	43
Case16	tension-torsion R=-1	128	128	0	72	72	0
Case17	Torsion R=0	0	0	0	280	140	140
Case18	Torsion R=0,5	0	0	0	320	80	240
Case19	Tension R= -5	77	230	-153	0	0	0
Case20	Torsion R=-0,7	0	0	0	175	150	25

Table 1. *Experimental results for fatigue tests under non-zero mean stress*

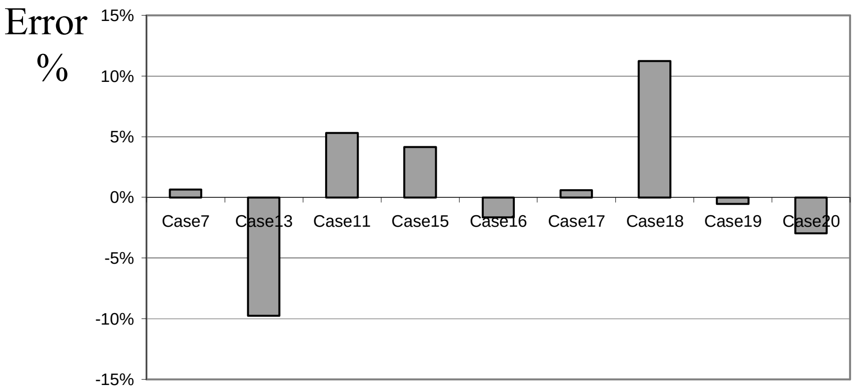

Figure 3. *Comparison between experimental results and calculated fatigue limit*

We can observe that the maximum error obtained by the criterion is 11%, the criterion gives good results in all the range of loading studied including torsion with high mean shear stress where this one exceeds the yield torsion stress.

Contrary to criteria that use relations between macroscopic stresses to describe the influence of the mean stress on the fatigue limit, the multi-axial fatigue criterion presented, based on the local stresses calculated with a cyclic plasticity model, gives good predictions of fatigue limit even if the maximum stress exceed the yield stress of the steel.

4. Application to automotive suspension spring

The objective of the criterion is to determine the fatigue life for a given defect or the defect size for a given fatigue life. The industrial application has been performed in the automotive context. For confidentiality reasons, the component presented is not the real one and values are not given. Nevertheless the methodology can be presented.
The criterion has been identified for a high strength steel used for the component : α, γ, and a as well as the hardening law are identified on experimental results.

The component is re-enforced against fatigue by shoot penning so that we have to take into account for this in the methodology. The computation is performed as follow in the case of a defect at a given position and constant amplitude loading (see Figure 4) :

- At the macroscopic scale, the component is meshed and boundary conditions are applied, material remains elastic.
- The stress tensor at the position of the defect is determined for the max and the min of the loading.
- Residual stresses are added at this macroscopic level by the mean of a given value of the hydrostatic stress.
- The stress tensor determined at max and min is applied as boundary condition on the cube representative of the mesoscopic scale. At this scale, the load is applied cyclically up to reach the stabilised value of the stresses at the tip of the defect and material hardening law is considered.
- Finally, the stress tensor is calculated after stabilisation at the tip of the defect and in the bulk at a given distance in order to compute the stress gradient. The equivalent stress including gradient effect is caculated so that a number of cycle to failure can be given and compared to experimental result.

In the case of this component the result is very good but needs to be confirmed by other tests to be validated.

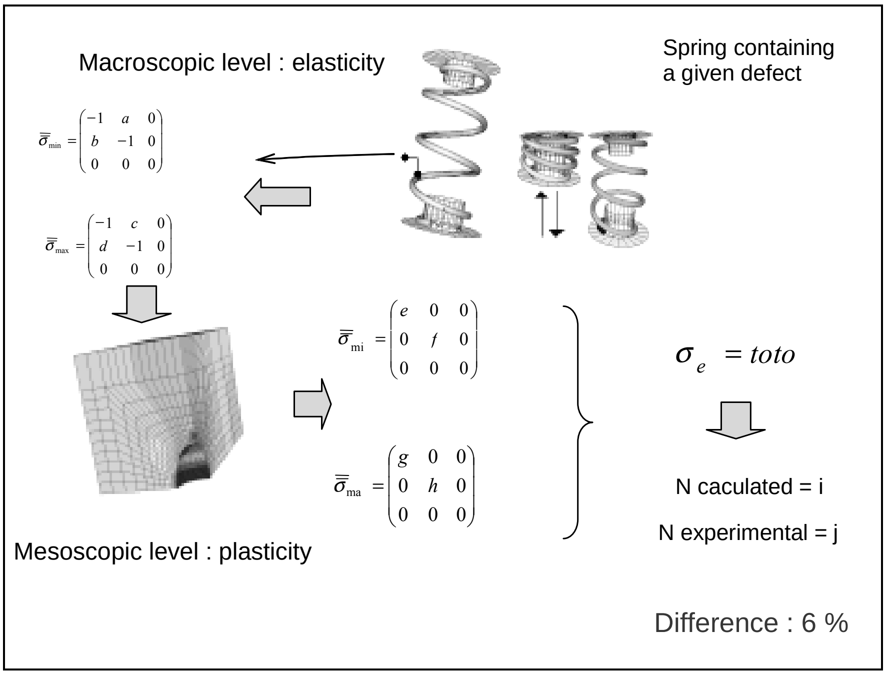

Figure 4. *fatigue life calculation of suspension spring for a given defect size*

5. References

1. T.Billaudeau, Y.Nadot, G Bezine: *Multiaxial fatigue limit for defective materials: mechanisms and experiments,* Acta Materialia, Vol 52(13), 2004, 3911-3920
2. Y. Nadot and T. Billaudeau: *Multiaxial fatigue limit criterion for defective materials,* Engng Fract. Mech in press 2005, available online
3. Crossland B: *Effect of large hydrostatic pressures on the torsional fatigue strength of an alloy steel.* Proc. Int. Conf. Fatigue of metals. London J. Mech. Eng; 1956, 138-49
4. Papadopoulos IV: *Critical plane approach in high-cycle fatigue on the definition of the amplitude and mean value of the shear stress acting*. Fat Fract Engng Mater Struct, 21, 1998, 269-285
5. Murakami Y: Metal fatigue: Effect of small defects and non metallic inclusion, Amsterdam, Elsevier, 2002
6. J L Chaboche: *Constitutive equations for cyclic plasticity and cyclic viscoplasticity.* Int. Journal of Plasticity, l5(3), 1989, 247-302
7. Sines G, Ohgi G: *Fatigue criteria under combined stresses and strain*, Transactions of ASME, Journal of Engineering Materials and Technology, 103, 1981
8. Smith JO: *The effect of range of stress on the torsional fatigue strength of steels.* Bulletin Series No. 316. Engineering experiment Station, University of Illinois, 1939.
9. Marquis G; Socie D: *Long-Life torsion fatigue with normal mean stress.* Fatigue Fract Engng Mater Struct 23, 2000, 293-300.
10. Susmel L, Tovo R, Lazzarin P: *the mean stress effect on the high cycle fatigue strength from a multiaxial point of view.* International Journal of Fatigue 27, 2005, 928-943