Fatigue design methodology for automotive welded structures under complex loading

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ABSTRACT. *This study discusses activities developed in order to create a new design methodology for automotive welded structures under complex loadings. This methodology associates a fatigue criterion, to predict fatigue limits, and a damage model to treat finite fatigue lifetimes. In a first step, the pertinence of the proposed fatigue criterion is evaluated under an automobile multiaxial load spectrum. This phase is performed using 1045 steel cylindrical specimens to identify material behavior. Linear damage accumulation seems not sufficient to simulate correctly fatigue lifetime. A new incremental damage model is thus introduced that fits better experimental data. The second step studies weld behavior. A welded specimen is designed to represent materials and manufacturing process of automobile chassis parts. A finite element model, based on a macroscopic study and instrumented tests, was created. This part of study will permit to transpose the methodology developed in the first step to welded structures.*

INTRODUCTION

Automotive chassis parts are submitted to complex variable fatigue loadings. These metallic structures contain welded joints, which are potential sites for initiation and propagation of fatigue cracks. A reliable and tractable fatigue design methodology is a challenge for automotive industry designers because it allows detecting the critical points from the upstream phase, avoiding oversizing or undersizing and reducing the number of physical prototypes. As these welded joints undergo complex loadings, a specific design tool has to be developed, including the effects of multiaxial fatigue.

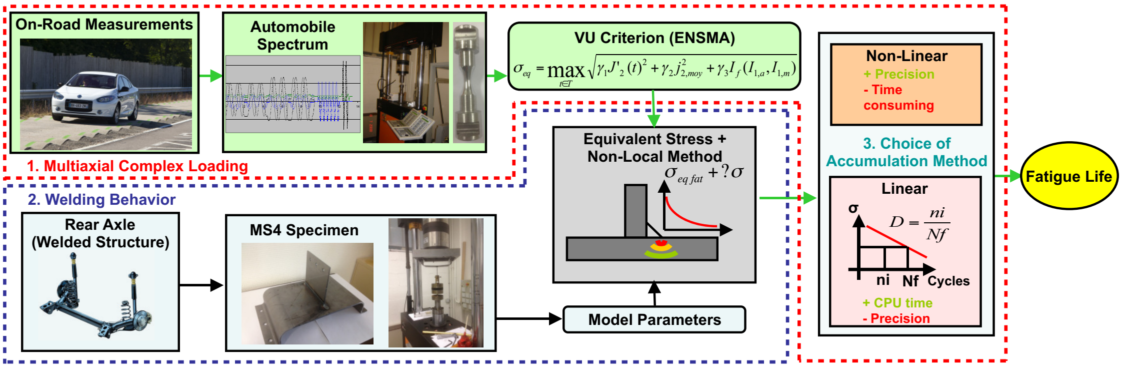

Figure 1 – Project organization

The proposed design tool is based on a multiaxial fatigue criterion (to predict fatigue limit) coupled with a damage model (finite lifetime domain). In a first step the criterion will be tested on cylindrical specimens (Figure 1 – Multiaxial Complex Loading) and then the methodology will be transposed to a welded specimen representative of the manufacturing process (Figure 1 – Welding Behavior).

I. MULTIAXIAL COMPLEX LOADING

The first step consists in evaluating the performance of the fatigue criterion under an automobile tension-torsion variable amplitude spectrum. In a previous study [1], the proposed criterion was validated for periodic loadings. The criterion is here tested for a non-periodic complex case. As far as finite lifetimes are concerned, a classical linear damage accumulation rule is compared to methods that are able to reveal a possible non-linear damage accumulation. The behavior of 1045 steel is identified from tests performed on cylindrical specimens. This material benefits from large experimental database ensuring results reliability.

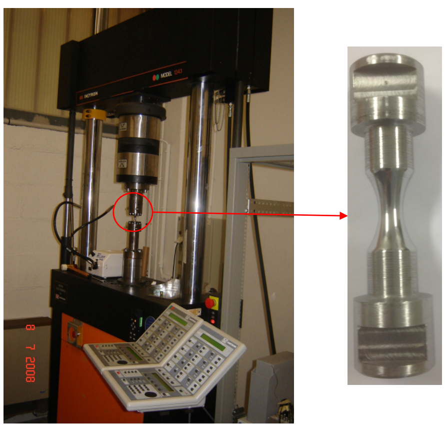

Figure 2 – Experimental tension-torsion device and cylindrical 1045 steel specimen

A. Automobile Spectrum

The loading spectrum used in tension-torsion tests is designed to represent a part of the real fatigue loadings undergone by in-service automotive structures. It is based on the loading spectrum used in automobile industry for rear-axles validation tests, and built using on-road measurements.

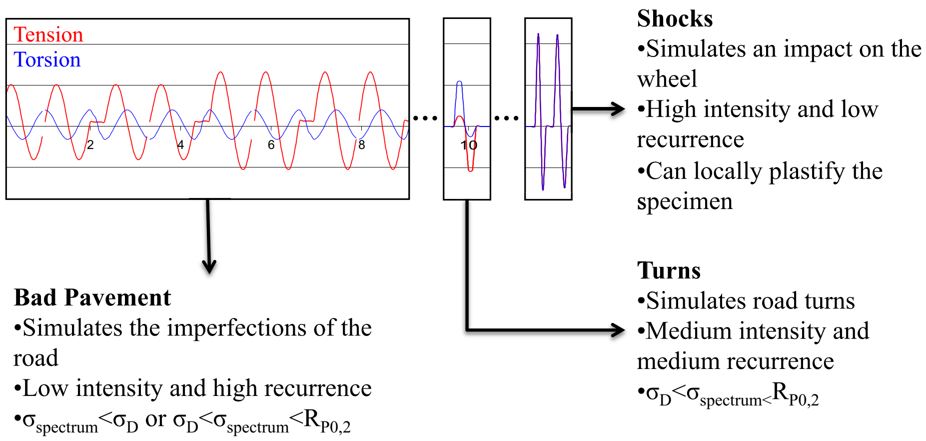

Figure 3 – Sample of loading spectrum used in tests

The spectrum reference parameter is the maximal Von Mises stress in the "shocks" block, the amplitude of other blocks is defined by a ratio with respect to this stress level.

B. Multiaxial Fatigue Criterion (Vu criterion)

In order to simplify its use, the fatigue criterion is built from the invariants of the macroscopic stress tensor. The pertinence of the criterion under periodic loadings has been demonstrated in previous studies [1]; in this study, the criterion assessment is extended to variable amplitude spectra. The spectrum presented in Section A serves as an example. Figure 4 shows the role of the principal terms of the criterion. The parameters of the criterion can be identified from two fatigue limits (such as fully reversed torsion and tension) and the ultimate strength R_m.

$$f_{MAX} = \max_{t\in T} \sqrt{\gamma_1 J'_2(t)^2 + \gamma_2 J_{2,moy}^2 + \gamma_3 I_f(I_{1,a}, I_{1,m})} \leq \beta$$

Second invariant of stress deviator

Phase shift effect (mean value of J'_2)

Hydrostatic stress effect (amplitude and mean value of hydrostatic stress)

Figure 4 – Vu criterion

C. Damage Accumulation

The fatigue criterion presented in the previous section is associated with a damage model in order to predict finite lifetimes (see more results in reference [3]). The incremental description of damage evolution takes into account the influence of the loading sequence order. This model is compared in this section with a more classical and simple approach, namely the linear accumulation rule (Miner [2]).

Vu's Damage Model

The proposed model is based on Flacelière – Morel – Dragon model [5], which explicitly couples plasticity and damage at the grain scale and combines isotropic and linear kinematic hardening laws. This model has been improved by Vu et al. [4] to account for non-proportional and block loadings. The neat description of damage represents correctly the sequence effects well known in HCF (i.e non-linear damage accumulation). The incremental character of this model allows its use for variable amplitude loadings. The proposed model was successfully tested on a number of non-proportional tests, such as sinusoidal out-of-phase tension-torsion tests with different values of amplitude ratio and mean stress [3] [4].

D. Comparison between linear damage accumulation rule and Vu damage Model

Figure 5 shows the comparison of incremental damage model, linear accumulation rule and experimental data for the automobile spectrum presented in Section A. The results are presented in S-N curves giving maximal Von Mises stress in "shocks" blocks vs. the number of tension cycles. Experimental data comes from cylindrical 1045 steel specimens tested until total rupture.

Firstly, two fatigue criteria (Vu and Crossland) are compared using linear accumulation. The Vu criterion better predicts finite lifetimes. This difference can be explained by the presence of the $J_{2,moy}$ term that can capture the effects of phase shift. The Crossland criterion predicts a large increase in fatigue limit for out-of-phase loadings, resulting in largely non-conservative predictions [8] [9]. As a threshold S-N curve is used for linear accumulation, loads below fatigue limit are not taken into account. In Figure 5 Vu and Crossland results are close for spectrums with low load levels. This is due to the fact that in this load levels "bad pavement" and "turns" blocks are below the fatigue limit and don't cause damage. Only "shocks" blocks, which are in-phase loads, are taken into account, so there is no phase shift effect.

However, the linear accumulation hypothesis seems not sufficient to estimate correctly fatigue lifetime. The Vu damage model [4] appears as an alternative to improve predictions quality. This model is able to take into account sequence effects and the non-linear damage accumulation. The plasticity induced by "shocks" is also an important factor well described by the model. Figure 5 shows a good correlation between Vu model and experimental data.

This first step clearly identified the need for a robust tool to predict complex loading paths. Although the fatigue criteria associated with linear accumulation rule offer the advantage of being computationally tractable, they may fail predicting correct lifetimes.

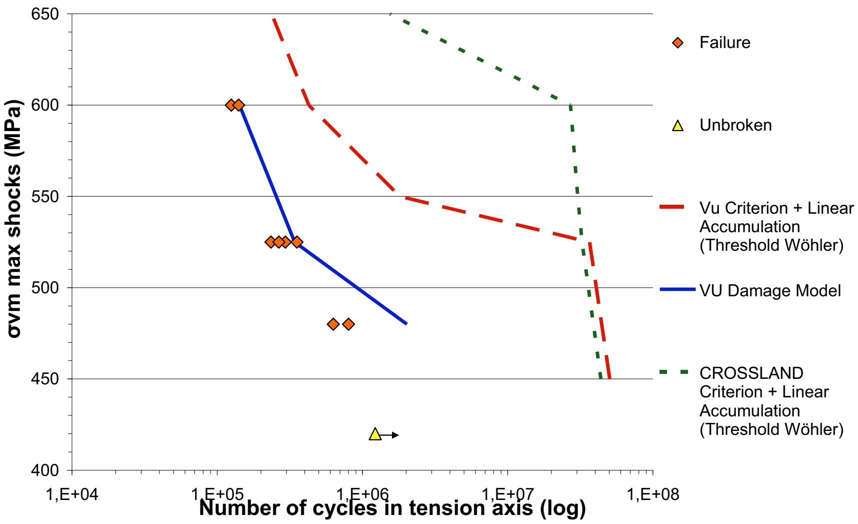

Figure 5 - Comparison of experimental data (1045 steel cylindrical specimens), CROSSLAND Criterion, VU Criterion and VU Damage Model

II. WELDING BEHAVIOR

Welded structures are less tolerant to fatigue loads. It can be explained mainly by the residual stress induced by welding process as well as their particular geometry that creates stress raisers, which are potential sites for initiation and propagation of fatigue cracks. In this second step a representative specimen of materials and manufacturing process is designed. The specimens are tested in different loading configurations and under an automobile spectrum (Section I.A) in order to activate different damage modes. The behavior of these specimens is simulated by the means of a FE model, and then compared with experimental data, in accordance with the methodology developed in Section I. The complex behavior of the weld joint is taken into account through an identification procedure carried out on welded specimen.

A. MS4 Specimen

To study welding behavior and methodology performance a specific specimen was developed. Figure 6 shows MS4 (Mini-Structure 4) that is composed by two steel pieces welded by GMAW process forming a “T joint”. The geometry and steel grades are representative of automobile rear-axles and the robotic welding process is the same used in manufacturing line.

B. MS4 Experiments

The chosen geometry shape allows three types of solicitations for fatigue test. Figure 7 shows loads (F1 Tension – F2 Bending) used in fatigue tests and the expected crack location. The different load modes and load ratios (R=-1, R=0 and R=0,5) aim to generate different damage modes and allow parameters identification for fatigue criterion and damage model. The experimental device uses bearings and flexible thin steel plates in order to isolate each load type using.

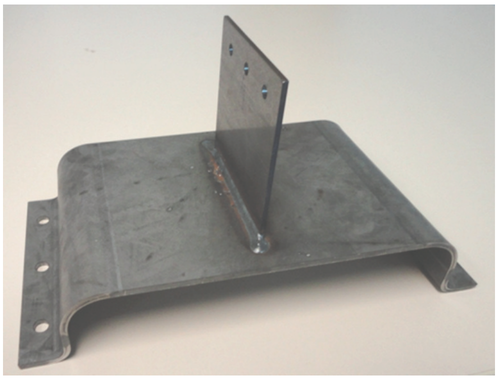

Figure 6 – Welded Specimen "Mini-Structure 4 (MS4)"

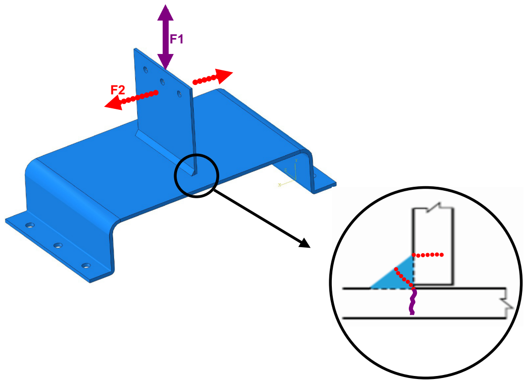

Figure 7 - MS4 study load cases and expected crack location

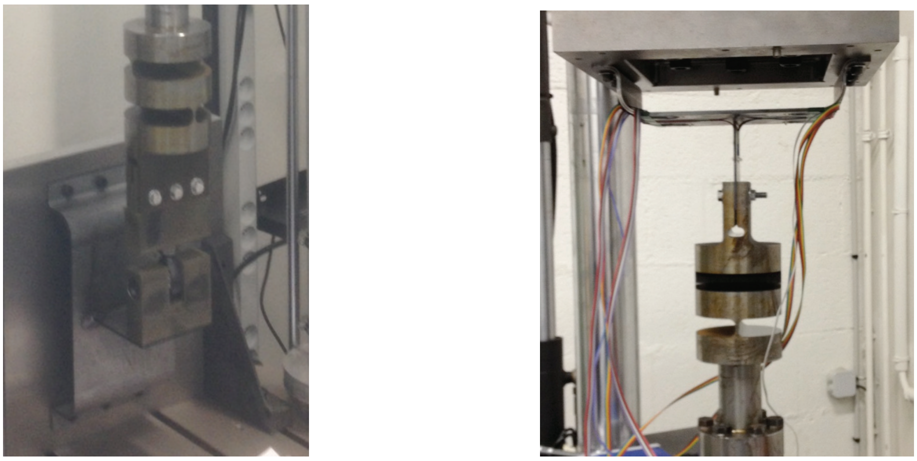

Figure 8 – Experimental devices to MS4: a) Bending, b) Tension (Instrumented)

C. MS4 FE Model

The MS4 FEA geometry was defined from successive cut planes along the weld joint. Boundary conditions are adjusted by correlating experiments performed in section II.B and the FE model behavior in static load cases (Figure 9).

A mesh optimization was performed to assure the quality of results at different analysis points.

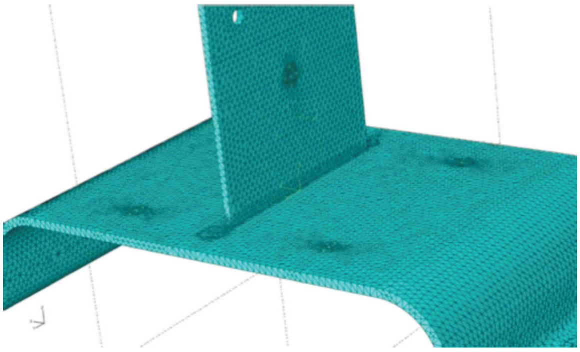

Figure 9 – MS4 FE model

D. Analysis of first MS4 fatigue result tests and perspectives

Figure 10 shows fatigue test results for MS4 in tension sinusoidal loads for three load ratios (R=-1, R=0.5, R=0). The results are presented in S-N curves giving stress amplitude vs. number of cycles. Experiments are stopped at the end of the crack initiation phase (crack size 500µm). The low dispersion of results demonstrates the good quality of experimental device and welding process.

Experimental curves can be fitted by a Basquin law. The curve slopes close to three, are in accordance with literature results [10]. No effect of mean stress can be observed, which confirms a high residual stress level in the welded structure [11] [12].

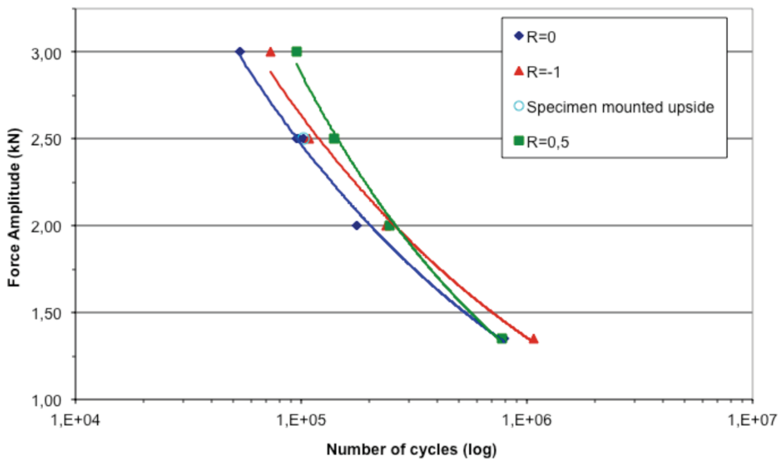

Figure 10 – MS4 tension fatigue tests. Sinusoidal loads with three load ratios R=0, R=-1 and R=0.5. Tests stopped at crack initiation.

In a next step MS4 will be tested under bending loading. Three load ratios will be used R=-1, R=0.5 and R=0.

The methodology defined in part I will be implemented in FE software and transposed for welded joints application. The set of all tension and bending results will permit the identification of fatigue criteria and damage model parameters. Non-local techniques (gradient, critical distance…) will be studied in order to choose the most suitable method to taking into account the notch effect of weld joint.

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