Focused on Multiaxial Fatigue

Gradient approach for the evaluation of the fatigue limit of welded structures under complex loading

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ABSTRACT. Welded 'T-junctions' are tested at different load ratio for constant and variable amplitude loading. Fatigue results are analyzed through the type of fatigue mechanisms depending on the loading type. A gradient approach (WSG: Welded Stress Gradient) is used to evaluate the fatigue limit and the comparison with experimental results shows a relative good agreement. Non-linear cumulative damage theory is used to take into account the variable amplitude loading.

KEYWORDS. Weld; Fatigue; Gradient.

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INTRODUCTION

The objective of this paper is to propose a methodology to evaluate the fatigue life of a welded structure submitted to variable amplitude loading. A previous study [1] was dedicated to the understanding of the variable amplitude loading on the material behaviour itself under variable amplitude loading. The fatigue criterion used [2] is able to take into account complex loading such as multiaxial with phase shift. A non-linear cumulative damage theory is used [1] in order to take into account the effect of the variable amplitude loading. This paper describes the test results, the criterion used and details a relative simple proposition to take into account the heterogeneous stress field around the hot spot of the welded structure. We propose a methodology based on the stress gradient measured in correlation with the geometry.

EXPERIMENTAL RESULTS

The welded sample is presented in Fig. 1b. The material is a high strength steel used in the automotive industry. The grip system used (Fig. 1a) allows tension or bending with good control of the boundary conditions (no pre-stress induced by the system). The cross section of the welded junction is presented in Fig. 1c. Fatigue tests are conducted up to a variation of the amplitude of the displacement of 10 % (Fig. 1d). This variation leads to a 2.5 mm depth fatigue crack in the middle of the welded junction as illustrated in Fig. 2. The welded junction is designed such as the crack is not very deep at the end of the welded line. The initiation site is systematically identified after the test and reported in a schematic drawing of the cross section of the welded junction. Fatigue tests are conducted at low frequency, under force controlled and sinusoidal wave. The load ratio is specified for each test. The fatigue results are presented using the amplitude of the force.

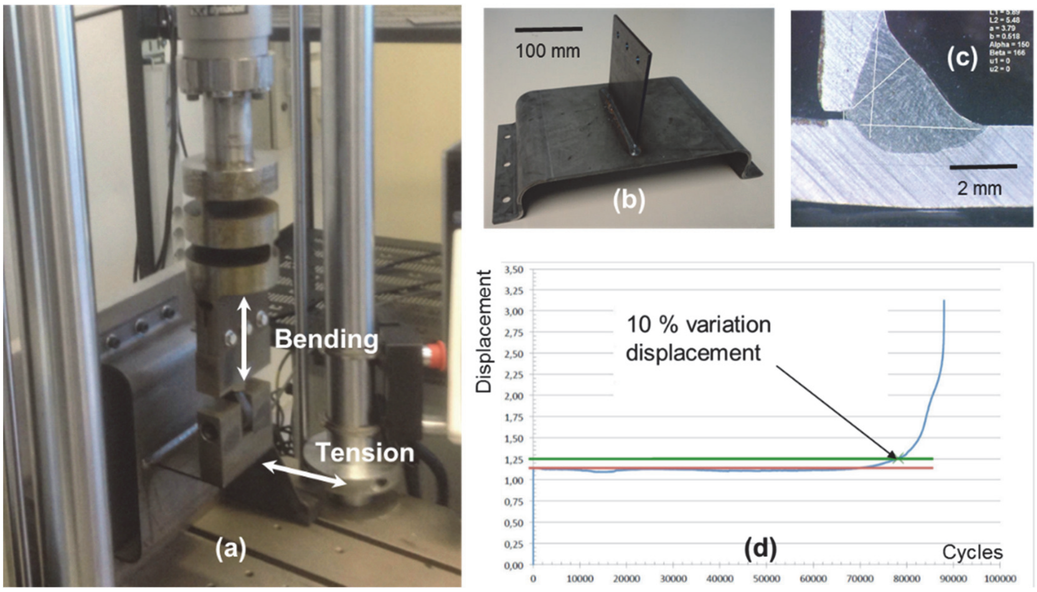


Figure 1: (a) Fatigue device with grip system; (b) welded sample; (c) cross section of welded junction; (d) arrest criterion.

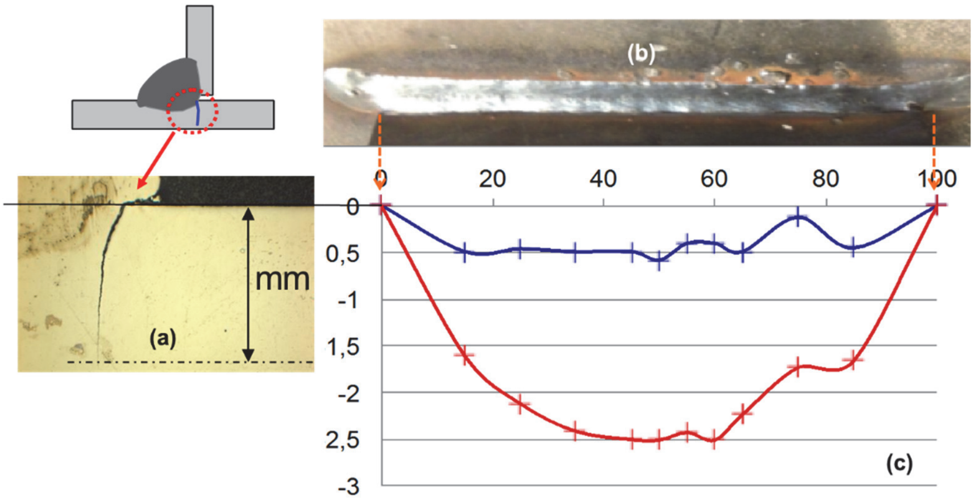


Figure 2: (a) Fatigue crack depth from the surface; (b) general view of the welded junction; (c) crack depth profile in depth.

Fatigue tests results under tensile constant amplitude loading are presented in Fig. 3 for three different load ratios. The initiation site is the same whatever the load ratio, at the root of the weld. We can conclude from Fig. 3 that the governing parameter is the amplitude of the loading whatever the load ratio, this result is classical for welded structures under high cycle fatigue loading. The slope of the Basquin curve 'm' is given for each loading, the results show that this parameter is close to 3, again a standard result for welded structures.

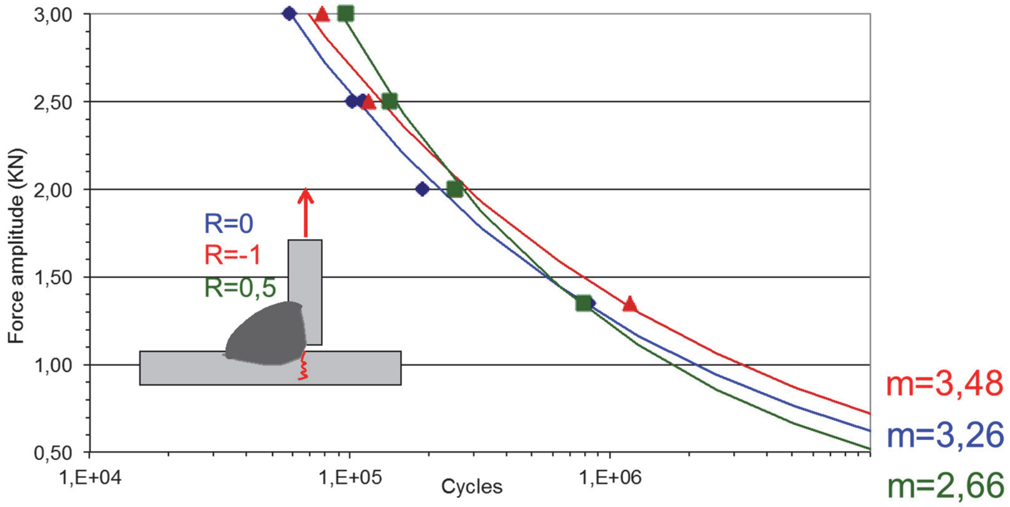


Figure 3: Fatigue life under tension for different load ratio.

Under bending loading the results are different from tension (Fig. 4). Two different initiation sites can be activated, the slope of the curve if different and the amplitude of the loading is not the unique governing parameter. Under bending, R = -1 and 0 when the initiation site is ‘Higher root’ the fatigue curve is a function of the load ratio with ‘m’ higher than 3 probably because initiation and propagation is mainly on the base material, so that the welded junction is less involved in the final mechanism. For bending R = 0, when the initiation site is the root and the propagation inside the welded part, the slope is close to 3. For bending R = 0.5 when the initiation site is the root and the propagation inside the welded part, there is a similar fatigue life compared to bending R = 0 (same initiation site) so that the amplitude seems to be the governing parameter; the slope of the curve is lower than 3 but only a few points are involved for this load ratio so that the important point to discuss is the similar result in term of fatigue life (controlled by the amplitude).

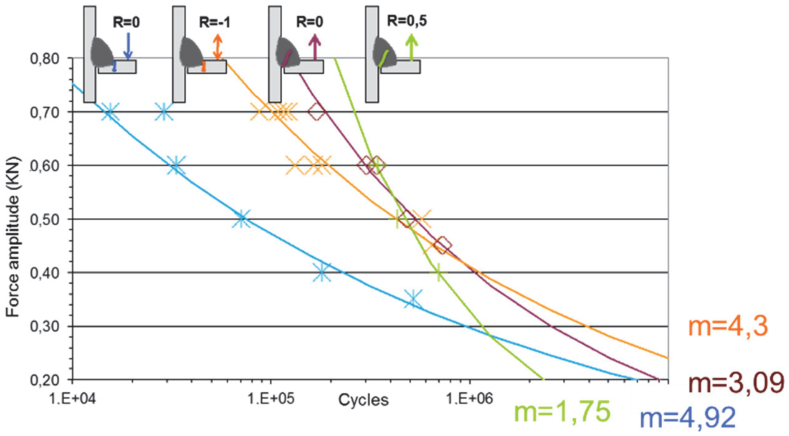


Figure 4: Fatigue life under bending for different load ratio.

The variable amplitude loading is presented in Fig. 5. This spectrum is a very strong uniaxial simplification of an automotive fatigue spectrum. This spectrum is a combination of a large number of small cycles plus a very small number of overloads close to the yield stress of the material. Fig. 6 presents the results obtained under variable amplitude loading compared to constant amplitude one. Under tension loading the crack initiation site is the same and the slope of the curve is similar. Under bending, the crack initiation site under variable amplitude loading is the same that the one obtained at R = -1 so that it seems that the part of the spectrum spent at R = -0.8 should play a major role in the spectrum.

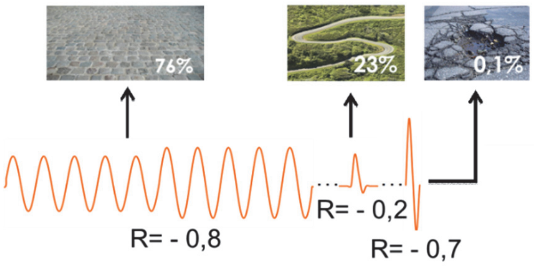


Figure 5: Simplified 'representative' fatigue load spectrum.

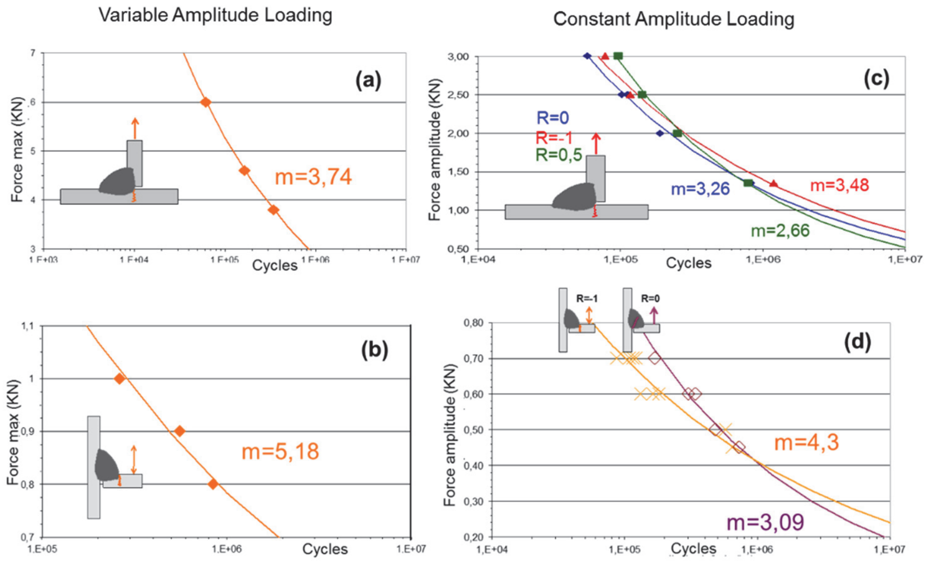
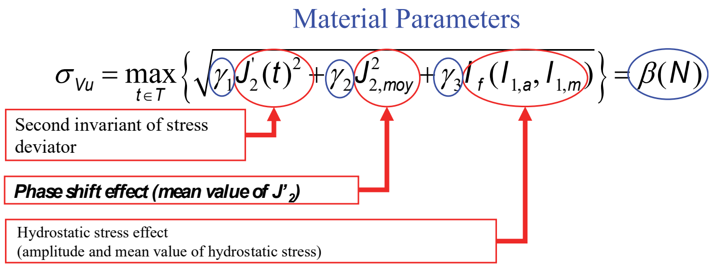


Figure 6: Comparison between constant and variable amplitude loading for tension and bending loading.

MODELING STRATEGY FOR THE FATIGUE LIFE

At this stage, we have the experimental database that we can use to simulate the fatigue limit and fatigue life for welded structures under both constant and variable amplitude loadings. In order to keep as simple as possible the global design methodology (automotive industry context) but with the key parameters, we will address the problem using the following steps:

1. The fatigue criterion used in this study is the criterion proposed by Vu et al. [2] in order to be able to take into account complex loading using stress invariant approach; all details of this criterion applied to this variable amplitude loading are given in [1]

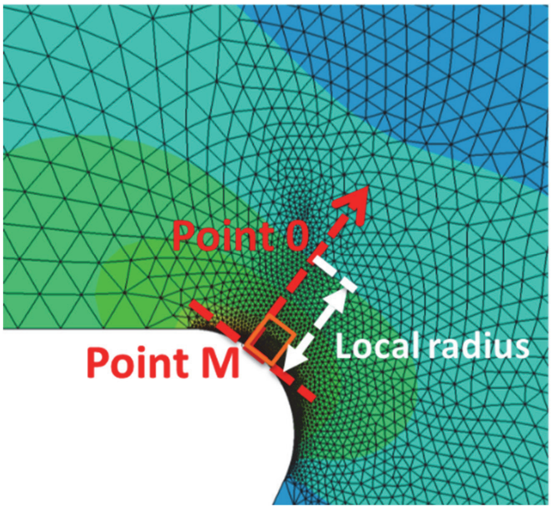


$$\sigma_{Vu} = \max_{t\in T}\left\{\sqrt{\gamma_1 J_2'(t)^2 + \gamma_2 J_{2,moy}'^2 + \gamma_3 I_f(I_{1,a}, I_{1,m})}\right\} = \beta(N)$$

2. In order to take into account the complex stress distribution, a stress gradient approach is used and called 'Welded Stress Gradient'. The idea is to compute a stress gradient related to the local geometry of the welded junction as explained in Fig. 7.

3. In order to take into account the variable amplitude loading, a non-linear cumulative damage theory is used. This theory is based on the 'Damage Curve Aproach' and already presented in [1]. A nonlinear cumulative damage approach is necessary because the spectrum is such that the overload induces strong non linearity.

Fig. 8 presents the results obtained using the equivalent fatigue stress (or Fatigue Indicator Parameter) proposed by Vu and computed at the local scale without any gradient correction and considering the identification procedure presented in Fig. 9. The parameters (γ_1, γ_2, γ_3 and β) are obtained directly through some of the fatigue tests conducted on the welded structure so that the parameters contain implicitly the information related to the welded material (geometry, heat affected zone and residual stresses) and for a given smooth gradient (so that we suppose that this gradient can be neglected). Results recorded in Fig. 8 show that the local values obtained at each initiation site are very different from a load case to another so that it seems that the local approach is not the one to be used for this context. This is the reason why the WSG approach presented in Fig. 7 is proposed. The identification of the gradient parameter is presented in Fig. 9 and the gradient material parameter obtained is equal to 51 µm. Fig. 10 presents the results obtained with the WSG approach compared to the local one. It is clear that the WSG approach is better than the local one, even if the error can goes up to 65 %.



$$\sigma_{Vu\nabla M} = \sigma_{VuM} - a_{\nabla} \nabla \sigma_{VuM}$$

$$\nabla \sigma_{Vu\,M} = \frac{\sigma_{Vu\,M} - \sigma_{Vu\,0}}{Local \;\; Radius_{\;M}}$$

Figure 7: Measurement of the stress gradient related to the local geometry.

Load case	Initiation site	σ_{Vu} calculated (MPa)
Tension R=-1	Lower root	396
Tension R=0		391
Tension R=0,5		445
Bending R=-1	Higher foot	157
Bending R=0 Root under compression		157
Bending R=0 Root under tension	Lower root	285
Bending R=0,5 Root under tension		271

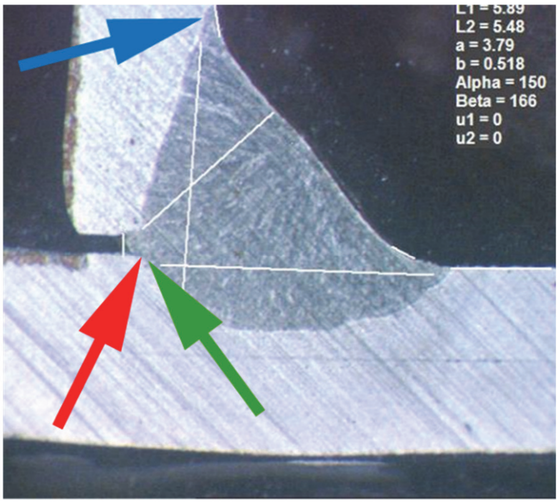
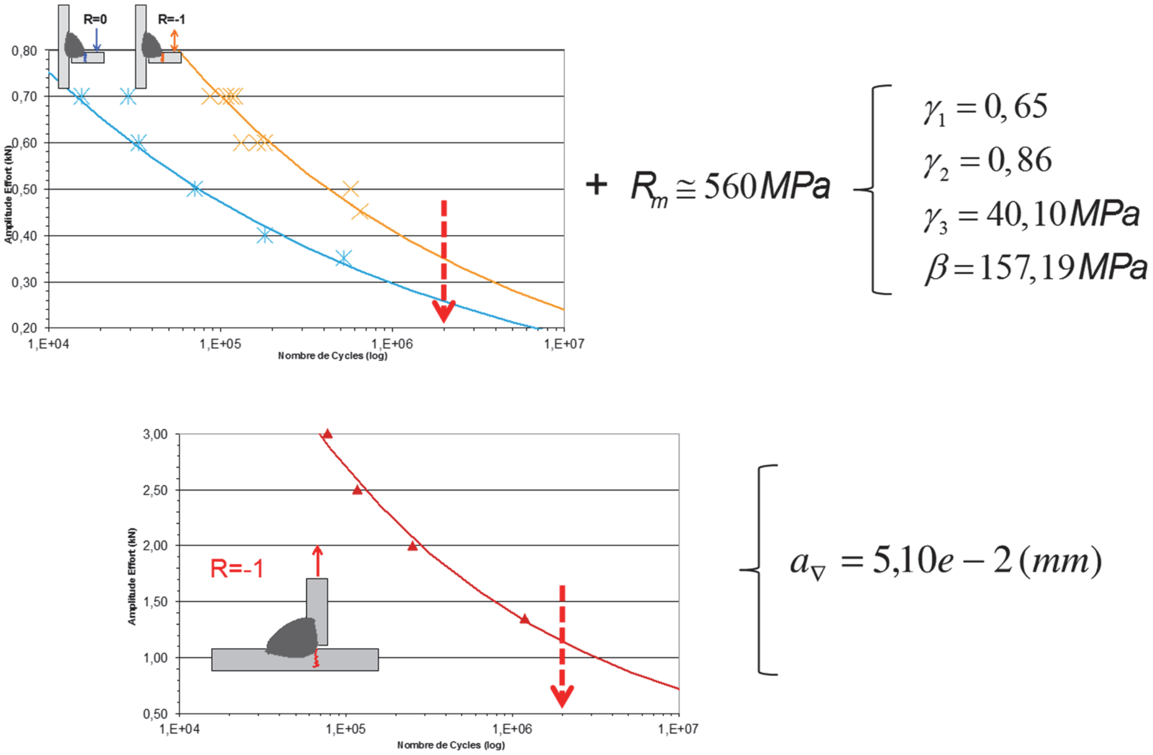


Figure 8: Fatigue stress (Vu criterion) computed at the hot spot for constant amplitude loading.



$$+\ R_m \cong 560\,MPa \quad \begin{cases} \gamma_1 = 0,65 \\ \gamma_2 = 0,86 \\ \gamma_3 = 40,10\,MPa \\ \beta = 157,19\,MPa \end{cases}$$

$$\begin{cases} a_\nabla = 5,10e-2\,(mm) \end{cases}$$

Figure 9: Identification procedure: fatigue criterion and gradient effect.

	Initiation site	Local Error (%)	WSG Error (%)
Tension R = -1	Lower root	-152	0
Tension R = 0		-149	-25
Tension R = 0.5		-183	-65
Bending R = -1	Higher foot	0	0
Bendin R = 0 Root under compression		0	0
Bending R = 0 Root under tension	Lower root	-82	-7
Bending R = 0.5 Root under tension		-72	-20

Figure 10: comparison between local criterion and WSG (Welded Stress Gradient) on different load cases

Under variable amplitude loading, the methodology and the results are presented in Fig. 11. A first computation is done using linear cumulative damage. Then the non-linear cumulative damage rule DCA [3] is tested using the 'α' parameter already identified for this spectrum but for another steel (1045 steel) and not welded [1]. Finally, an optimized 'α' parameter is given for the welded structure under fatigue spectrum for both tension and bending loading.

CONCLUSION

High cycle fatigue tests have been conducted on welded structure under tension and bending, different load ratios under constant and variable amplitude loading. The design methodology is based on a fatigue criterion including complex loading, gradient effect and a non-linear cumulative damage rule. From this study the following conclusions can be drawn:

- A local criterion is not able to correlate the 7 different load cases with different initiation sites (up to 180 % error).
- The Welded Stress Gradient criterion proposed improves the estimation of the fatigue limits but still some case leads to 65 % error.
- Under fatigue spectrum (variable amplitude loading) the evaluation of the fatigue life needs nonlinear cumulative damage rules. The value of the material parameter used in the damage rule is a function of both material and spectrum so that further studies are needed to improve these theories.

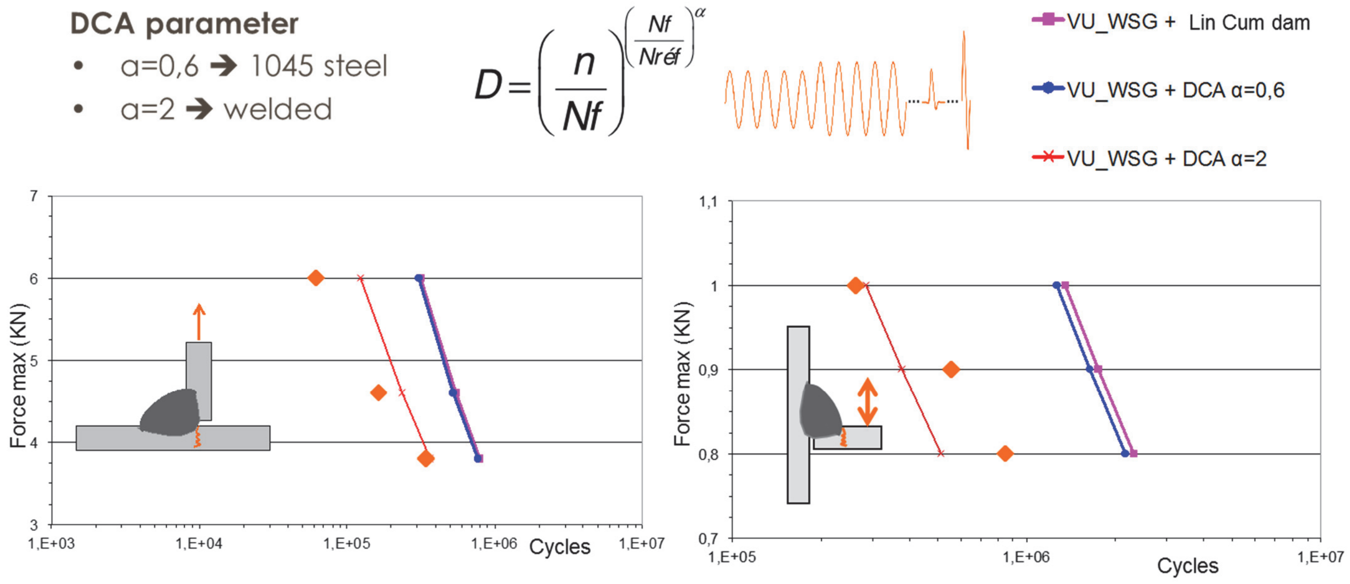


Figure 11: Comparison between linear and non-linear cumulative damage under tension and bending.

REFERENCES

[1] Dal Cero Coelho, F., Nadot, Y., Halm, D., Fatigue life assessment under complex multiaxial loading, Procedia Engineering, 133 (2015) 102 – 106.

[2] Vu, Q.H., Halm, D., Nadot, Y., Multiaxial fatigue criterion for complex loading based on stress invariants, Int J Fatigue, 32(7) (2010) 1004-1014.

[3] Manson, S., Halford, G., Practical implementation of the double linear damage rule and damage curve approach for treating cumulative fatigue damage, International Journal of Fracture, 17(2) (1981) 169–192.