Investigations on the cumulative fatigue life for a type 304-L stainless steel used for pressure water reactor

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Abstract

Fatigue-life curves are used in order to estimate crack-initiation, and also to prevent water leakage on Pressure Water Reactor pipes.

In order to investigate on cumulative damage effect in fatigue, multi-level strain controlled fatigue tests have been performed to investigate on cumulative damage effect in fatigue. In the present case, experimental results show that linear Miner's rule is not verified. A loading sequence effect is clearly evidenced. High-to-Low loading sequences conduct to an important fatigue-life reduction. On the contrary, Low-to-High loading sequences conduct to a fatigue-life increase.

A first application of the double linear damage rule ("DLDR") seems to be promising, since it leads to a significant improvement of fatigue life predictions. However, complex sequences and random fatigue tests are needed to conclude, and to give a very efficient damage rule.

1 - Introduction

In-service loadings are complex with significant fluctuations. For this reason, it may appear unobvious to predict fatigue-life for components, from results themselves obtained on laboratory specimens performed with a constant loading (controlled strain or stress-amplitude). The most widely used theory, which was selected for design, is the Linear Damage Rule commonly referred as the Miner's Rule [1]. However, literature shows that such approach may lead to inaccurate fatigue-life predictions [2 to 4].

All the materials are elaborated in accordance with the RCC-M specifications [5].

2 - Experimental conditions

Specimens are taken from a Type 304-L stainless steel sheet. Fig.1 presents the specimen geometry. A very accurate surface state is machined to prevent premature crack-initiation and failure. All the tests are performed on a hydraulic device with a strain-controlled condition at room temperature with a comparable mean strain rate ($d\varepsilon / dt \sim 2 \cdot 10^{-2}\ s^{-1}$). The strain-controlled signal has a sinusoidal evolution. In addition a null mean stress for each cycle is also monitored during the entire fatigue-life test, even after the level change. Although tests have been performed at room temperature, a temperature increase is connected to the plastic deformation, as it has been detected on thermocouple placed in gage length.

The stress response evolution shows a slight initial hardening followed by a continuous softening up to the specimen failure (Fig.2). To establish a reference fatigue-life curve (Fig.3), some tests must be obviously performed with a constant strain-amplitude ("continuous fatigue tests") before performing the multi-level test programme itself.

Following the "continuous fatigue tests" programme, a multi-level programme has been carried out. In this frame, twenty eight tests have been performed with two-level, three and four-level loading sequences. Among these, four tests have been performed with "alternated sequences". Only two

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strain conditions are applied during fatigue- life ±0.2 or ±0.4%. Test has been started with one of the both, and the strain-amplitude level is shifted when the fatigue-life ratio has been attained 0.13. In all the tests, damage D_i corresponding to the $\Delta\varepsilon_i$ level is simply defined as:

$$D_i = n(\Delta\varepsilon_i)/N_F(\Delta\varepsilon_i) \quad \text{(eq.1)}$$

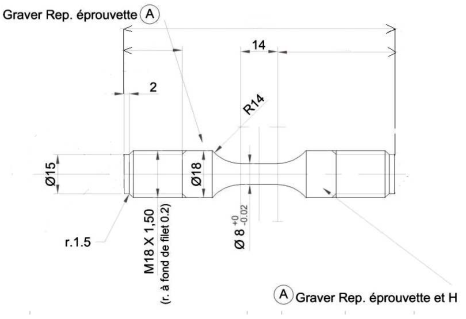


Fig.1: Geometry of specimen used for fatigue tests.

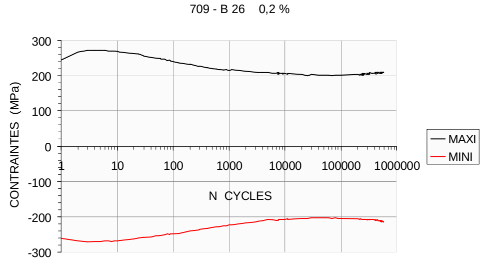


Fig.2: Stress response for a constant strain-amplitude of 0.2%.

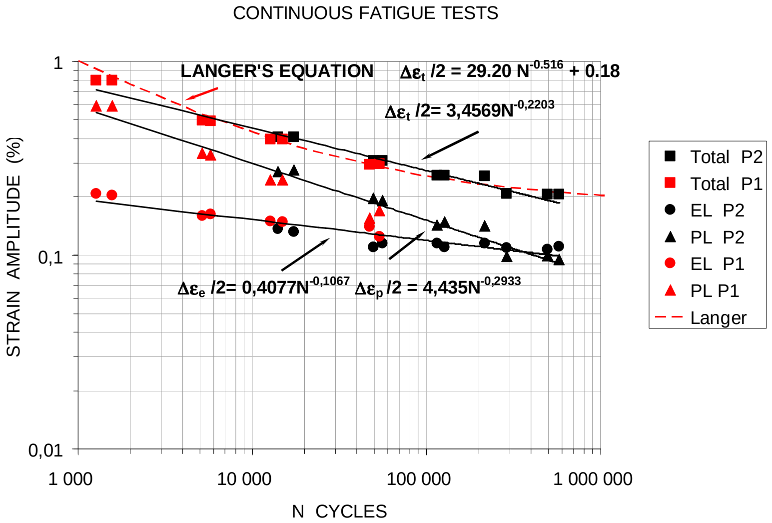


Fig.3: Fatigue-life curves, elastic, plastic and total strain-amplitudes as a function of the fatigue-life.

3 - Main results

In our conditions, the Linear Damage Rule or the Miner's rule is not verified for the two-level tests as emphasized by Fig.4. In this Figure, the Miner's rule, corresponding to the characteristic equation $n_1/N_{F1} + n_2/N_{F2} = 1$, is represented by the inclined line. Only, two tests are in good agreement with Miner's prediction. All the other High-to-Low loading sequence tests are situated below this line. The remaining life ratio (n_2/N_{F2}) determined on tests for the High-to-Low sequence (H-L) is smaller than the one estimated by applying the Miner's rule [1]. On the contrary, the Low-to-High loading sequence (L-H) tests are above this line. Furthermore, let us note the very important difference between the inversed tests: first level of both H-L and L-H tests exactly corresponds to the same fatigue-life ratio or damage value (vertical lines in the Figure). As a result, a loading sequence effect is clearly evidenced.

Fig.5 gathers all the three-level and four-level loading sequence tests: the strain-amplitudes are 0.3%, 0.5% and 0.8% in the first case, and 0.2%, 0.25%, 0.3% and 0.4% in the second case. Let us note that the remaining fatigue-life ratio $(n_L/N_{FL}\ \text{MINER})$ estimated from the Miner's rule is close to 0.6 when the measured one can range between 0.2 and 1.2. The previous trend is plainly confirmed: for a H-L sequence the remaining fatigue-life ratio estimated from the Miner's rule is higher than the measured one, for a L-H sequence the remaining fatigue-life ratio estimated from the Miner's rule is lower than the measured one.

However, the evolution is not so obvious for "mixed sequence" test: when the evolution of the strain-amplitude levels is not monotonic. Fig.6 shows that sum of fatigue-life ratios can be either lower or higher than 1. In the first case, one could roughly assimilate the loading sequence with a two-level L-H sequence, since first level is very short (90 cycles) and the third is not long enough. In the second case, one could roughly assimilate the loading sequence with a two-level H-L sequence. But, in other cases, extrapolation to two-level sequence does not appear possible.

When tests have been performed following an "alternated sequences", rupture has been ever occurred (cross symbols) significantly before "LDR" estimations (full symbols) as it was shown in Fig.7. Such underestimation of fatigue-life is obtained indifferently of the first level strain-amplitude.

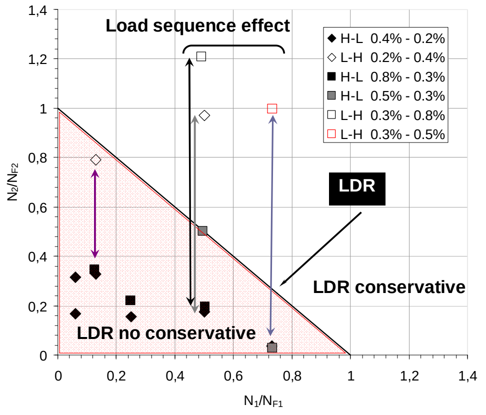


Fig.4: Two-level tests, comparison between tests and predictions from the Miner's rule, n_1/N_{F1} and n_2/N_{F2} correspond to first level, and remaining fatigue-life respectively.

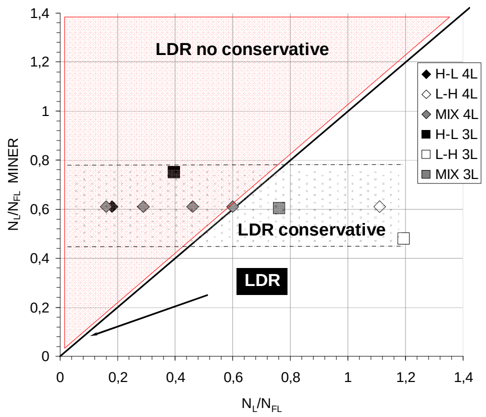
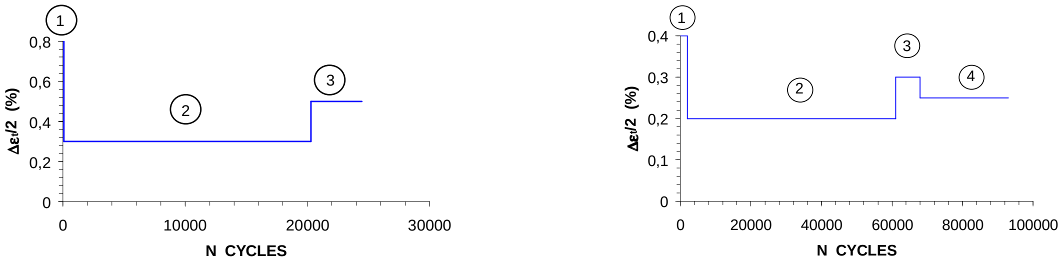


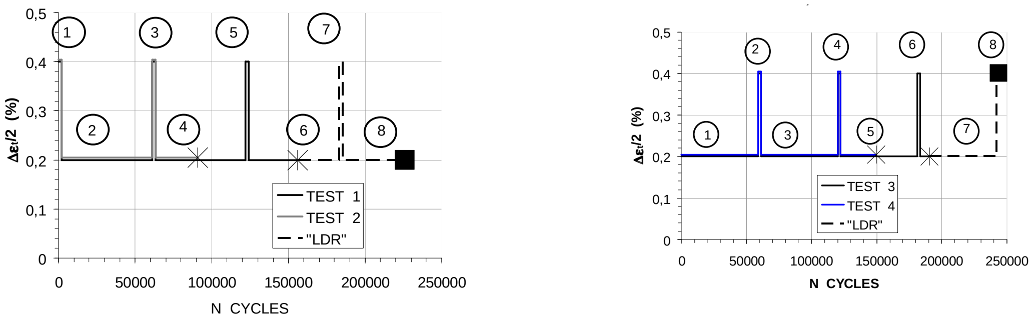
Fig.5: Three and four-level tests, remaining fatigue-life ratio values deduced from the Miner's rule as a function of measured values.



Sum of fatigue-life ratios **D = 1.22**

Sum of fatigue-life ratios **D = 0.55**

Fig.6: Three and four-level tests performed with a mixed loading sequence.



Sum of fatigue-life ratios: 0.40% first test 1 **D = 0.79**, test 2 **D = 0.58**, 0.20% first test 3 **D= 0.45**, test4 **D = 0.45**

Fig.7: Tests performed with "alternated sequences". The first level corresponds to ±0.2% (left side) or to ±0.4% (right side). The strain-amplitude level is shifted when the fatigue-life ratio has been attained 0.13.

4. Analysis of the multi-level tests with the Double Linear Damage Rule

The subject of cumulative fatigue damage is extremely complex. The most widely known and used procedure is the Miner's rule [1]. Such methodology is based on two assumptions: damage evolution is linear under a constant-amplitude level ($D = n/N_F$), and fatigue damage results from a linear summation of cycle ratios under a sequence including several levels ($D = \sum_i n_i / N_{F,i}$). Failure occurs when damage is equal to unity. In order to predict fatigue life for a complex sequence, Miner's rule is generally used in association with a rainflow-counting algorithm method: spectrum of varying loading is reduced into a set of simple load reversals. However, one of the limitations of the Linear Damage rule is that it does not take into account the effect of order of loading (history loading). Although LDR has been founded to be in reasonable agreement with experimental data in many cases, non-conservative fatigue life predictions can be also obtained, as it was previously shown on Fig. 4 to 7.

One concept that developed early to explain deviations from the Linear Damage Rule or the Miner's rule was that fatigue damage process was at least a two stage process: crack-initiation and crack-propagation. The "crack-initiation phase" itself is ended when crack has crossed over several grains (~200 µm crack-length). More precisely, crack is considered as initiated when crack deviates from a shearing path ($45°$) to a normal path to the tensile direction ($90°$) in case of "push-pull" tests. As mechanisms and processes are completely different during these two stages [7, 8], there is no reason for expectation of a same linear damage accumulation rate for all the fatigue life. Furthermore, relative importance of these two stages depends strongly on the fatigue regime. Indeed, the crack-initiation phase itself is ended only after a small cycle ratio in LCF regime, whereas it may represent more than 90% of the fatigue life in the HCF regime. Therefore, a mixture of loadings involving several life levels would not be amenable to analysis by a single-linear analysis.

An intermediate conjuncture proposes to consider two separate linear damage rules: one for crack-initiation and one for crack-propagation. In that frame, the concept of "Double Linear Damage Rule" was proposed first by [3]. However, an improvement is proposed by [8], so-called "Knee-point Damage Rule". The reference to "crack-initiation" and "crack-propagation" can be replaced by "Phase I" and "Phase II", since physical meaning of these two phases seems to be unclear.

- The number of cycles corresponding to "Phase I" is given by $N_I = \mathrm{Max}\left(\left(N_F - PN_F{}^a\right), 0\right)$ where N_F is the total fatigue life.
- The number of cycles corresponding to "Phase II" is given by $N_{II} = \mathrm{Min}\left(PN_F{}^a, N_F\right)$.

When $N_F \le N_{F,th}$, fatigue life corresponds only to "Phase II" and a simple linear damage rule is obtained. This case corresponds mainly to the LCF regime where crack-initiation phase becomes very small or negligible.

When $N_F > N_{F,th}$, failure occurs after two separated phases. An important part of fatigue life is occupied by crack-initiation. Manson proposes a bilinear evolution [3], the knee-point corresponding to the slope change is given by:

$$\beta_{CP} = 1 - A\left(\frac{N_{F,th}}{N_F}\right)^{\alpha} \quad D_{CP} = B\left(\frac{N_{F,th}}{N_F}\right)^{\alpha}$$

with $A = 0.65$, $B = 0.35$ and $\alpha = 0.25$ in the case of a 316 austenitic stainless steel (eq.2)

In such way, evolution of damage D as a function of the cycle ratio β is given by the two relations:

- In case where $0 \le \beta \le \beta_{CP}$: $D = \frac{D_{CP}}{\beta_{CP}}\beta$
- In case where $\beta_{CP} \le \beta \le 1$: $D = D_{CP} + \frac{(1 - D_{CP})}{(1 - \beta_{CP})}(\beta - \beta_{CP})$

In a case of a sequence involving two load-levels, two knee-points referring respectively to N_{F1} and N_{F2} are obtained. However, Manson proposes to define the knee-point coordinates normalized by replacing $N_{F,th}$ by N_{F1} in equation 2. Thus, damage evolutions depend only on the ratio N_{F1}/N_{F2}. Good predictions are obtained for several materials including 316 steel. Two coordinates of the knee-point for the second level are given by:

$$\beta_{CP2,N} = 1 - A\left(\frac{N_{F1}}{N_{F2}}\right)^{\alpha} \; , \; D_{CP2,N} = B\left(\frac{N_{F1}}{N_{F2}}\right)^{\alpha} \text{ with } A = 0.65 \, , \; B = 0.35 \, , \; \alpha = 0.25 \qquad \text{(eq.3)}$$

Fig.8 represents an example of application for H-L and L-H loading sequence tests. The damage evolution is given as a function of the fatigue-life ratio $\beta = N/N_F$. The DLDR evolutions are simply deduced by applying equation 3. Load-Levels correspond to strain-amplitude of 0.20%, 0.25%, 0.30%, 0.40% respectively.

As observed on the first two analyzed tests, "DLDR" leads to an important improvement for both estimations for last level fatigue-life ratio and for sum of the fatigue-life ratios: regarding last level fatigue-life ratio, values are 0.18 and 1.00 instead of 0.58 obtained with "LDR", and close to experimental values of 0.18 and 1.11.

Furthermore, Fig.9 confirms plainly such evolution for all the multi-level fatigue tests. It shows a relatively small value of the standard-deviation (0.20) compared to the one obtained with the Miner's rule "LDR" (~0.50).

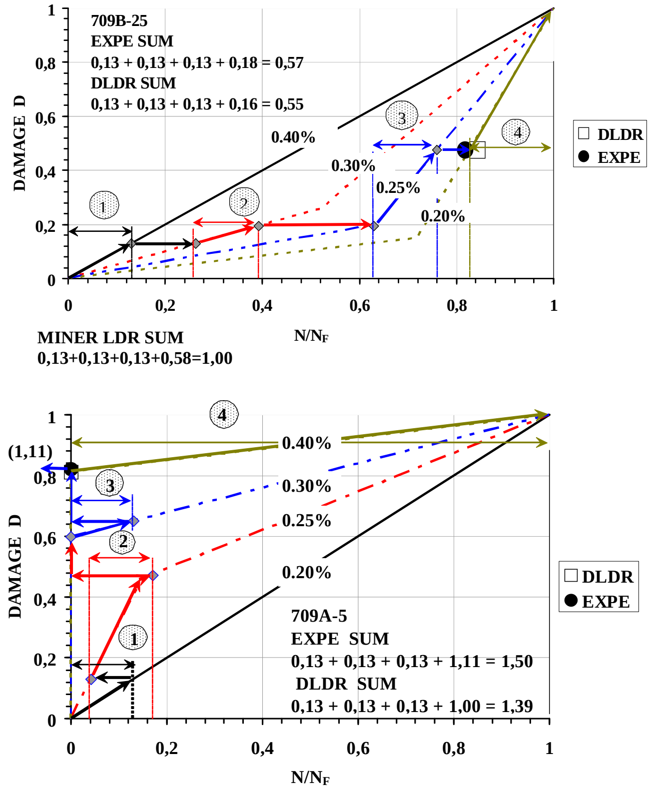


Fig.8: Application of the Double Linear Damage Rule for H-L and L-H four-level tests. Full and open symbols correspond to experiment and prediction respectively.

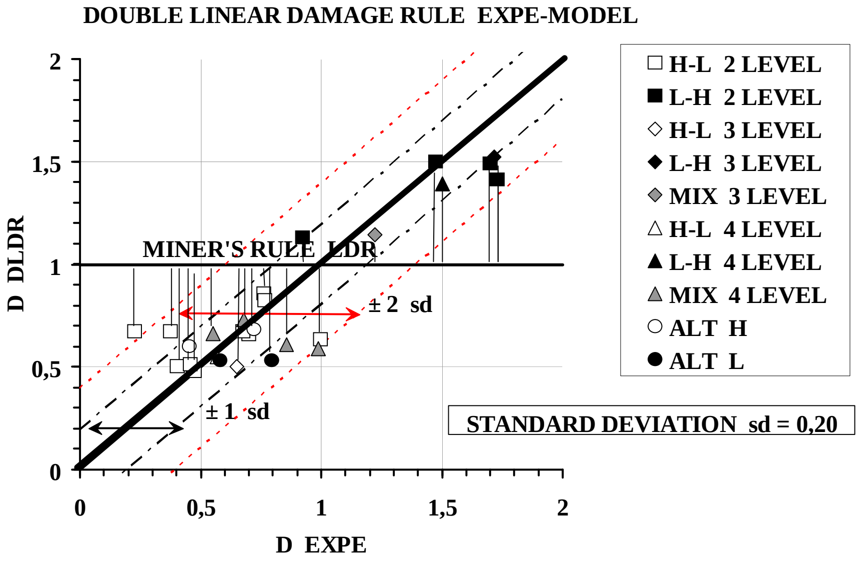


Fig.9: Application of the Double Linear Damage Rule, sum of fatigue-life ratios. Comparison between experiments and predictions.

5 - Conclusion

Multi-level strain controlled fatigue tests have been performed to investigate on cumulative damage effect in fatigue. In the present case, experimental results show that linear Miner's rule is not verified. A loading sequence effect is clearly evidenced. High-to-Low loading sequences conduct to an important fatigue-life reduction. On the contrary, Low-to-High loading sequences conduct to a fatigue-life increase.

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