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Prediction and evolution of the fatigue crack initiation in S355 Steel by the probabilistic method

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Abstract: *In many industrial fields, such as aircraft industry, automotive or under pressure reservoirs… pieces and organs ar subjected to different types of solicitations ; thermal, mechanic or even cyclical load. This type of cyclical loads causes a progressive degradation of material's characteristics, leading thereafter to a brutal rupture ; it is the fatigue phenomenon. The work presented in this paper is a contribution to the characterization of the fatigue damage risks, and the evolution of cracking mechanisms under cyclical load of a S355 steel piece used for under pressure reservoirs, having as crucial aim, the study of the first stage of crack initiation, as well as the percentage of this stage in the life duration of a steel piece, while being based on a probabilistic method using the Weibull distribution.*

Keywords- Fatigue crack initiation, Weibull distribution, Life expectancy.

I. INTRODUCTION

During operation, most structures are subjected to mechanical stresses that vary over time, leading to their break up and cause serious accidents. The lifespan of a mechanical structure can be decomposed into three stages: Stage I; priming stage, stage II slow propagation stage, stage III; sudden propagation. The fatigue behavior of mechanical parts is directly related to the number of cycles before the initiation and slow crack growth [1], in an area of stress concentration, or more generally a manufacturing defect. The aim of this study is to predict the number of priming cycles of a fatigue crack on a structure of steel S355 for a good maintenance planning. Our results show that the priming stage represents over 90% of piece life [2], using probabilistic analysis of failure.

The cyclic stresses applied to a mechanical piece results in the appearance of localized damage in a zone of stress concentration and the strength of the structure decreases continuously during the stress. This decrease remains as important as the number of cycles increases. Indeed, the damage is an irreversible physical process due to the presence of defects in the material [3]. The priming stage may be very important [2]. The fatigue crack initiation depends on the quantity, size, nature and distribution of inclusions or flaws in the material, and their shapes compared to the direction of stress [4]. The general experience shows that the crack initiation results from the concentration of plastic deformation that occurs in a small field of finite dimension [5]. Our goal is to study the part of each stage. We are particularly interested in the priming stage of a S355 steel structure.

I. MATERIALS AND METHODS

II.1 MATERIAL

The material used in our test program is S355 steel, whose chemical composition is reported in Table 1.

Table1: Chemical composition of steel S355

	Composition (%)					
S355	**C**	**Mn**	**P**	**S**	**Si**	**Cu**
	0,2 9	0,80-1,20	0,09	0,05	0,15-0,30	0,20

Static tensile tests were conducted on smooth specimens; the results reported in Table 2 give the mechanical Characteristics of the S355 steel.

Table 2: Mechanical properties of steel S355

Specification	Properties		
S355	σ_u (Mpa)	σ_e (Mpa)	E (Gpa)
	621	372	200

II.2.TEST TUBE

The tests were conducted on flat test doubly notched whose dimensions are shown in Figure 1 below.

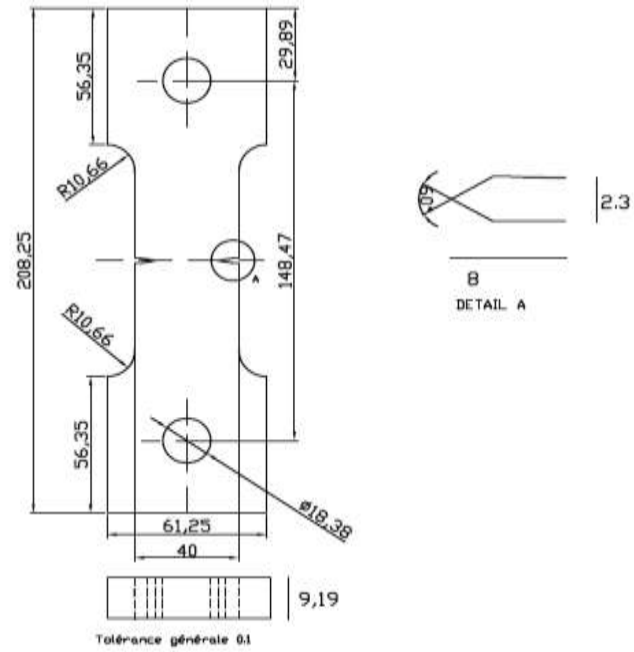


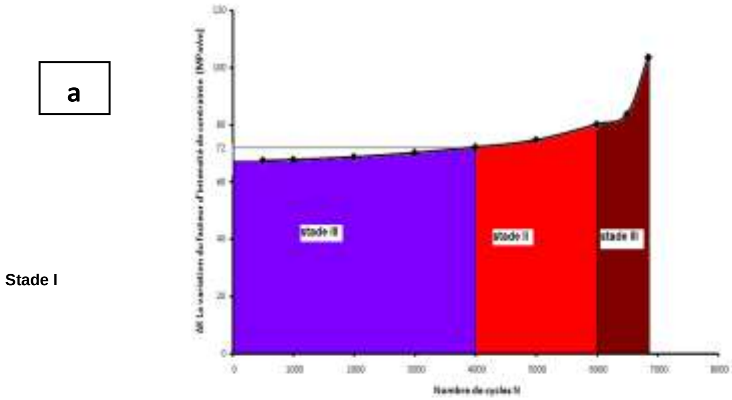
Fig 1: Dimensions of the test tube (mm).

II.3.TEST TO DETERMINE THE LIFETIME TO FAILURE.

Fatigue tests with constant amplitude were performed on samples of S355 steel, under different stress levels, 352, 282 and 248 MPa. These tests aim to determine the number of cycles to failure (Nf) [6].

II. RESULTS AND DISCUSSION

III.1.DISTRIBUTION OF THE PHASES I AND BOOT PROPAGATION II AND III



b

c

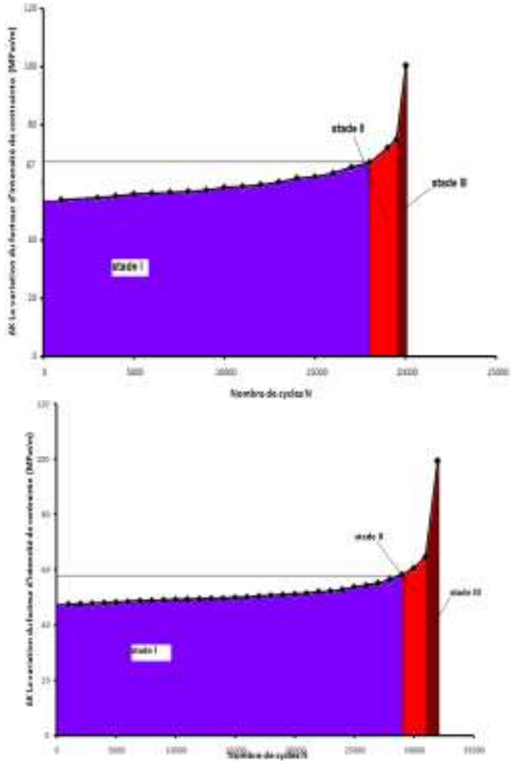
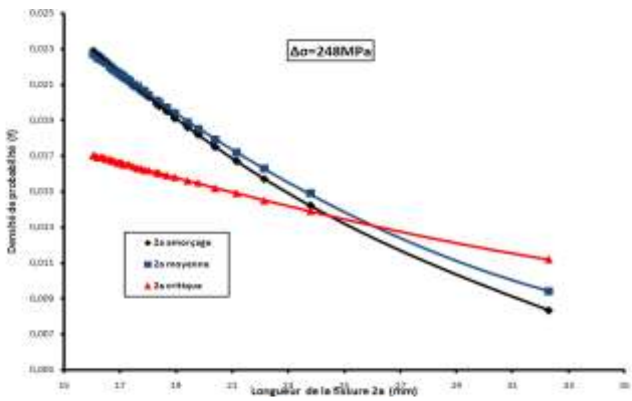


Fig 2 (a, b, c): Distribution of the initiation and propagation stages at different stress levels

On Figure 2, we present the variation of stress intensity factor, depending on number of cycles for the three levels of stress Δσ = 352 MPa studied, 282 MPa, 248 MPa. We note that the field of stage I (priming) decreases while the other stages are widening, when the level of stress increase. We can also conclude that stage I was

more dominant in the lifespan of the part. Stage I can determine ΔK priming, from which the crack propagation arises, it becomes important by increasing the applied load. The ΔK priming has a big importance in industry, especially in maintenance planning, in view of optimizing its cost.

a



III.3.THE PROBABILITY DENSITY FUNCTION OF THE PROPAGATION OF THE CRACK.

The Weibull distribution [7] is suitable to model structures with a large number of small defects. It was first used in the study of materials fatigue. It was very useful in studying the distributions of failure of vacuum tubes and has currently an almost universal use in reliability [8].
A continuous random variable x is distributed according to the Weibull distribution when the probability density function is characterized by:

$$f(x) = \frac{\beta}{\eta}.\left(\frac{x-\gamma}{\eta}\right)^{\beta-1} \exp\left[-\frac{x-\gamma}{\eta}\right]^{\beta} \quad (1)$$

Where
γ = offset of the origin,
β =shape parameter,
η = scale parameter.
Its distribution function is expressed

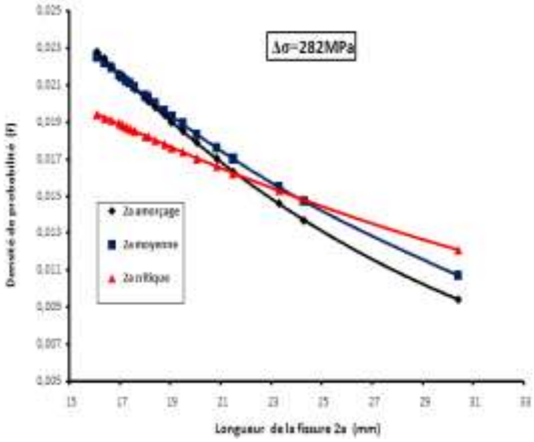
$$F(x) = 1 - \exp\left[-\frac{x-\gamma}{\eta}\right]^{\beta} \quad (2)$$

From (1), Marchal [9] demonstrated that the probability of the rupture is depending on the size of the crack

$$f(a)_a = \frac{1}{a_m} \exp\left[-\frac{a}{a_m}\right] \quad (3)$$

where
$a_{average}$ is the mean value of the crack size,
$a_{critical}$ is the critical length of the crack,
$a_{priming}$ is the length of the crack initiated (notch).
The results given in Figure 3 show the probability densities calculated for the three parameters in crack length.

b



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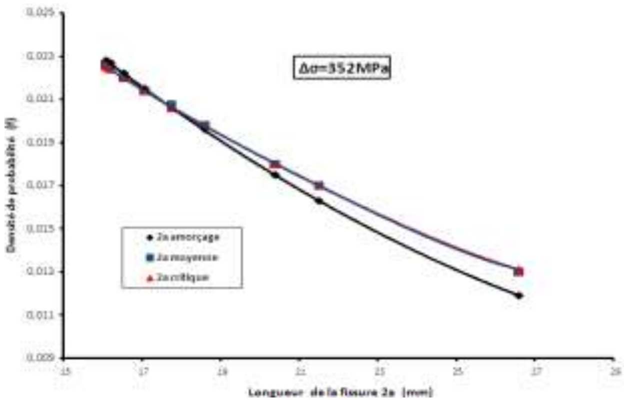


Fig 3 three figures (a, b, c): The density of probability function of the crack length for Δσ = 352MPa, 282MPa, 248MPa.

The probability density of rupture calculated respectively with $2a_{average}$ and $2a_{priming}$ significantly decreases gradually as the crack length increases, while it decreases slightly if calculated with $2a_{critical}$. The curve representing $2a_{critical}$, cut the curves representing respectively $2a_{average}$ and $2a_{priming}$ at two points, which are respectively the end of Stage I and the end of stage II, and we plot the Table 3 which represents the percentage of different stage of lifespan.

Table 3: the different stages depending on the applied stress.

	StageI (%)	**StageII (%)**	**StageIII (%)**
248 Mpa	**90**	**6**	**4**
282 Mpa	**83**	**10**	**7**
352 Mpa	**60**	**29**	**11**

III.4.THE PERCENTAGE OF STAGE I ACCORDING TO THE NUMBER OF CYCLES TO FAILURE

Fig 4: The percentage of stage I according to the number of cycles to failure

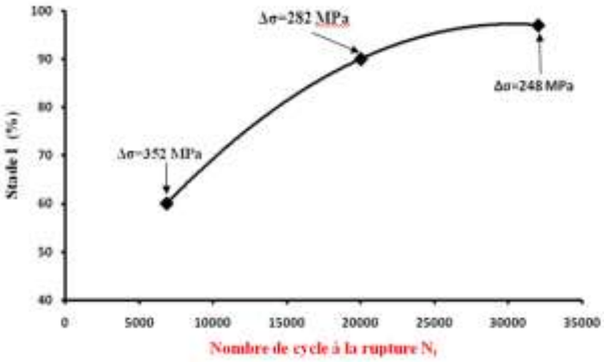


Figure 4 shows that the percentage of the priming stage compared to the number of cycles to failure, and for three load levels. For a charge level of 352 MPa and for a number of cycles Nf of 6851 cycles, the priming stage has a percentage of 60% of the life of the structure. This percentage increases while diminishing loading amplitude, for a load level of 248 MPa, the priming stage present 90% of the life of the steel structure S355.

III.5.PROBABILITY DENSITY FUNCTION OF THE CRACK LENGTH

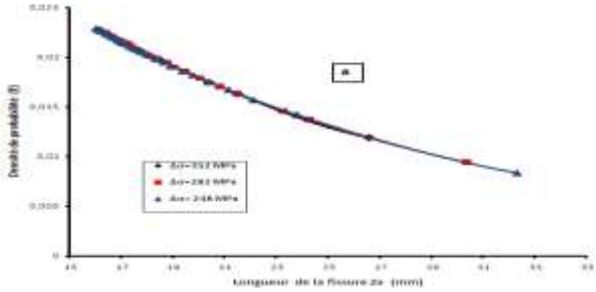
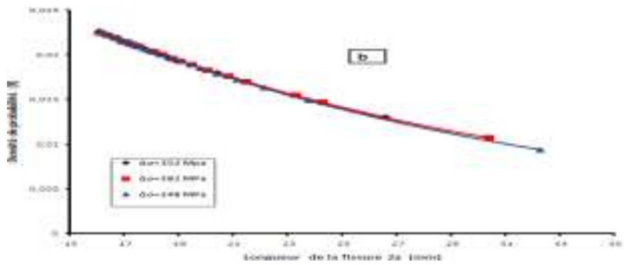


Fig 5 three figures (a, b, c): the probability density function of the length



crack for Δσ = 352MPa, 282MPa, 248MPa

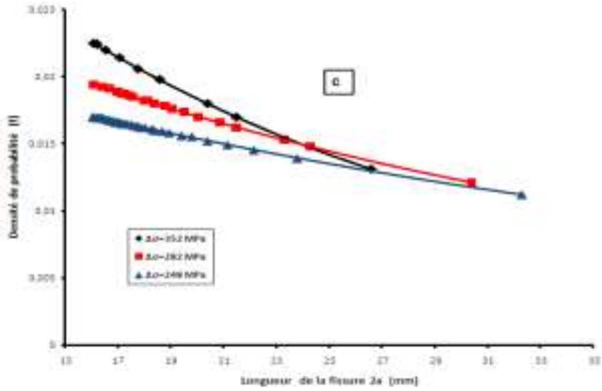


Figure 5 shows the probability density at fracture for the three levels of applied stresses and for the three parameters of crack length (2aaverage ,2apriming and 2acritical). For the average critical (the probability density calculated with respect to the critical crack length) the shape of the curve follows the value of the load amplitude, ie a probability density corresponds to a significant large amplitude, but, the three curves converge at the end of life cycle of the part. This is due the calculated values of the probability density are taken from the critical crack length at which the sudden propagation of the crack arises.

On the other side the curves given by the probability densities calculated from the average crack length and priming stage are confounded no matter the load, it seems normal because there we work beyond the stage III, in an area where the propagation of the crack is controllable.

CONCLUSION

Studies conducted during this work, allow us to conclude that the prediction of the three stages of propagation ie, initiation, slow propagation and sudden propagation, can be done more accurately, and we can see that the priming stage may represent up to 90% of the life of a part for low stresses. Our results show that we can neglect the propagation phase when we are conducting tests with a large number of cycles.

Thus, our results show that when the defect size approaches a critical value, the probability of rupture depends on the level of applied load, for cons, this probability is independent of load level values as low as the default in phase of slow initiation or propagation. In addition, in this study, we can predict ΔK priming below which the crack does not spread.

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