Comparative Verification of Fatigue in Steel Using Bending Tension Tests Carried Through Different Environments

Castro, C. A. C., Bracarense, A. Q.

Abstract— **The fatigue is the most common way of structural imperfection and, over the time, it has been a problem to the imposed requests and the type of applied load. In this paper, there is a study of the way the resistance fatigue ASTM A-36 is made among two environments: refrigerated and immerged into water at 5 atm hydrostatic pressure through bending tension fatigue tests. After that, some analyses and comparative results with the tested material were carried out. For this study, a mechanism was developed to test fatigue for bending tension to be used inside and outside hyperbaric chamber for the hydrostatic pressure simulation. This study is worth because any resistance confirmation does not exist in immerged fatigue of virgin materials; in other words, all the tests of fatigue were or have being accomplished in materials done in the air. Curves S-N were determined for each atmosphere. The methodology used for verification of resistance to the fatigue was the regression model from a data originated from accelerated life tests and it was possible to verify the environment influence in the phenomenon of the fatigue.**

Index Terms— **fatigue, bending tension, fracture, curve S-N.**

I. Introduction

Due to the expansion of hydroelectric and petroliferous plants, studies related to the metallic components shelf life are in constant development in universities and industries to make existing technologies perfect [1]. This strategy aims at guaranteeing a larger durability of the structures in order to increase the competition between companies and to prevent accidents that can be harmful for the environment and for the economy.

The modern petroliferous platforms are projected to support efforts done by storms, hurricanes and great amounts of waves. Those efforts apply carrying the structure leading to a fatigue failure of some components.

It is considered that the shelf life of some structures submitted to that phenomenon is of a great importance in a project work or equipment to guarantee its stability [2]. For this reason, a study is far necessary for the analysis of the structures under fatigue work.

All the solicitations that vary in intensity and/or in direction provoke variations on the structure tensions and can cause failure for fatigue. The live loads and environments are important in this association because they possess the biggest parcel load in structure [3]. It must be considered the action of the hydrostatic pressure set up with other efforts for failure underwater fatigue.

In the last decades, the progress of the underwater technology turned the innovative projects a challenging for the coastal and the oceanic structures to assist the innumerous economic necessities. A significant part of these structures used mainly on gas and oil industries is immersed in aquatic environments under hydrodynamic efforts as presented in Figure 1.

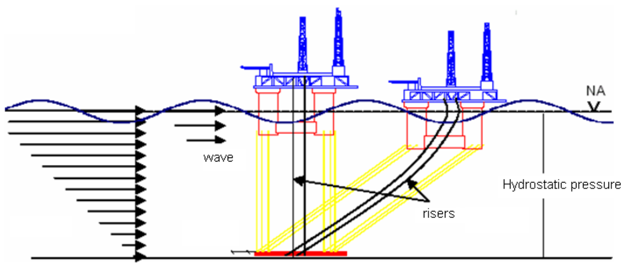

Figure 1. Interaction fluid-structure

In general, a structure is projected to work as an appropriate safety and economy. The collapse of a structure can happen through two different mechanisms [2]:

- The occurrence of high tension levels that exceeds the resistance capacity of the material, causing failures, for example, rupture or instability of a structural component;
- The structural collapse caused by accumulated damage produced by repetitive action of variable loads even for lower tension levels generating a fatigue process.

Another variable in the fatigue process is influenced by the environment. Normally, the essay in controlled atmosphere causes the increase or the reduction in the fatigue limit. As an example, an essayed ferrous material in saline or acid atmosphere, its limit decreases to the point of disappearing. However, in the case of a material to be essayed in extremely basic environment can present an increase of its fatigue limit [4].

Steverding [5] developed a machine for bending tension essay of fatigue to work in the vacuum and it was evidenced when essaying some materials that the values endurance limit fatigue in this environment was greater than the air. This was associated with the oxygen presence and affinity that the same has been done with metal. In Figure 2, it is possible to see the comparison between these two environments.

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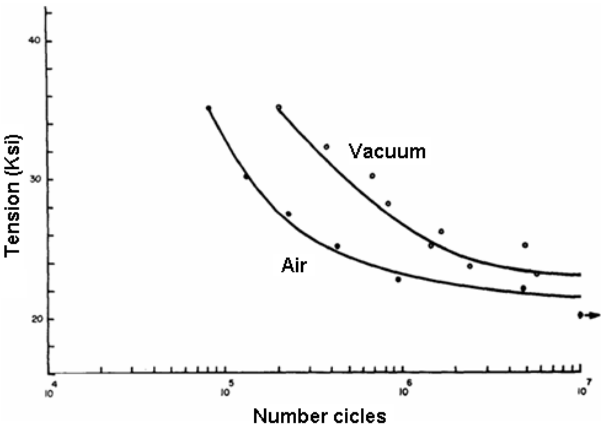

Figure 2. Comparative curve of air and vacuum

II. FATIGUE

The term fatigue can be defined as a gradual and located process with irreversible nature that occurs in material under tensions or floating deformations. These efforts can result cracks or complete failure materials. [6].

The mechanism formation imperfection for fatigue in metals is initiated with slipping bands formation [7]. These are caused by movement disagreements in reticulate crystalline metal, leading the intrusions and extrusion formation. As consequence, they are formed local for nucleation cracks, for accumulating great located plastic deformation. These cracks propagate in each cycle of tension until instability.

For the fatigue degradation study it is necessary to develop essays that present typical cycles for each situation. The operating tensions in component must be known will be analyzed to regulate randomly.

The method S-N is the study of fatigue through S-N diagram located with tension variation versus number of cycles. It is called high cycle due to a great amount of cycles of imperfection for fatigue occurrence. The trials for the diagram S-N are made by samples or components of the structure, guided by norms [8] with the total reverse carried out as presented in Figure 2.

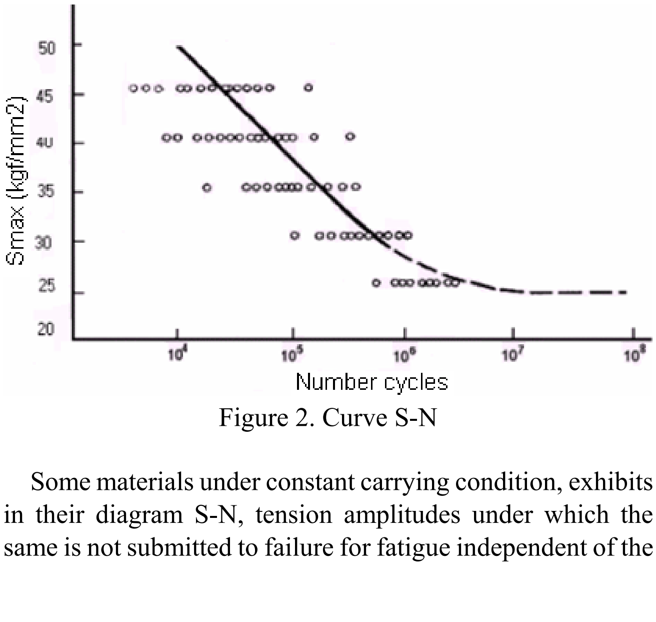

Figure 2. Curve S-N

Some materials under constant carrying condition, exhibits in their diagram S-N, tension amplitudes under which the same is not submitted to failure for fatigue independent of the number of cycles. This is called limit of fatigue or limit of endurance. This limit varies between 35 and 50% limit rupture material. Some metals, as aluminum and its leagues do not present this defined limit [9].

Although its great use in engineering curves S-N present some limitations [1] the method is not capable of separating initiation stages and propagation crack, bringing difficulties in evaluate the behavior of the mechanical elements with accented incisions and structures with failures.

A. Determination limit fatigue resistance (S_e)

The values obtained on the laboratory for the limit of fatigue are used as base for sizing some piece. However, hardly ever the value of the breaking material in practice, when submitted to some repetitive effort, is the same to the one obtained in a laboratory. There are innumerable variations that influence some practical values of fatigue rupture, from exposed environment and piece format.

For this work the regression model was used for the data originated from life tests and adjustments for resistance determination limit fatigue.

The accelerated life test means to accelerate appearance cracks in tests with products. The obtained experimental results are led in stressful conditions and used to project conditions. This can be applied in fatigue occurrence studies [1].

B. Description regression model

This model requests some hypotheses. One of them is that the variability is the same for each tension level, but, that is not always true. However, when it is done in a different scale, logarithmic for example, the idea becomes almost acceptable [8].

The log-normal distribution is the one that better describes life times whose failure mechanisms involve chemical interaction, found in a corrosion process and degradation contacts. It is also indicated for failure mechanisms for fatigue in materials [6].

The mathematical equation that better describes the relation between the tension (*S*) and the number of cycles to failure (*N*) is of linear regression (regression curves), given by the Equation 1 and 2, [9]:

$$\log(N) = b_0 - b_1 \log(S) \tag{1}$$

$$Y_i = \beta_0 + \beta_1 x_i \tag{2}$$

Where, Y_i is logarithmic *N* and x_i is logarithmic tension.

C. Adjust regression model

The adjustment for this model considers the distribution of values in log-normal. Afterwards, the reliability function of log-normal distribution is used and it has made the inverse calculation to establish resistance limit to fatigue for steel.

The reliability function of the log-normal is given for: R(T)=P(T ≥ t), where the probability of time to failure metal, either bigger than a defined time *t* [1, 8] and is given by

Equation 3.

$$x_0 = \frac{1}{\beta_1}\left[\Phi^{-1}\Gamma + \ln(t) - \beta_0\right]$$

(3)

Where, Φ^{-1} is the value of z (normal standard) corresponding to the interest percentage. Parameters: Γ, β_1, β_0 and they are esteem by model, t is time interest life and x_o is tension level.

The calculation for resistance limit fatigue is made using value x_0. This is the probability of the samples that comes to fail after a number of cycles. This value is used in the verification obtained by direct calculation method using log-normal distribution (Method of regression models for deriving data of accelerated life test).

D. *Verification model*

One of the most meaningful tools to verify the adaptation of a regression model is residue analysis. With that analysis, it is possible to find out if residues model are satisfactory, that is, to verify if the variability of suppositions variance equality, normality and independence are accomplished. Those validities can be verified by the meanings of some graphics [10].

III. METHODOLOGY

For work, the steel chosen for the survey of curves S-N was ASTM A-36 [11], acquired in market in circular bars diameter of 1/2 ". Where removed samples. This type steel very is used in under water structures, for treat with a material that is classified as a steel carbon of average resistance mechanics.

The samples had been essayed in fatigue machine bending tension to verify the number of cycles necessary to rupture. The assays occurred with sample rotating to one determined speed and with load application provoke fatigue [6].

The applied tension is directly related to the weight. The disposable weights in equipment are: 44,72; 38,38; 19,43; 18,67; 9,43; 5,29; 3,76; 2,36; 0,79; 0,49 *N*. To some determined tension values it was used some of the described weights.

For refrigerated essays, after it samples to be fixed in machine without load application. The necessary weight is applied to have the wanted tension. After that, is motor worked.

For assays sheet water in hydrostatic pressure with 5 atm (done inside of hyperbaric tank), after to position machine and to prepare it was necessary weights, the recipient is completed with water. Soon after, it works motor leading off test fatigue. To failure sample, the machine turns off automatically.

The chosen Experimental Plan for accomplishment of rehearsals was Plan of Commitment [1, 8, 12]. In this plan three levels of tension are used: high, intermediate and low.

The high level is chosen by practical considerations. Intermediate and low levels are chosen to minimize the asymptotic variance of estimator 100P %, relative to percentile distribution time of useful life of sample. The commitment have ratio of allocation (ratio of samples that the tests in each level of tension will have to be submitted) either always in 4:2:1, for levels low, intermediate and high, respectively.

In present work, five levels tensions, being two for linear interpolation had been used, with exception cooled assay that had been seven levels. For two environments same tensions with purpose had been used to compare results.

IV. RESULTS AND DISCUSSION

To establish the curves S-N, 5 levels of alternate tension were used for essays in underwater pressurized at 5 atm. For refrigerated atmosphere, 7 tension levels were used, because it was not known what was the best tension for the process, as presented in Figures 3 and 4.

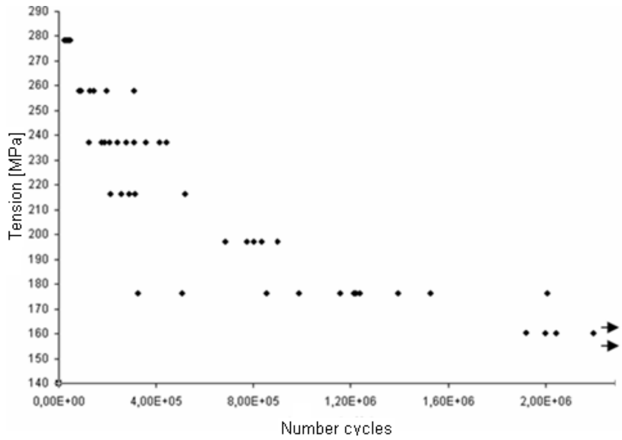

Figure 3. Refrigerated atmosphere samples

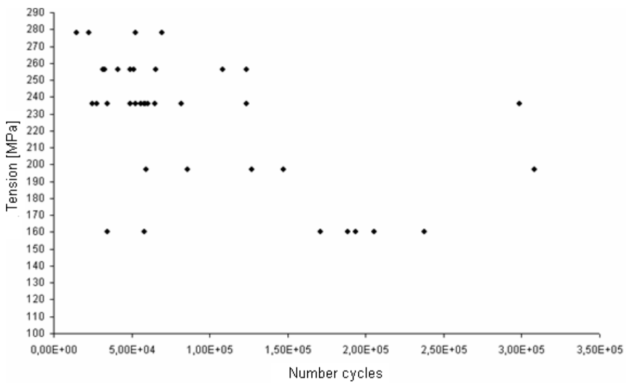

Figure 4. Pressure in water 5 atm atmosphere samples

A. *Adjustment model regression for samples refrigerated and pressure in water 5 atm atmosphere*

The estimate for parameters and verification of the model was made using the software MINITAB, version 13 and Microsoft Excel, 2000. In Figures 5 and 6, values of standardized residues are presented, after those values of variables.

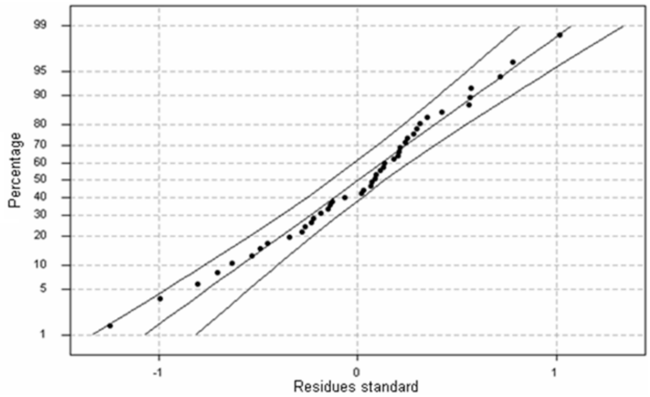

Figure 5. Residues standard refrigerated

The results from the graphic were:
Intercept = 19,02899,
Coefficient variable predictor = -0,02874,
Parameter scale Log-normal distribution = 0,43843.

The model obtained above according to the result is given by Equation 4:

$$Y = \ln(T) = 19{,}02899 - 0{,}02874x + 0{,}43843\varepsilon \quad (4)$$

For adjustment model regression for pressure in water at 5 atm.

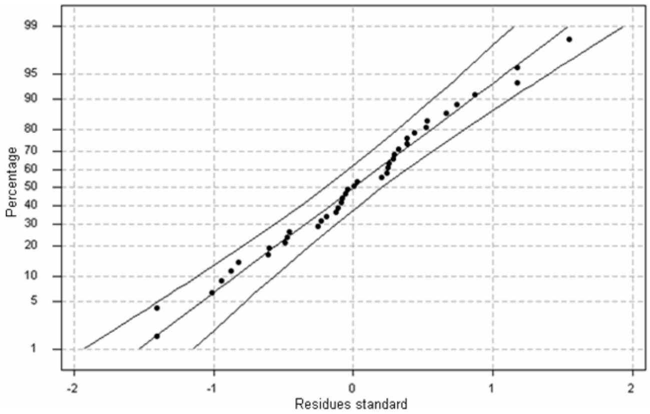

Figure 6. Residues standard for pressure in water at 5 atm

The results were:

Intercept = 13,51672,
Coefficient of variable predictor = -0,01042,
Parameter scale Log-normal distribution = 0,73778.

The model obtained above according to the result is given by Equation 5:

$$Y = \ln(T) = 13{,}51672 - 0{,}01042x + 0{,}73778\varepsilon \quad (5)$$

The analysis indicates that the value residues (adjusted values - observed values), positioned in the graphic of normal distribution, approaches a straight line and they are inside of a 95% of reliability and without any configuration that demonstrates unsatisfactory behavior. The model in question was adjusted for the study.

B. Calculation resistance fatigue limit using regression model

With the values from the curves S-N the environments were applied for refrigerated adopted 2.000.000 cycles with a 50% as a failure probability, is given by Equation 6:

$$x_0 = \frac{1}{-0{,}02874}\left[0 \times 0{,}43843 + \ln\left(2 \times 10^6\right) - 19{,}02899\right] = 157\,MPa \quad (6)$$

For pressurized atmosphere with water to 5 atm obtained values of curve S-N it was adopted 500.000 cycles as failure probability of 50% for samples, is given by Equation 7:.

$$x_0 = \frac{1}{-0{,}01042}\left[0 \times 0{,}73778 + \ln(500.000) - 13{,}51672\right] = 38\,MPa \quad (7)$$

Based on the works of Sterverding [13] and Hudson (1972) it was verified that fatigue resistance limit is influenced by applied atmospheric pressure. That can be associated in essay pressurized to 5 atm with water.

In relation to these values, Hahin [14] made a research and said that steel SAE A-36 has a resistance fatigue limit to the air of 23Ksi (158,58 MPa) using bending tension essay. The value found is in accordance with literature values as presented in Figures 7.

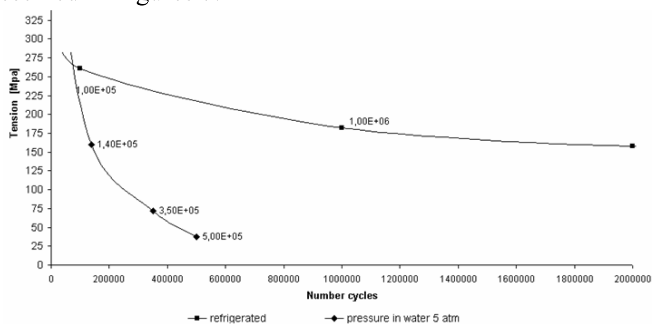

Figure 7. Resistance limits fatigue for two atmospheres with probability of failure of 50%.

V. Conclusion

For the pressurized essays with water at 5 atm, because of the low number of cycles, it was considered a probability of failure of 500.000 cycles.

In this paper it was found two hypotheses to explain those differences obtained in pressurized essays to 5 atm:

Some of them associated to dissolved air, or air bubbles in water that could contribute to decrease resistance fatigue. That was noticed at the end of the test because the area of fracture was presented oxidized, with pits reducing number of cycles for the crack nucleation. It is also verified that the tension effect has a result in the life fatigue of material [1];

The other, it deals with cavitation phenomenon that occurs for movement and turbulence of fluids in a metallic surface. This happens due to collapse of air bubbles in surface metal, pressure and speed test. Salient that the cavitation displays material to corrosive consuming and assists in formation pits [1].

It evidences that pressure has an important role. Therefore in essay under pressurized water to 5 atm precocious ruptures far occurs.

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