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Improvement of the test equipment for a stress corrosion lab through the Axiomatic Design

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Abstract

Choosing the best material for a given design environment is more and more important in the modern Oil and Gas industry. This issue affects the economical sustainability and the integrity of the oil field equipment since the aqueous environment where there are hydrogen sulphide or carbon dioxide is highly corrosive. Many experiments have been drawn out in order to investigate the strength of common carbon steels and corrosion resistant alloys in different conditions and many others are needed; nevertheless achieving reliable and accurate data for these kind of tests is quite difficult because of both the complexity of the subject and the lack of a standard test procedure among laboratories. Another difficulty is represented by the need to customize the test device and the system whose they take part in order to overcome several degrees of freedom which are present and could affect the accuracy of the results. At first the Axiomatic Design theory is used for identifying those critical aspects of the standard proof ring device which may affect the results from stress corrosion tests. After, this method is employed to drive and evaluate various equipment customizations to achieve results in compliance with the NACE TM0177 regulation.
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1. Introduction

Among several mechanism of corrosion, that one which is given by the presence of hydrogen sulphide or carbon dioxide in aqueous environments is a key obstacle to sustain operational success in the Oil and Gas industry due to its high severity and occurrence. The environmental conditions of places where new oil fields have to be built are harsher and harsher, therefore, more advanced technologies and technical knowledge are required [1].

The environmental corrosion affects the economy and has consequences for safety of the people and the integrity of the oil field equipment. Nowadays the adopted trend in order to mitigate this issue is the achieving of economic returns and satisfactory performances. This is achieved through the accurate forecasting of the working life of components due to the choice of the most suitable material for a given environmental and operative condition. In this scenario, qualifying the materials performances is becoming more and more important in order to properly select them for specific design environment. This allows to lower the maintenance costs, which are typically high in the case of an underestimated choice, or the purchasing cost, avoiding an overestimated material. Available materials for the production of the oil well equipment are several carbon steels and, more often, the corrosion resistant alloys (or CRAs) which have an higher purchasing cost but also higher performances than traditional steels.

A lot of experiments have been performed in the last years for making available data for several common steels and many others have to be made in order to qualify the behavior of new alloys. Previous experiences have sometimes shown that data are incomplete or incorrect because of the encountered difficulties in taking into account the large amount of parameters which have a role in the execution of these tests and the lack of a common experimental procedure among laboratories. On the other hand, the employed devices for executing the tests are parts of complicated systems rather

than single instruments and have to be adapted for the specific laboratory, so a customization of the equipment is often needed in order to satisfy the normative requirements and achieve valid results. The Axiomatic Design theory [2 - 4] can be used as an useful tool for customizing and improving the laboratory equipment in order to obtain correct and reliable data about the performances of several alloys in given environments. The authors are going to analyze a proof ring device for stress corrosion tests from an axiomatic design point of view since some preliminary measures which were aimed to investigate the accuracy of its response had given undesired results. The analysis will be useful for identifying harmful causes for the undesired results, moreover suggesting the needed customizations of the device.

Nomenclature

d mean annulus diameter of the anchorage nut
I information content of a specific solution
K torque coefficient
L the nearest specific limit to the mean value of the data
T_F friction torque between the anchorage nut and the ring
T_T the applied tightening torque to the anchorage nut
T_0 the twisting moment along the specimen axle
Z sigma level of the proof ring loading process
p probability to satisfy the boundary conditions.
θ the mean diameter of the contact surface between the anchorage nut and the ring
μ mean value of the data distribution
σ standard deviation of the data distribution
τ friction coefficient between the anchorage nut and the ring surface

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2. The stress corrosion test using the proof ring device

The test through the usage of the proof ring device is aimed to investigate the susceptibility of the material to the sulphide stress cracking phenomenon (or SSC) in terms of its time to failure in a given corrosive environment and under a constant load. The results of some groups of tests in different conditions (both for environmental and the applied load) allow to define the working field for a specific alloy and identify the threshold conditions within which failures do not occur [5]. Researchers have drawn out several maps which define the boundaries of the safe working condition for a lot of alloys; an example is given in Figure 1.
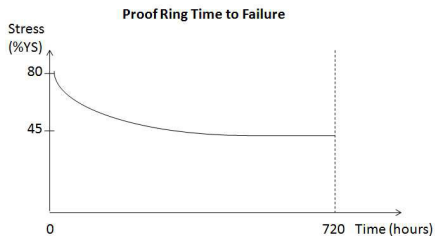

Fig. 1. Proof ring time to failure for the X100 steel in the NACE TM0177 solution A (the dashed line indicates the test maximum duration of 720 hours).

The proof ring device is composed by a high stiffness steel ring to pull a specimen which is sunk in a corrosive solution within a Plexiglas vessel [6]. The vessel allows the linkage between the opposite sides of the ring and the specimen while it is sunk in the solution which is bubbled by hydrogen sulphide (or carbon dioxide or a mixture of both). The ring has the main function to apply a constant load to the specimen. It works since the lower end of specimen is fixed, united to the ring, whilst at the other side it is screwed to a threaded rod which crosses the ring through a hole and is than screwed into a nut. When the nut is tightened through the application of a torque, it compresses the ring, so both the threaded rod and the specimen are pulled with a constant load that is directly proportional to the ring deflection through its overall stiffness.

The system behaviour is very similar to one of a spring whose the force depends on the deflection through its overall stiffness. The applied load is thus controlled through the measurement of deflection by a dial gauge, fixed on the device frame. Obviously an accurate control of the imposed deflection has to be performed since the qualification of steels and CRAs requires the correct definition of the test conditions. A general scheme of the proof ring layout is given in Figure 2.
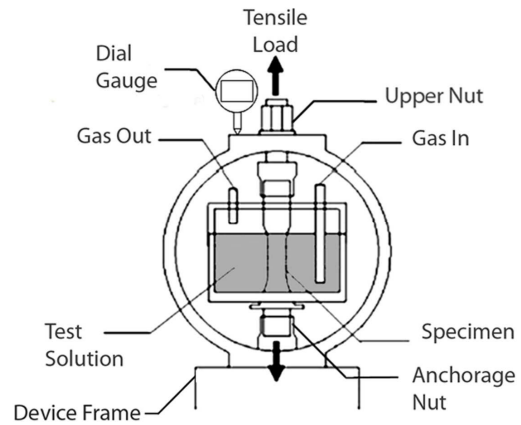

Fig. 2. Proof ring device layout.

The NACE TM0177 is the standard for this kind of experiments and requires that the maximum error over the applied tensile load is not greater than 1% of the same value [7]; so a very strict regulation of the given deflection through the dial gauge has to be performed. The fulfillment of the NACE specifications requires several modifications and layout set-ups in order to minimize data variation and not introduce macroscopic errors during the loading of the specimen.

Two macroscopic effects which affect the dial gauge signal and consecutively the effective applied load are the bending of the ring and its twisting around the specimen axle. The tightening of the nut is achieved through the application of a torque by a wrench. This action is performed manually, so it implies the application of a torque and a force during the thrust. What can be experienced is thus the shift of the contact point between the ring and the stylus of the dial gauge due to both the bending and the twisting. In this scenario the

deflection measurement, which is the input parameter in order to set the load over the specimen, may be inaccurate, resulting in tests to be discarded.

In this paper the authors are going to investigate how the Axiomatic Design theory can help to spot causes of data variability and how modify the experimental equipment in order to achieve more stable and accurate results.

3. The current design

The current design of the proof ring is not able to produce reliable data since the measurements of the applied deflection and the corresponding force are affected by an high dispersion which results in an high uncertainty on the overall test conditions. In order to verify the fulfillment of the required maximum error about the applied load by the proof ring device, the authors are going to replace the specimen with a load cell and perform several measures, imposing the same deflection and noting down the corresponding values for force.

The amount of imposed deflection and the corresponding load shall be known accurately in order to achieve the desired conditions for stress corrosion tests with reduced errors. Force values have been measured for several steps of deflection through the whole working range, but, in the following passages, only one of them will be considered as an example of the device overall behavior. Figure 3 shows a time series of force measures which are taken for the same deflection value by two operators.
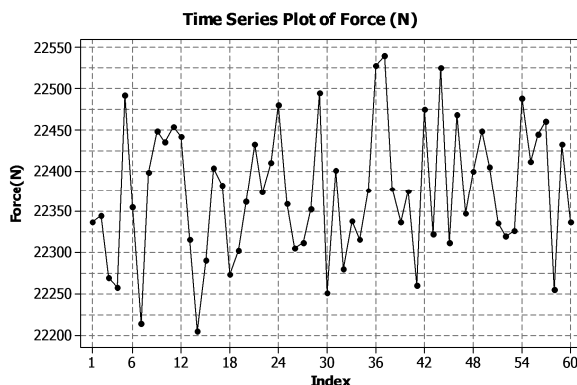

Fig. 3. Series of force measures for the same deflection. The measurements are spread in a wide range.

The measures are spread within a pretty wide range that is big enough to overcome the maximum accepted error about the load. Figure 4, which shows the same layered data by operator, points out a different behavior between the two. This may depend on a non exactly equal sequence of actions in order to reach the desired deflection and, therefore, apply the load.

In Figure 4 the continuous line represents the normal distribution given by the measures which are obtained by operator 1, while the dashed line represents the series which is obtained by the operator 2. These experimental evidences show an high uncertainty about the applied load for the same value of deflection, resulting in an unacceptable result in order to accurately and confidently qualify materials.
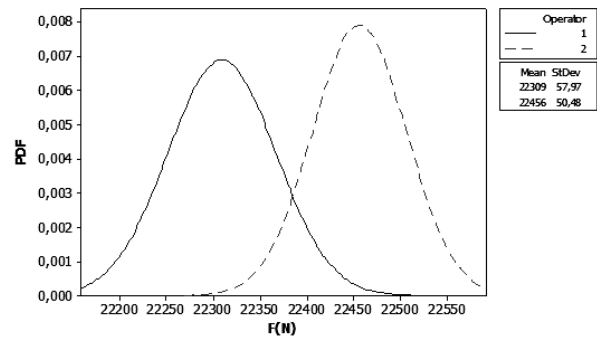

Fig. 4. Series of layered values in respect with the operator who has performed the measures.

The authors have tried to identify those critical aspects which may affect the system behavior through the usage of the axiomatic Design as a tool for spotting the causes for the data variance at the imposed deflection.

This goal is achieved through the examination of the current design from a functional point of view using the zigzag method. The authors have mapped the functional and design domains finding some correlations among functional requirements (FRs) and design parameters (DPs), identifying some intervention factors to improve the accuracy of the applied force values by the test equipment. The functional analysis reveals that the low accuracy of the force measures could depend on the poor overall stiffness of the system and the difficulties in reproducing the initial test conditions in addition to the contact position of the dial gauge probe on the ring. The low stiffness is due to several clearances that are given by the non optimal tightening of several screwed parts and structures of the test device. The FRs for the test equipment are defined below:

- FR1: Estimate the applied load
- FR1.1: Maximize the overall stiffness
- FR1.2: Reproduce the initial position of the dial gauge probe
- FR1.3: Reproduce the initial condition for the load application
- FR1.1.1: Prevent the system bending
- FR1.1.2: Prevent the system twisting
  The corresponding DPs are:
- DP1: Proof ring device
- DP1.1: Mechanical clearances
- DP1.2: Clearances in the dial gauge probe
  Both the DP1.3A and the DP1.3B satisfy the FR1.3:
- DP1.3A: Contact point between the ring surface and the dial gauge probe
- DP1.3B: Differences among the operators
- DP1.1.1: Bending Modulus
- DP1.1.2: Twisting Modulus

In Figure 5 the resulting design matrix for the proof ring device is shown. The second level of the matrix is highly coupled since several design parameters affect more than one requirement. The FR1.1 can be further decomposed in two single issues which can be solved independently.

	DP1	DP1.1	DP1.1.1	DP1.1.2	DP1.2	DP1.3A	DP1.3B
FR1	X						
FR1.1		X			X		X
FR1.1.1			X				
FR1.1.2				X			
FR1.2		X			X	X	X
FR1.3		X			X	X	X

Fig. 5. Design Matrix for the current layout.

The information content, i.e. the probability not to satisfy the given limits, can be computed referring to the NACE TM0177. This normative reference provides a criterion for evaluating the capability of the system for providing reliable data since it establishes the maximum acceptable shift for the applied force in respect with a reference value which corresponds to the imposed deflection.

Treating the force distribution as the output of a common industrial process, its sigma level can be computed as the ratio that is given by the formula [8]:

$$Z = \frac{L-\mu}{\sigma} \tag{1}$$

Where "*L*" is the nearest specific limit to the mean value, "μ" is the average and "σ" is the found standard deviation among the measured data. Obviously data have to be distributed according a gaussian curve in order to calculate the sigma level for the current process. In this case the series of data is pretty similar to a gaussian curve since the P-value for the Anderson-Darling normality test is higher than the commonly accepted threshold value of 5%.

The force distribution is placed in respect of the upper and lower specific limits (USL and LSL) which are built by the reference value of the measured data, that is taken equal to the mean. Once the position of the data distribution in respect of the boundaries is known, the sigma level is calculated. The probability to satisfy the boundary conditions is achieved considering the area under the curve which falls within the boundaries. Figure 6 shows the boundary limits, computed as the mean value plus or minus the maximum error, according the NACE TM0177.
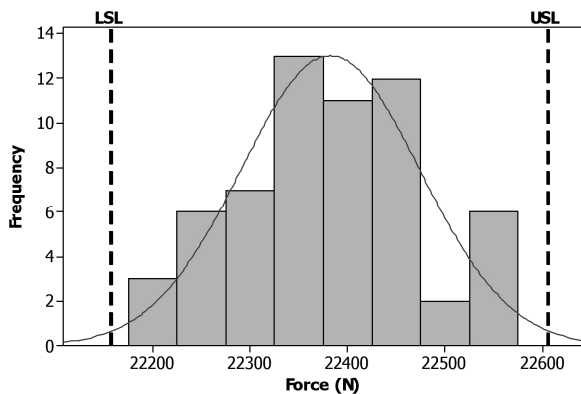
Fig. 6 Data placement within the specific limits.

The calculated sigma level for the loading process is almost 2 that corresponds to a probability to satisfy the specific limits approximately equal to 95.5%. It results in an information content of 0.07, according the formula [2]:

$$I = log_2 \frac{1}{p} \tag{2}$$

Where "*p*" is the probability to satisfy the specific limits and it has been considered equal to 0.955.

4. The modified design

The design matrix shows that the current system is coupled and allows to spot several aspects which affects the accuracy of the results. The authors suppose that each DP is characterized by its own distribution which affects the overall force distribution, contributing with the others to enlarge the data dispersion through the transfer function. Note that the overall transfer function, which provides the force distribution, taking into account the effects of each DPs and those from their interactions, is unknown and can be just assumed but this is not important at this stage. Clearly the number of DPs and the width of their distributions deeply affect the overall dispersion of the applied force. Such behaviour can be seen in Figure 7.
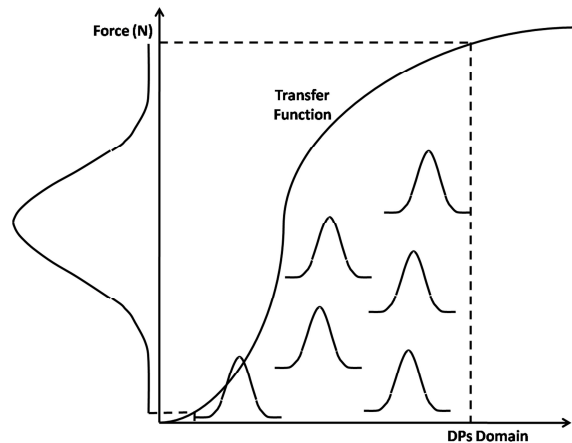
Fig. 7 Effects overlapping given by several DPs distribution over the force, through the transfer function.

The aim of this paper is the improving of the current design in order to reduce the impact of some DPs and eventually exclude their effect on the force dispersion. The proof ring device presents several screwed parts which may lead clearances and low data accuracy, especially whether different operators use the test instruments in a different manner and tighten the parts without a fixed value for torque.

The mechanical set-up of the system is a challenging issue since, in a first stage, it affects directly the reproduction of the same initial conditions for measuring, and affects the stability of the system during the application of the force to the specimen through the tightening of the proper nut.

The movement of the system during the tightening of the nut deeply affects deflection values which are measured by the dial gauge and introduces several errors in the estimation

of the uncertainty of the correlation between the ring deflection and the applied force. The increase of the moment of inertia of the joint resistant section, which anchors the ring to the base, minimizes the bending amplitude of the specimen axle. Such joint is just a fixed screw in the current design and its resistant section is the annulus threaded one. Since the load can be considered applied to the specimen axle during operations, the whole system can be modelled as a fixed beam with a shear force and a torque at its free end. The scheme is shown in Figure 8.
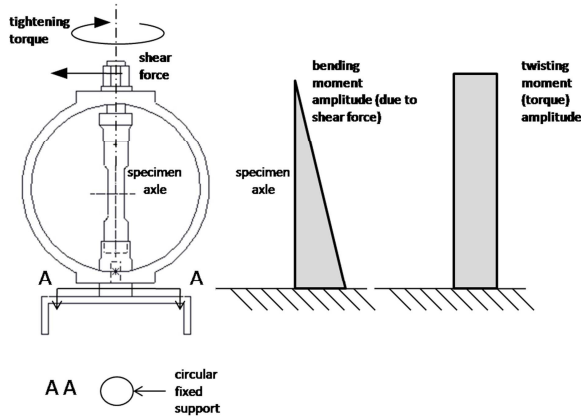

Fig. 8 Load scheme of the current system.

The amplitude of the bending moment is maximum in correspondence with the section of the fixed support. The bending modulus has been improved replacing the circular fixed support with a fixed prismatic aluminum plate which supports the entire flat end of the ring. This modification is shown in Figure 9. It improves greatly the moment of inertia of the most stressed section since the outer fibers are much more distant from the neutral axle than in previous layout (circular support) [9].
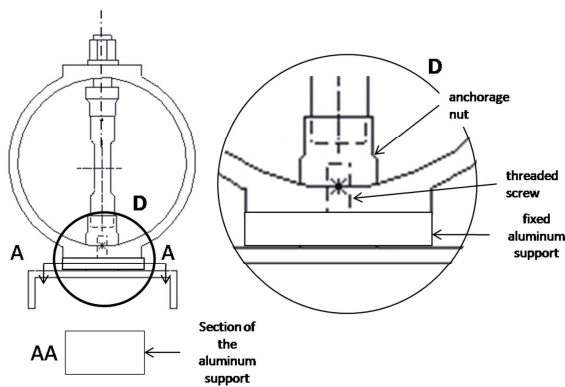

Fig. 9 Proposed modification to reduce bending of the specimen axle under shear forces.

The twisting moment around the specimen axle is applied to the upper nut and acts over the ring which rotates, if it is not well tightened. This harmful effect is eliminated applying

a tightening torque to the lower anchorage nut (shown in the detail D in Figure 9) by a dynamometer wrench. This torque produces a friction resistant moment which is opposed to the torque applied to the upper nut. The friction torque can be calculated through (3) [9,10]:

$$T_F = \tau \cdot \left(\frac{T_T}{K \cdot d}\right) \cdot \frac{\partial}{2} \qquad (3)$$

The friction torque shall be greater than the calculated twisting moment by the maximum applied load T_0, according the equation (4):

$$T_0 \leq T_F \qquad (4)$$

The tightening torque which is applied to the anchorage nut is identified in 50 Nm and has been proceduralized in order to reproduce the same setup conditions for the system before the force application.

The clearances in the couplings between the two parts of the dial gauge stylus have been eliminated adopting instruments with a single piece probe while the contact point has been fixed through a pen sign, directly marked on the upper flat surface of the ring. Finally a procedure for the loading process has been written and each operator has been trained for its correct execution. Referring to Figure 7, the introduced proof ring modifications are aimed to eliminate some DPs which affect the overall performance or to reduce their distributions.

The design matrix for the modified proof ring is drawn out according to the following FRs and the corresponding DPs; it is shown in Figure 10:

- FR1: Estimate the applied load
- FR1.1: Maximize the overall stiffness
- FR1.2: Reproduce the position of the dial gauge probe
- FR1.3: Reproduce the initial conditions for the load application
- FR1.1.1: Increase the bending modulus
- FR1.1.2: Increase the twisting modulus
- DP1: The proof ring test device
- DP1.1: Reduction of mechanical clearances
- DP1.2: Marked contact point between the ring and the dial gauge
- DP1.3: A known procedure among operators
- DP1.1.1: Increased moment of inertia
- DP1.1.2: Tightened anchorage nut by an assigned torque

	DP1	DP1.1	DP1.1.1	DP1.1.2	DP1.2	DP1.3
FR1	X					
FR1.1		X	————	————		
FR1.1.1				X			
FR1.1.2					X		
FR1.2					X	
FR1.3						X

Fig. 10. Design Matrix for the modified proof ring.

Some new measures, acquired by the modified design, show a better performance in terms of accuracy and reduction of the information content. Figure 11 shows a series of layered value by operators after the implementation of the procedure and the training stage. Both the two operator's performances are pretty similar in terms of average and data dispersion.
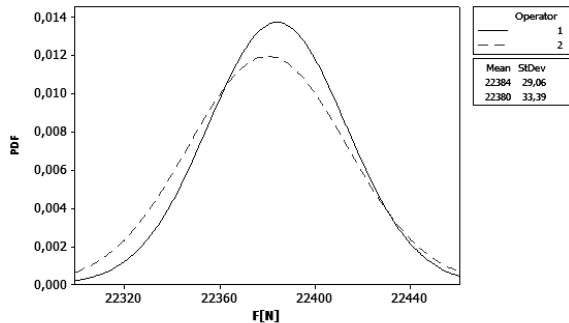

Fig. 11. The new series of layered values in respect with the operator who has performed the measures.

Figure 12 shows the overall system performance among both the specific limits. The achieved sigma level is near 8 which corresponds to a probability of success greater than 99.9%, besides a lower information content.
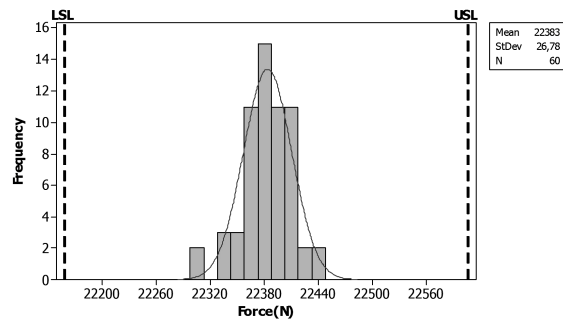

Fig. 12. Data distribution and histogram in respect with the specific limits for the modified design.

5. Conclusions

In this paper the standard design for a commercial proof ring device for stress corrosion tests has been analyzed through the Axiomatic Design. A modified design for the proof ring test device has been found and a better performance in terms of accuracy and reproducibility has been achieved in respect with the first results. The Axiomatic Design method is used with different purposes in different stages of the project since it is as a tool for spotting harmful causes which can affect the current design at first and for finding out some better solutions after. The proposed modifications act in order to reduce the number of harmful variables (or DPs) which affect the overall distribution through the transfer function of the mechanical system or to reduce their impact over the results. The effectiveness of the found solutions has been evaluated through the comparison of the design matrices of both the current and the modified layout. The information content has been calculated through the sigma level of the loading process before and after the implementation of the found modifications. As a result of the implementation of the method, the amount and the amplitude of several harmful parameters, which affected the overall performance, have been reduced, finding a diagonal design matrix for the modified system, a four times higher sigma level and thus, a minor information content.

6. References

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