Reliable NDT data for risk based inspection for offshore structures

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Abstract

The monitoring of existing structures is more and more based on probabilistic approaches suck as risk based inspection (RBI). In order to minimise risks and costs in monitoring, reliable inspection data are of great importance, all the more inspection, maintenance and repair (IMR) campaigns are carried out at a low frequency. This is the case for offshore structures, with expensive non-destructive underwater inspections. This kind of harsh environment leads to lower in-situ performances than those obtained in laboratory. PoD data are often used in current RBI approaches. However, false alarms are not considered in spite of some results of the ICON project (InterCalibration of Offshore NDT), showing a significant number of false indications.
In this paper, some data on underwater inspections on tubular nodes are presented. It is shown how ROC curves, Pod and PFI data where obtained within the ICON project. From a structural point of view, this paper then underlines the role of false alarms in a RBI process, using a cost function and both the probability of detection and the probability of false alarm. The basic policy “repair when crack is detected” and “do nothing when no crack is detected” is shown to be not optimal, underlining the necessity to use false alarms.

The ICON project

Goal and main Objectives

Existing offshore structures are designed to pre-defined safety levels they must maintain during their lifetime. They are submitted to aggressive environmental conditions, which can reduce their structural integrity, leading to the necessity to reassess their structural reliability using in-situ inspections. The aim of such inspections is to detect damages such as fatigue cracks, corrosion damages that may have occurred, and to verify that they remain in acceptable boundaries.

In order to target the safety levels, reliable inspections are necessary to make sensible engineering decisions. Due to the harsh conditions of underwater inspections that affect NDT performances and the wide range of non-destructive techniques available for such inspections, a comparison of the performances of underwater NDT tools has been achieved through the ICON (InterCalibration of Offshore NDT systems) project. It consists in experimental assessment of non-destructive tools in terms of: costs, technical performances and operational ease of use. The trials are reproducible blind tests on realistic fatigue cracked tubular welded connections.

Typical results

A wide range of NDT equipment (about 24 manual tools, as well as 10 aided tele-manipulation systems) have been tested, using rigorous tests procedures (see Bar93) to ensure reliability and reproducibility of measurements. For a given technique, the performance results obtained during the blind trial are presented table 1. These are typical ones, and are representative of what can be found in the ICON database software (Though much data on the equipment itself, the inspection procedure and tool specifiactions can be also found but are not presented herein). This underwater NDT tool is able to characterise both length and depth of cracks. In table1, the first line "range" shows the crack size class, the line "defects" the number of existing defects in each class (characterised using a specific rigorous procedure, combining the use of several NDT systems, partial destructive testing, in order to get reliable reference data for the trials). The next two lines "detected" and "spurious" show the inspection results, as reported during the blind trials. Basically, the probability of detection PoD as a function of crack size can be calculated by dividing the number of detected defects by the number of existing defects. The probability of detection curves are one of the main result of the ICON project. For the probability of false alarm, it is more difficult to evaluate it, since false alarms are considered as noise disturbing the measurements. The way false calls have been treated within the ICON project was to compute a false call ratio (abbreviated FCR) given by the following formula:

$$FCR\% = 100 * Nb\ of\ spurious * Mean\ length\ of\ the\ class\ range / Total\ length\ of\ welds$$

Depth (mm)	Range	0-1	1-2	2-3	3-5	5-7	7-10	10-15	15-40
Total nb of :	defects	45	8	7	7	5	9	6	10
	Detected	3	1	5	5	5	7	6	10
	Spurious	14	0	0	0	0	0	0	0
Length (mm)	Range	0-9	9-31	31-50	50-80	80-108	108-150	150-250	250-671
Total nb of :	Defects	34	18	12	4	4	6	8	11
	Detected	2	4	6	3	4	5	7	11
	Spurious	2	5	0	1	1	1	3	1

Table 1: raw blind trial results for a given technique.

Following this calculation, graphs similar to Receiver Operating Characteristics (ROC) have been obtained, as illustrated from table 1 data, see figure 1. When possible, the crack size has been treated under the form of a scatter diagram comparing the real crack size and the measured crack size. However, this aspect is not considered herein.

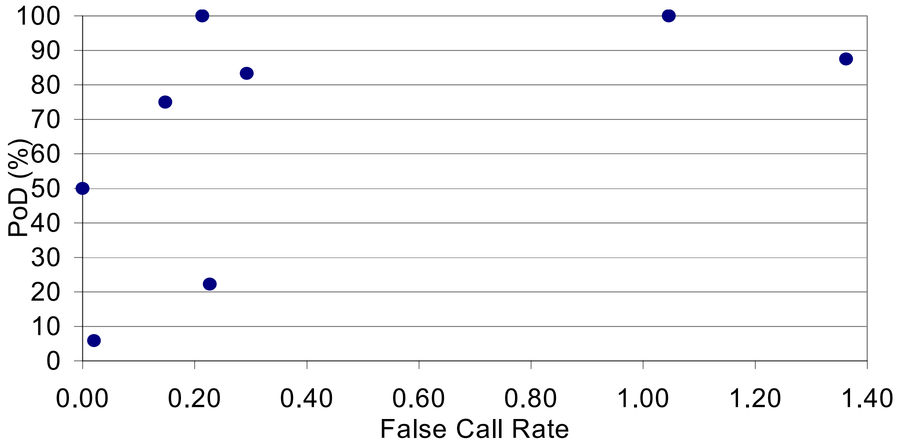

Figure 1: Relative Operating Characteristics data – Length case.

All the raw data of such blind trials have to be post-processed so that they can be used. We will thus use idealised ROC curves in our applications.

Probabilistic detection model for inspection results

The data given (under the form of ROC curves) by the ICON project are the characteristics of the inspection performances. However, such data cannot be directly used in a RBI process: one must take into account the inspection results. Hence, a model of "inspection results" is necessary and has been developed. In this work, a probabilistic point of view has been adopted: it is consistent with the global approach used, risk included. In this section, this model developed (Rou02) allowing the use of inspection results is presented. It deals with detection only, hence crack size will not be considered. From a detection point of view, we note X the random variable which value is $X=1$ in case of crack presence, $X=0$ otherwise. To make an inspection is to make a decision on the state of the inspected area. Thus a detection is modelled by a random decision function $d(.)$ on the state X of the inspected area: crack detection is $d(X)=1$, and no crack detection is $d(X)=0$. This is resumed on figure 2. These definitions allow defining the probability of detection PoD and the probability of false alarms FPA, using bayesian statistics:

$$PoD(X) = P(\, d(X) = 1 \mid X = 1) \tag{1}$$
$$PFA(X) = P(\, d(X) = 1 \mid X = 0) \tag{2}$$

Using inspection results imply to know whether or not there is a crack after detection or non-detection. Thus, we define the events E_i related to crack presence/absence conditional to crack detection/non-detection, using Baye's theorem:

$$P(E_1)=P(X=0 \mid d(X)=0) = \frac{(1-PFA(X)).(1-\gamma)}{(1-PoD(X)).\gamma+(1-PFA(X)).(1-\gamma)} \tag{3}$$

$$P(E_2)=P(X=0 \mid d(X)=1) = \frac{PFA(X).(1-\gamma)}{PoD(X).\gamma+PFA(X).(1-\gamma)} \tag{4}$$

$$P(E_3)=P(X=1 \mid d(X)=0) = \frac{(1-PoD(X)).\gamma}{(1-PoD(X)).\gamma+(1-PFA(X)).(1-\gamma)} \tag{5}$$

$$P(E_4)=P(X=1 \mid d(X)=1) = \frac{PoD(X).\gamma}{PoD(X).\gamma+PFA(X).(1-\gamma)} \tag{6}$$

where γ is the probability of crack presence in a given crack size range:

$$P(X=1) = \gamma \; ; \; P(X=0) = 1- \gamma \tag{7}$$

and where the events E_i are:

- E_1: no presence of crack, conditional to no crack detected;
- E_2: no presence of crack, conditional to one crack detected;
- E_3: presence of crack, conditional to no crack detected;
- E_4: presence of crack, conditional to crack detection.

Events E_2 and E_3 are linked to a bad detection. They will thus always be used to characterise the cost overrun due to a bad detection event. Concerning the parameter γ, one can demonstrate that low values are in correspondence with large crack size, whereas large values deal with short cracks. On a more general basis, γ is in correspondence with the distribution of crack size, see (Rou01a) for more details.

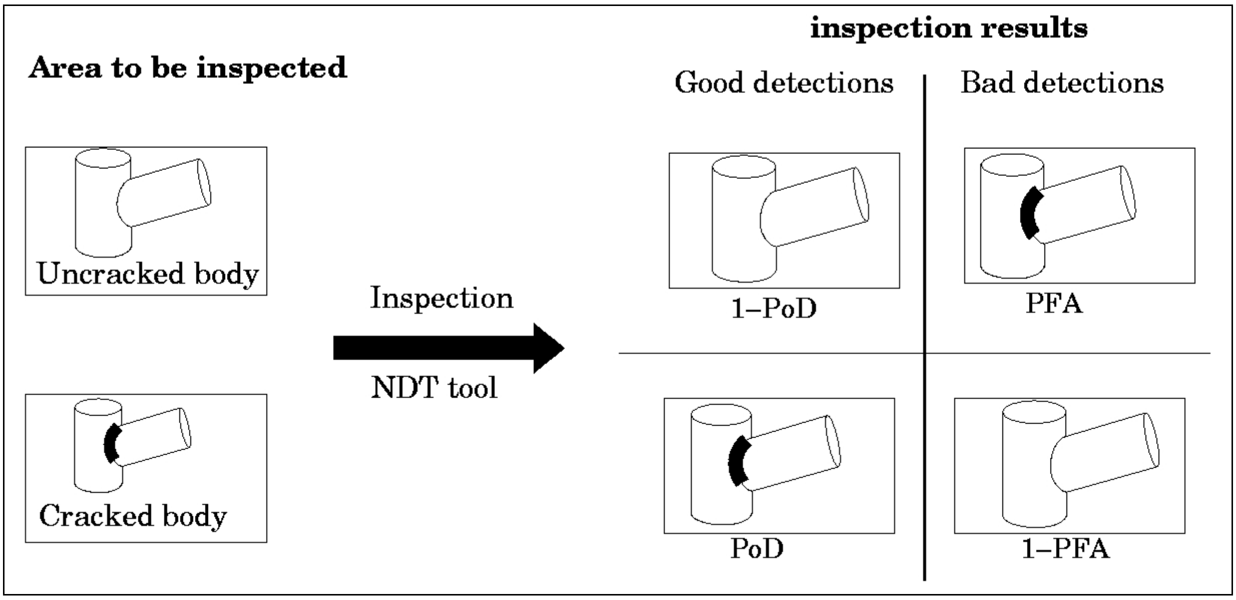

Figure 2: Probabilistic model of inspection results.

Risk evaluation: the cost function

To avoid the loss of its structural integrity, an offshore structure is managed using inspection, maintenance and repair plans. In order to optimise costs of these plans (on a more general basis the maintenance of the structures, given that it has to fulfil its safety level requirements), research on methodologies has been carried-out: optimisation of inspection planning (Goy00, Fab00) and risk-based inspection (Mad87, Jia92, Tan96, Ono99, Goy00). They provide suitable models of inspections results in order to perform mechanical and fatigue computing. The definition of the probability of detection is mainly devoted to this aim.

In order to make sensible engineering decisions for the management of the structure, a Risk Based Inspection analysis can be undertaken. It mainly consists in choosing the action that minimises the global risks. Here, the global risk is defined as the expected cost $E(C)$ of the undertaken actions, direct and indirect consequences included:

$$E(C) = \sum_i C(E_i)P(E_i) \tag{8}$$

where $C(E_i)=C_i$ is the cost associated with the i^{th} event E_i and $P(E_i)$ the probability that the event E_i occurs. In our case, C_i will either represent the cost of inspection, either of repair or of structural failure for example, and will depend on the chosen policy of maintenance. The total expected cost depends on the inspection result:

- In case of non-detection, we use the previously defined events E_1 and E_3 (associated with non detection $d(X)=0$):

$$E(C) = C_1P(E_1) + C_3P(E_3) \tag{9}$$

where C_1 is the cost linked to the action planned in the case "no crack conditional to no crack detection" and C_3 is the cost linked to the action planned in the case "crack presence conditional to no crack detection". Let underlines once again that E_3 (as well as E_2) is associated with a cost overrun, since it is an event where the crack presence is considered in spite of the inspection result (no crack detection). So will C_2 and C_3.

- In case of crack detection, we similarly have:

$$E(C) = C_2P(E_2) + C_4P(E_4) \tag{10}$$

Case study

In this section, the impact of false alarms in a RBI cost analysis is presented using previous models. The repair strategy is based on the following maintenance policy:

- no crack detection leads to do nothing,
- and crack detection leads to repair.

Two non-destructive techniques are of concern, and for each one, two ROC points marked 1,2 and 3,4 are tested. These ROC curves are plotted figure 3 (one can see a set of two other ROC curves too on this graph).

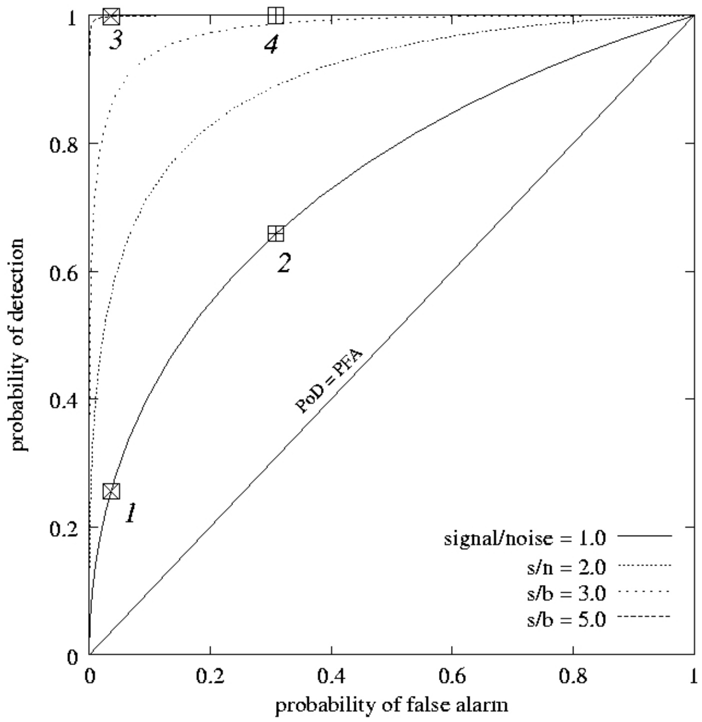

Figure 3: Roc curves and points.

The cost model is given by the following relative costs (see table 2):

Cost of failure	$C_f = 1.0$
Cost of repair	$C_r = 0.02$
Cost of inspection	$C_i = 0.002$

Table 2: Cost model.

Assuming that the crack size is exponentially distributed (see Moan99/00), with a parameter $\lambda = 10$cm and considering crack size classes of *5*cm leads to the following values of γ_i see head of table 3. Note that for clarity reasons, not all the γ_i values are presented. According to the definitions given in the previous section, and using the defined strategy, we have:

- in case of non-detection:

$$E(C)=C_i+C_f\,P(E_3) \tag{11}$$

the cost overrun is then represented by $C_f\,P(E_3)$;

- in case of crack detection:

$$E(C)=C_i+C_r \tag{12}$$

the cost overrun is then represented by

$$E(C)= C_r\,P(E_2) \tag{13}$$

Note that in this case, the cost is deterministic: all the action happens. Thus, for the optimisation of the expected cost, we will only work with the cost overrun due to bad decisions. We compute the cost overrun $E(C)_{Nd} = C_f\,P(E_3)$ in case of no crack detection and the cost overrun $\overline{E(C)_d} = C_r\ P(E_2)$ in the case of crack detection. Theses values are then integrated over all the γ_i classes. This gives the expected cost for each ROC point (in bold table 3). Finally, we compare these costs for the different ROC points. The global minimisation consists then in choosing the one who minimises both the costs overrun in case of detection and non-detection.

CASE	ROC point	E(C)	a∈[0 ; 5] γ_0=0.393469	a∈[5 ; 10] γ_1=0.238651	A∈[10 ; 15] γ_2=0.144749	a∈[40 ; 45] γ_8=0.007207	$\sum_{i=0}^{+\infty}\gamma_i E(C)$
1	PoD=0.25611 PFA=0.03593	$E(C)_{Nd}$	0.33558	0.19676	0.11751	0.00757	**0.206020**
		$\overline{E(C)_d}$	0.00356	0.00618	0.00906	0.01902	**0.007427**
2	PoD=0.65896 PFA=0.30854	$E(C)_{Nd}$	0.24440	0.13590	0.07905	0.00557	**0.146727**
		$\overline{E(C)_d}$	0.00838	0.01198	0.01469	0.01969	**0.012265**
3	PoD=0.99852 PFA=0.03593	$E(C)_{Nd}$	0.00300	0.00248	0.00226	0.00201	**0.002565**
		$\overline{E(C)_d}$	0.00105	0.00206	0.00351	0.01664	**0.003398**
4	PoD=0.99999 PFA=0.30854	$E(C)_{Nd}$	0.00201	0.00201	0.00200	0.00200	**0.002008**
		$\overline{E(C)_d}$	0.00645	0.00992	0.01292	0.01954	**0.010553**

Table 3: Expected cost overrun

According to table 3, the best compromise is given by ROC point 3. This is in accordance with its position on the ROC plan, see figure 3: the more the point near point (PoD=1, PFA=0) is, the better the performances are. It should be emphasised that case 3 does not have the best PoD value (see case 4), neither the best PFA value (see case 2).

Conclusions

Non destructive testing plays a great role in Risk based inspection methods. The performances of inspections tools cannot be modelled from a deterministic point of view, needing a probabilistic approach. This leads to the classical probability of detection and probability of false alarm parameters. In the view of inspection results use, it is shown how to combines both these parameters and inspections results from a detection point of view. Based on a given general maintenance policy, the risk study shows that false alarm can play a significant role in reducing costs in inspections plans. Thus, having the best PoD curve for an inspection tool does not necessarily lead to an optimal cost maintenance plan. This is a compromise between the probability of false alarm and the probability of detection. From this point of view, ROC curves are of great importance and give strong indications of the inspection performances results.

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