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# STRUCTURAL INTEGRITY EVALUATION OF JACKETS SUBMITTED TO THROUGH CRACKS

**Antoine Rouhan\*, Franck Schoefs**

Laboratoire de Génie Civil de Nantes Saint-Nazaire, Faculté des Sciences et des Techniques  
2 rue de la Houssinière, BP92208 44322 Nantes Cedex 03, France

Tel: +33 (0) 1 51 12 55 55 Fax: +33 (0) 1 51 12 55 57

E-mail: Antoine.Rouhan@physique.univ-nantes.fr, Franck.Schoefs@physique.univ-nantes.fr

## ABSTRACT

The study of the impact of through cracks on structural integrity of jacket platforms still a challenge. The detection of such cracks is of great importance and a miss, or a spurious indication can lead to maintenance costs overrun. In the context of risk-based inspection and monitoring of such structures, a global methodology is proposed.

The detection of large cracks is first addressed. A probabilistic model is proposed, taking into account the *in situ* inspections performances and the probability of crack presence. This is achieved by the use of the detection theory.

Second, a finite element that is able to represent the structural behaviour of through cracked tubular nodes is proposed and a global structural integrity measure is suggested.

Finally, inspection results are introduced in order to compute the expected platform structural integrity. It is illustrated by considering FMD inspections results of a tripod structure. Effects of false alarms can then be underlined.

Key words: structural integrity, through cracks, NDT inspections, jacket structures.

## INTRODUCTION

Fixed offshore platforms such as jackets, experience harsh environmental conditions, and are submitted to extreme events. Most of them currently reach or will reach soon their initial design lifetime and need structural integrity reassessment (Moa00) from an economic point of view. Regarding the fatigue effects on

jacket platforms, cracks at the weld connection in tubular nodes are propagating. These are surface cracks and then reach the wall thickness with time: this is the through crack. Then, the tube detach from the node, which is not satisfactory. However, this can happen during extreme events such as hurricanes (Val00; Bay00). Through crack is often considered as critical the crack size beyond which repair is needed. To avoid such damages, the structure is managed using Inspection, Maintenance and Repair plans (Ter; Goy94; Guo92; Moa99; Eng00; Blo00; Fab99). In order to optimise costs of these plans, research on methodologies has been carried out: optimisation of inspection planning (Goy00; Fab00) and risk-based inspections (Tan96; Mad87; Jia92; 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 devoted to this aim.

When studying cracks on welded joints, two physical states are generally considered: the surface crack and the through crack. This classification is mainly based on the fact that through cracks allow water penetration in the tubular component, and that the residual lifetime is not well know and assumed to be small in this case. Lot of works consider a reliability based criteria with a critical size equal to the member thickness, introducing both events after inspection: crack found or not (Mad87). The crack growth model is the classical Paris-Erdogan's law. The case of ageing structures, 20 or 30 years old, is particular in the sense that their redundancy allows to reassess their structural integrity in a less conservative way than design was. Moreover, it has been shown that the residual lifetime of a joint after trough-crack

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\*Address all correspondence to this author.

initiation is not so weak.

The present paper proposes to consider the effect of through cracks on the structural response. A specific probabilistic modelling of inspection results is performed including techniques such as Flooded Member Detection. The probability of false alarm is introduced. An original way for taking into account the loss of integrity is proposed. It is based on the energetic response of the damaged joint and not on the crack length.

### THROUGH CRACK DETECTION MODEL

The detection of cracks in steel offshore jacket structure is a great challenge.

First, by the cost induced by underwater inspections. Through crack detection is cheaper using FMD (Flooded Member Detection) techniques, than classic ones such as MPI, ACFM or ultrasonic. However the kind of information given is quite different: FMD is only able to say whether or not a through crack has been detected whereas other techniques can detect smaller cracks in order to follow or repair them. These cracks do not have the same impact from a structural integrity point of view.

Second, the harsh environment and bad conditions of underwater inspections lead to lower detection performances than in laboratory tests. From the detection point of view, it means that during an inspection campaign, crack detection does not imply crack presence as well as non-detection does not imply crack absence. The first case is known as the probability of false alarm  $PFA$  or of false indication, whereas the second case is referred to the probability of detection  $PoD$ .

This probabilistic approach is presented figure 1.

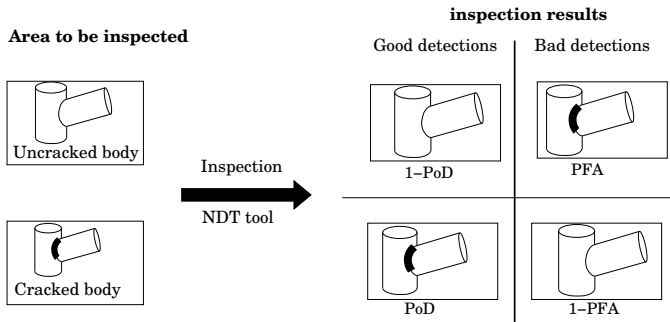


Figure 1. PROBABILISTIC MODEL OF INSPECTIONS.

### Probabilistic model of inspections

Let us note  $X$  the random variable which value is  $X = 1$  in case of crack presence,  $X = 0$  otherwise. To inspect is to make

a decision on the state of the inspected area. Thus a detection is modelled by the random decision function  $d(\cdot)$  on the state  $X$  of the inspected area: crack presence is  $d(X) = 1$ , and no crack detection is  $d(X) = 0$ . Finally, the probability of detection and the probability of false alarm can be modelled as follows:

$$PoD(X) = P(d(X) = 1|X = 1) \quad (1)$$

$$PFA(X) = P(d(X) = 1|X = 0) \quad (2)$$

The events related to crack presence/absence conditional to crack detection/non-detection are (Rou00):

$$P(E_1) = P(X = 0|d(X) = 0) \quad (3)$$

$$= \frac{(1 - PFA)(1 - \gamma)}{(1 - PoD)\gamma + (1 - PFA)(1 - \gamma)} \quad (4)$$

$$P(E_2) = P(X = 0|d(X) = 1) \quad (5)$$

$$= \frac{PFA(1 - \gamma)}{PoD\gamma + PFA(1 - \gamma)} \quad (6)$$

$$P(E_3) = P(X = 1|d(X) = 0) \quad (7)$$

$$= \frac{(1 - PoD)\gamma}{(1 - PoD)\gamma + (1 - PFA)(1 - \gamma)} \quad (8)$$

$$P(E_4) = P(X = 1|d(X) = 1) \quad (9)$$

$$= \frac{PoD\gamma}{PoD\gamma + PFA(1 - \gamma)} \quad (10)$$

where  $\gamma = P(X = 1)$  is the probability of crack presence and where the events  $E_i$  are:

- $E_1$ : no presence of crack conditional to no crack detection,
- $E_2$ : no presence of crack conditional to crack detection,
- $E_3$ : presence of crack conditional to no crack detection,
- $E_4$ : presence of crack conditional to crack detection.

One can demonstrate that low values of  $\gamma$  are in correspondence with large crack size, whereas large values deals with short cracks, see (Rou01a) for more details.

### Effects of false alarms in RBI

When the probability of false alarm is null  $PFA = 0$ , the probability of events  $E_i$  can be rewritten as functions of  $PoD$  and  $\gamma$ :

$$P(E_1) = 1 - P(E_3) = \frac{1 - \gamma}{1 - \gamma PoD} \quad (11)$$

$$P(E_2) = 0, P(E_4) = 1 \quad (12)$$

In that case, it is clear from equation 12 that crack detection is possible only when a crack exists. But according to equation 11, no crack detection does not imply crack absence. The probability of event  $E_3$  (presence of crack, conditional to no crack detection) is plotted figure 2a as a function of  $PoD$ , with  $\gamma = 0.4$ . This curve shows that for  $PFA = 0$ , the probability of occurrence of such a bad event is quite low, all the more  $PoD$  is high. This is only relevant for high probability of crack presence, *i.e.* for short crack sizes and becomes less significant for low probability crack presence.

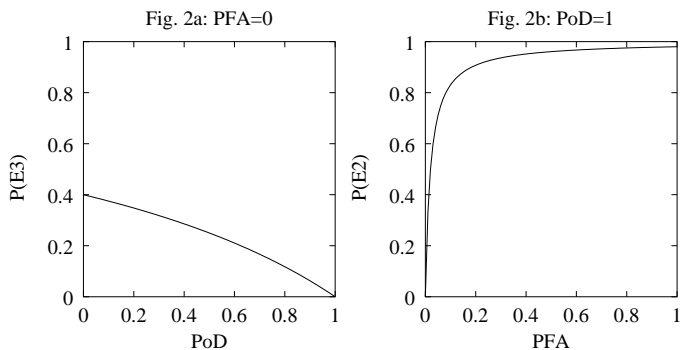


Figure 2. PROBABILITIES OF BAD EVENTS.

In order to study the effects of false alarms, consider now the case when the probability of detection is equal to one  $PoD = 1$ . The probability of previous events can be rewritten as functions of  $PFA$  and  $\gamma$ :

$$P(E_1) = 1, \quad P(E_3) = 0 \quad (13)$$

$$P(E_2) = 1 - P(E_4) = \frac{PFA(1 - \gamma)}{\gamma + PFA(1 - \gamma)} \quad (14)$$

In that case, it is clear from equation 13 that the probability to miss a crack in case of no crack detection is equal to zero: no crack detection is possible only when no crack exists: cracks cannot be missed. But according to equation 14 detecting a crack does not necessarily imply crack presence. The probability of event  $E_2$  (no presence of crack, conditional to crack detection) is plotted figure 2b, with  $\gamma = 0.02$  which is representative of low crack presence probability (mainly large cracks). It can be seen that the probability of occurrence of such a bad event is quite high, even for low  $PFA$  values. However, this behaviour becomes less sensitive for shorter crack sizes.

This underlines the role of false alarms in crack detection, when large cracks are of concern. In general, NDT tools have *in situ* performances with  $PoD < 1$  and  $PFA \neq 0$ . The probability of false alarm is thus not insignificant, as shown in the results of the

ICON project (Rud96; Bar93). Suppose that the inspected joint is crack free, and that a crack is detected. When assuming that detection is conditional to crack presence, a basic RBI policy would be to plan a repair in case of detection. This causes a cost overrun in the global management of the structure in time (Rou01a). This is of course not optimal. It is then necessary to take such event into account in the risk study.

In the following, the use of inspection results according to their performances is presented, so that the structural integrity of a jacket structure can be performed on the basis of the inspections campaign data.

## GLOBAL STRUCTURAL INTEGRITY MEASURE APPROACH

Most of jacket platforms are redundant structures. Hence, a through crack at a given node does not necessarily leads to a global structural failure. Such cracks propagate with a significant rate in laboratory tests (Gan00; Lie80; Dov95). Thus, through cracks are considered as critical crack size from the life point of view. However, as the tubular node is part of the structure, this rate is lowered. In order to study the impact of such cracks on the loss of stiffness of the assembly, a cracked beam finite element has been created and is shortly presented in the next section. The classical through crack failure criterion can no more be used in our case. As an alternative, a global structural criterion is proposed and presented.

### Modelling of a through cracked tubular node

To study the impact of through cracks on the global structural behaviour, a new beam finite element is presented. Its full description can be found in (Rou02). This element is based on a simplified mechanical model that is suitable to represent the main behaviour of a through cracked tubular node, see figure 3. The main behaviour of the damaged node is:

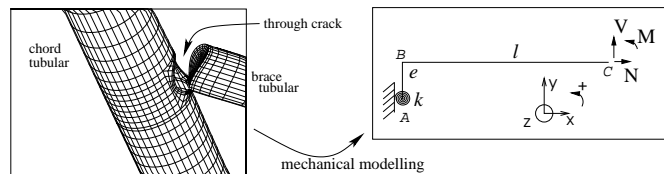


Figure 3. PROBABILISTIC MODEL OF INSPECTIONS.

1. a coupling effect between normal stress  $N$  on the brace tubular and bending moment  $M$ ;

2. a local loss of stiffness at the connection chord wall/brace wall.

The mechanical model consists in two parameters. The eccentricity  $e$  represents the coupling effects (1) and the bending spring with stiffness  $k$ , the loss of stiffness (2).

This element is build as follows. Firstly, the compliance matrix is evaluated by writing the complementary strain energy of the model. This defines the shape force function. Second, by applying the complementary virtual principle and the static equilibrium to the mechanical model, a relationship between the nodal displacements and the nodal external forces can be set. Finally, using both previous equations, one can compute the stiffness matrix of the finite element. The nodal variables are the usual nodal displacements of a classical beam element.

The parameters  $e$  and  $k$  are identified by exact semi-analytic formulas. They are obtained by using a least-square technique, minimising the difference between the displacement vector from experimental data and the displacement vector from the mechanical model, at the brace wall end.

The described finite element has been programmed into the finite element code *cast3M*, allowing to compute the entire structure with damaged elements. Thus, the effect of structural degree of freedom release due to large through crack presence can be evaluated. One way to achieve this is to compute the total potential energy of the structure.

### Structural integrity measure

Crack growth of the through crack of the tubular node can be computed using Paris's formula:

$$\frac{da}{dN} = C(\Delta K)^m \quad (15)$$

where  $a$  is the crack size,  $N$  the number of applied cycle of load,  $\Delta K$  the stress intensity factor range, and  $C$  and  $m$  material constants. The stress intensity factor  $K$  can be linked to the energy release rate  $G$ , see (Lem85). For mixed loading, (Rou01b) proposed a simple formula with relative errors not exceeding 4%. Rewriting equation 15 using the energy release rate leads to the following modified Paris crack growth law:

$$\frac{da}{dN} = C'(\Delta G)^{m'} \quad (16)$$

where  $C'$  and  $m'$  are material constants and  $\Delta G$  the energy release rate range. One interesting things is that  $G$  is closely linked to the total potential energy  $\pi$ :

$$G = -\frac{\partial \pi}{\partial A} \quad (17)$$

where  $A$  is the created surface during crack propagation. Note that the variable  $G \geq 0$  is always positive and  $\pi$  is a decreasing function of  $A$  and  $N$  too. Finally, this gives a relationship between the crack growth and the total potential energy  $\pi$ :

$$\frac{da}{dN} = C' \left[ -\Delta \left( \frac{\partial \pi}{\partial A} \right) \right]^{m'} \quad (18)$$

In linear elastic mechanics, and using the finite element method,  $\pi$  is approximated by (Rou01b):

$$\pi \approx \tilde{\pi} = \frac{1}{2} \mathbf{u}^T \mathbf{K} \mathbf{u} - \mathbf{u}^T \mathbf{F} \quad (19)$$

$$= -\frac{1}{2} \mathbf{u}^T \mathbf{K} \mathbf{u} \quad (20)$$

$$= -\frac{1}{2} \mathbf{F}^T \mathbf{K}^{-1} \mathbf{F} \quad (21)$$

where  $\mathbf{u}$  is the nodal displacement vector,  $\mathbf{K}$  the stiffness matrix of the structure and  $\mathbf{F}$  the nodal external forces applied. Hence, at the scale of the structure and for constant loading, the local loss of stiffness can be underlined by the variations of  $\pi$  through the variations of the stiffness matrix  $\mathbf{K}$ . We propose to use the total potential energy  $\pi$  as a measure of the global structural integrity. According to equation 20, it is not intrinsic as it depends on the external loading. A more convenient form consists of normalising  $\pi$  by forces:

$$\tilde{\pi} = -\frac{1}{2} \frac{\mathbf{F}^T \mathbf{K}^{-1} \mathbf{F}}{\mathbf{F}^T \mathbf{F}} \quad (22)$$

Some work still to be done about this topic. By the following, only the measure  $\tilde{\pi}$  is used.

Here are some comments on  $\pi$ : it is energy. Using only external forces as loading and no (or null) imposed displacements (*i.e.* boundary conditions), then  $\pi$  is (in absolute value) the strain energy of the structure. It is always negative in linear elasticity. Variations of  $\pi$  can be interpreted as follows. One assumes that the vector  $\mathbf{F}$  is constant. During crack propagation, the energy release rate increases (as the stress intensity factor does). In the same time, the local and global compliance of the structure increases too. As a result and using equation 21,  $\pi$  is a decreasing function with the crack size  $a$ . From equation 16, it follows that  $\pi$  decreases with  $N$ .

### Illustration

The structure used is presented figure 4. It is a tripod. The 3 piles of this structure are plugged in the soil and modelled as clamped in  $A, B$  and  $C$ . The node  $G$  has a through crack at the

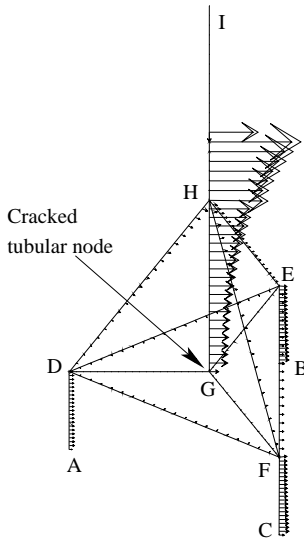


Figure 4. TRIPOD STRUCTURE.

crossing of beams  $DG$  and  $GH$ . The structure is supposed to be symmetric in the ( $DGH$ ) plane, and submerged in a depth of  $d = 30$  meters.

The swell waves are propagating along the  $DG$  direction. They are supposed to be deterministic, with a height of  $H = 8$  meters and a period of  $T = 7.5$  seconds. The loading due to the swell is computed using Morison's model (Gra92) and uses the classical Airy kinetic model (Gra92). The phase of the swell that gives the maximum value of the propagating parameter  $\Delta G$  is computed. The corresponding loading is represented on the structure figure 4.

## STRUCTURAL INTEGRITY EVALUATION AFTER INSPECTION

Suppose that the previous structure has to be inspected at a given time in its life. The aim is to evaluate the structural integrity of this structure depending on the inspection results. Both the inspection and finite element models previously presented are used. Two NDE tools detecting through cracks are considered: they are FMD (for Flooded Member Detection) tools. They do have the following *in situ* performances:

First tool:

$$PoD = 0.86$$

$$PFA = 0.1$$

Second tool:

$$PoD = 0.86$$

$$PFA = 0.4$$

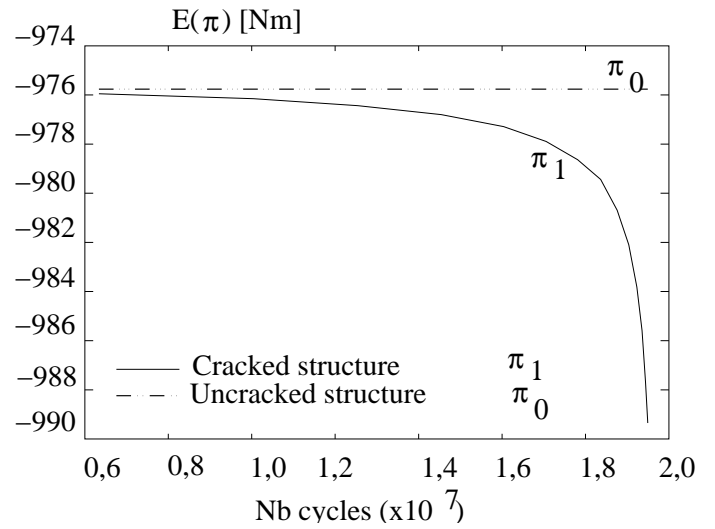


Figure 5. TOTAL POTENTIAL ENERGY EVOLUTION.

The probability of crack presence is assumed to be equal to  $\gamma = 0.1$ . One assumes that such a value is representative of the probability of through cracks presence in the structure. The aim is to give sense to the inspection results, in order to evaluate the structural integrity of the structure. Assuming that the inspection was performed using an ideal tool (*i.e.*  $PoD = 1$ ,  $PFA = 0$ ) leads to:

- crack detection means crack presence. Thus the evolution of the structural integrity according to crack growth is pointed out by  $\pi = \pi_1$  (structure with a through crack);
- no crack was detected, meaning no crack presence. Thus, the evolution of structural integrity is constant with time, and pointed out by  $\pi = \pi_0$ .

These are deterministic results. As the used tool is not perfect and that the inspection was realised in harsh conditions, one must use the probabilistic approach. On way to estimate the structural integrity  $\pi$  according to the inspection result is to compute its expected value, using events  $E_i$ :

- in case of crack detection:

$$E(\pi) = \pi_0 P(E_2) + \pi_1 P(E_4)$$

- in case of no crack detection:

$$E(\pi) = \pi_0 P(E_1) + \pi_1 P(E_3)$$

The evolutions of the expected values of  $\pi$  depending on the NDT tool performances are reported figures 6. The comparisons of

these two graphs show the effect of false alarm: in case of crack detection, the more the  $PFA$  is high, the more the “detection” curve tends to be closer to the  $\pi = \pi_0$  curve. This can be explained by the fact that, first the probability of crack presence is low ( $\gamma$  value); second the probability of a false indication is high. Thus, the belief in the inspection result lowers, and one tends to believe that no crack exists. A deterministic model would imply that a crack exists, given detection. A basic RBI policy would be to repair. The proposed model can estimate the expected structural integrity, taking into account bad inspections results and the probability of crack presence. Thus repair would not be necessary in our case, according to inspection performances. This shows that inspection results should be taken from a probabilistic point of view in risk-based inspections, in order to minimise the cost management.

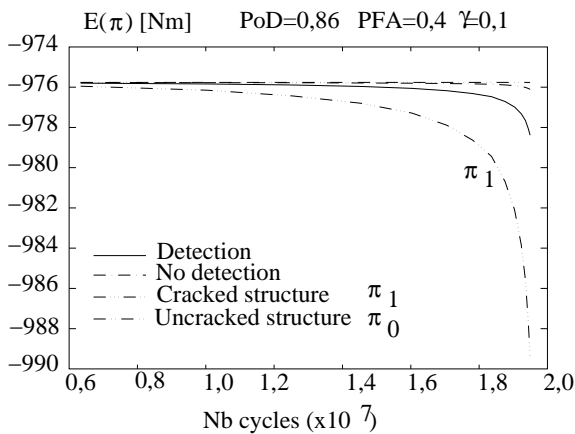
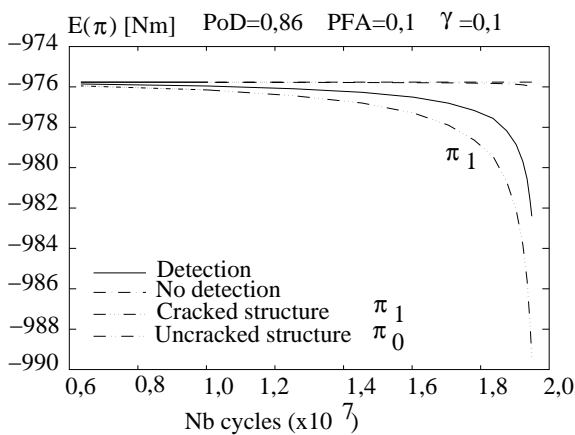


Figure 6. EXPECTED VALUES OF  $\pi$ .

## CONCLUSIONS

Both a complete probabilistic inspection model for through cracks and a structural integrity measure are presented in this paper. The probabilistic inspection model is based on the detection theory, and the structural integrity measure based on the total potential energy of the damaged structure.

An example on FMD inspections on a tripod structure is presented. It illustrates how to use crack detection data from inspections, and how to evaluate the structural integrity of the structure, according to *in situ* inspection performances. The impact of false alarms on this evaluation is underlined, and shows their importance in RBI strategies.

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