# NON-DESTRUCTIVE EVALUATION as a FOUNDATION of STRUCTURAL INTEGRITY ASSESSMENT

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***ABSTRACT -*** *The author provides an overview of the development from quality control type non-destructive testing (NDT) to quantitative non-destructive evaluation (NDE), describing the driving forces and the major characteristics of both NDT and NDE. The basic elements of NDE reliability – i.e. applicability, reproducibility, repeatability and capability – are defined. Finally, the role of NDE in structural integrity assessment is presented.*

***Keywords:*** *non-destructive testing, non-destructive evaluation, NDE reliability, structural integrity*

## 1. INTRODUCTION

Non-destructive testing (NDT) has become an integrated part of production systems, and its application is essential during the operational period of engineering structures and complex plants. The expansion of its role and its importance are based on several factors. There is an increasing need to better utilize the capability of production systems, which can result in the operation of the systems beyond their design life. A gradual increase in the rigorousness of safety requirements as a consequence of changes in our relation to safety and security has also contributed to the increasing importance of NDT.

In most cases the outputs of NDT methods are images or signal responses resulting from application of the interrogating process or field. The response never depends on one single factor; it is the resultant of the interaction of several parameters that usually are not fully known. This means that the result of NDT contains uncertainties. Following the widespread adoption of fracture mechanics in construction and operation, the testing results are one of the most important elements of input data for structural integrity assessment. Reducing the uncertainty requires a comprehensive knowledge of each NDT element as well as of relationships between the individual elements. This paper deals with the elements of NDT reliability, the factors that influence this and their impact on the structural integrity of engineering components.

## 2. ABOUT NON-DESTRUCTIVE TESTING

### 2.1. NDT HERITAGE AND EVOLUTION

Initially, NDT was used in the industry as a quality control (QC) tool (QC-NDT). The details of NDT performance were usually set out in standards; the flaw detection capability of the procedures was mainly unknown. Despite these deficiencies, the various NDT methods were accepted because they could demonstrate their capability in practice, i.e. they were able to detect flaws (inclusions, pores, lack of fusions, and cracks). Their success might also be supported by the fact that substantial design margins were applied to address many uncertainties in design, manufacturing and operation processes. The results were mainly “allowable / non allowable” and strongly dependent on the NDT personnel.

Over time, the potential risk of industrial plants has required quality improvement in general, technological development and harmonization between the regulations of different industrial areas. This development process was led by the aircraft industry, the space program and the nuclear industry. New structural materials have been applied, and new methods in design have been introduced as a consequence of the development of fatigue and fracture theory. Risk assessment, condition monitoring and life management have developed. The "safe life" design was substituted by the concept of "damage tolerance" [1]; see Fig. 1 as an example of the application of this in nuclear power plant construction.

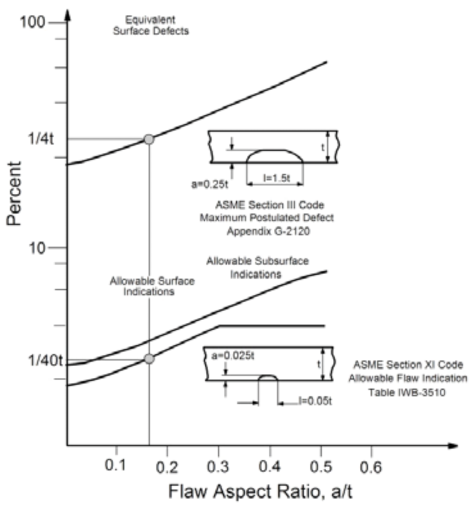


***Figure 1*** *Maximum postulated flaw (Section III) and allowable surface flaw (section XI) [2]*

Fig. 1 shows the recommendation of the ASME Boiler and Pressure Vessel Code (BPVC) Section III, Appendix G, for a postulated surface flaw for a wall thickness from 102 to 305 mm, the depth of which should be 25% of the wall thickness.

This was considered the largest flaw which could be missed by ultrasonic testing, at least with the technique available at the time the code was established. Fig. 1 shows the size of the allowable flaw during in-service inspection (the safety factor is 10) given by Section XI of the ASME BPVC. These changes were revolutionary in engineering practice and they had a similar revolutionary impact on NDT. The new criteria for quantitative flaw detection moved the QC-NDT practice into the new world of reliable detection and sizing.

Academic research and industrial application have both been accelerated by the need for scientific recognition and development of NDT methods. The concept of quantitative non-destructive evaluation (QNDE) was born. The differences between the conventional (safe life) and damage tolerant design principles and their relation to the NDT/NDE are shown in Table 1 [3].

Application of the QNDE concept requires an exact definition of the "defect". During non-destructive testing the NDT personnel first make an interpretation of the indication (signal or image response, described earlier). As a result of this interpretation, he/she decides if the indication is real (i.e. a flaw), irrelevant or a false indication. If there is a real flaw, the next step is evaluation. During the evaluation, any feature or the actual size of the flaw is compared with the relevant acceptance standards. A flaw is deemed a defect if it exceeds the acceptance level. Consequently, we can say that "flaws" are an engineering category and "defects" a regulatory one.

***Table 1*** *Comparison of safe life and damage tolerant design and NDT/NDE [3]*

| Aspect | Safe life structures | Damage tolerant structures |
|---|---|---|
| Material selection | Experience in use | Quantified damage tolerance properties (e.g. crack growth resistance) and experience in use |
| Loads, fatigue calculations, environmental effects | Structure properties and experience in use | Quantified loads and use analysis combined with damage tolerance analysis, lifetime assessment and experience in use |
| Structural integrity | "Flaw free" assumption resulting from production practices, QC-NDT and use | Calculated "critical initial flaw size" and growth of the flaw |
| NDT/NDE acceptance criteria | "No flaws" | Flaw type, size, location, orientation, and nearest neighbor |
| NDT/NDE procedures | Prescriptive NDT procedures validated by previous experience and use in the industry. New applications are based on engineering judgment. | Validated procedures characterized by applicability, reproducibility, repeatability and capability |

## 2.2. CLASSIFICATION OF NON-DESTRUCTIVE TESTING

Given the goal of non-destructive testing, it is possible to distinguish between two types of NDT/NDE: quality control (QC-NDT) and fitness for service (FFS). The relative importance of the latter has been increasing in recent decades. Testing methods and techniques are usually the same in both types, but there may be significant differences between the two areas in the competence, mentality and communication ability of the NDT personnel.

In QC-NDT the basic task is a decision on compliance or non-compliance with the requirements. Here, the deviations are usually expressed as analog (reference) signals because the requirements are also given in this form. An exception is visual testing, where there is the possibility of determining the actual flaw size. In this case the acceptance standards are, of course, also expressed as real dimensions. In ultrasonic testing, the flaw indication is compared with the indication originating from an artificial reference reflector. Closeness of the comparison (i.e. the analog relationship) depends on the closeness of the flaw surface as reflecting surface morphology to that of the artificial reflector. The flaw type can be estimated from the nature of the indications.

The registration level depends on the testing method. For dye penetrant or magnetic testing, the level can be determined by taking into account the size of the penetrant fluid or magnetic particles. In the case of radiography, the registration level can be selected depending on the X-ray film sensitivity, and for ultrasonic or eddy current testing it can be fixed arbitrarily. Flaw allowability, i.e. the acceptance level, is determined on the basis of both product criticality and NDT method. The difference between registration and acceptance levels should be determined in a way that will not lead to the registration of too many disturbing signals (noise) and its value should be large enough to be able to register signals close to or exceeding the acceptance level.

With FFS type inspection of an operating structure, one of the most important pieces of input information when determining the structure's remaining service life is the bounding rectangle or square (i.e. the size) and location of a flaw present in the structure. If structural integrity is assessed in a probabilistic way then the distribution functions of flaw size and location have to be known. In design, the materials are selected on the basis of correlation functions or fracture mechanics principles, see Table 1. In design a worst-case flaw is assumed, which is usually a surface crack equal to 25% of wall thickness; the aspect ratio of the semielliptical crack is 0.3, see Fig. 1. Qualification of the NDT system enables a reduction of the postulated flaw.

The area between the postulated flaw and the registration level can be divided into two parts. In the vicinity of the registration level, the evaluation of analog signals is allowed, similar to quality control. This is done usually with the assumption of degradations requiring a longer incubation time (e.g. creep). This area should be decreased to zero if the incubation time is short, i.e. the degradation starts after a short period (e.g. corrosion). The analog evaluation area is also decreased if the flaws induced by operation load and the environment make a significant contribution to the risk of catastrophic failure of the component (e.g. planar flaws perpendicular to the surface).

In the second part, the bounding flaw size has to be determined and compared with the size calculated by fracture mechanics. The allowable flaw sizes are given in standards (e.g. ASME BPVC XI or similar), usually as a function of a/t, a/l and Y; here a = through wall flaw size, l = flaw length, t = wall thickness, Y = coefficient expressing flaw/surface interaction. If the flaw size measured by NDT is smaller than the allowable flaw given in the standard then the structure or component is suitable (fit) for further operation; if not – i.e. there is a defect – then an individual fracture mechanics calculation should be carried out. Fig. 2 illustrates this.

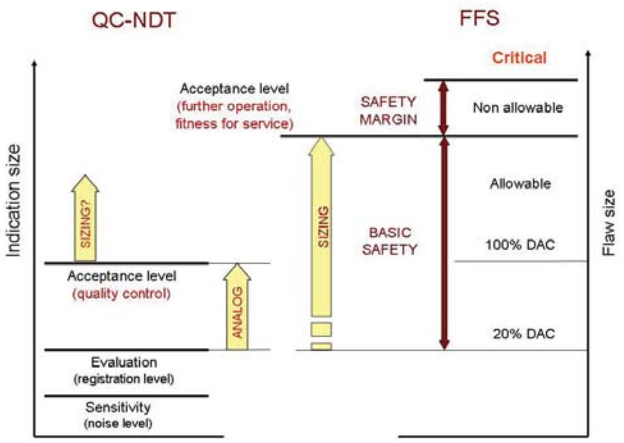


***Figure 2** Evaluation differences between QC-NDT and FFS NDT/NDE*

## 3. RELIABILITY OF NON-DESTRUCTIVE TESTING

NDT of high risk structures and components whose failure may lead to significant damage to the environment, health or assets requires greater than average reliability. It is expected that inspections that are critical for safety should be able to detect degradations which, if they were to develop and grow to a critical size, could cause human injuries or death. It is also expected that the NDT characterizes the flaws with high reliability in order to take the right decisions over mitigating measures (repair or replacement). Finally, it is also expected that the inspection itself will make possible a substantial risk reduction. The greater the need for risk reduction by the NDT, the greater the need for NDT system reliability and for demonstration of its capability. The following elements create reliability in non-destructive testing:

- applicability – a proper signal/noise ratio,
- reproducibility – a correct system calibration,
- repeatability – stability of the NDT system,
- capability – probability of detection.

Probability of detection (POD) is a possible measure of NDT capability. To determine POD a reproducible calibration and appropriate acceptance level are necessary.

POD methods are useful for development of repeatable NDT procedures, but a precondition of their application is a stable NDT procedure [4].

### 3.1. APPLICABILITY

The output of NDT is the indication originated from the flaw and characterized by the NDT method. Form, intensity and other features of the indications primarily depend on the NDT method, the test object characteristics and the NDT procedure. An NDT method is applicable if, in the range of a given flaw, it is able to reliably discriminate between the indication and noise, i.e. the signal/noise ratio is great enough.

Fig. 3 shows the probability density distribution of signal and noise values and the relation of distribution curves to each other and to the acceptance level. The left hand graph of Fig. 3 is typical for NDT that is applicable: the two distribution curves are situated far enough from each other. Moreover the acceptance value lies outside both curves. The graph to the right of the figure characterizes an NDT system where the signal/noise ratio is small and the distribution curves overlap each other. This can result in false call and miss.

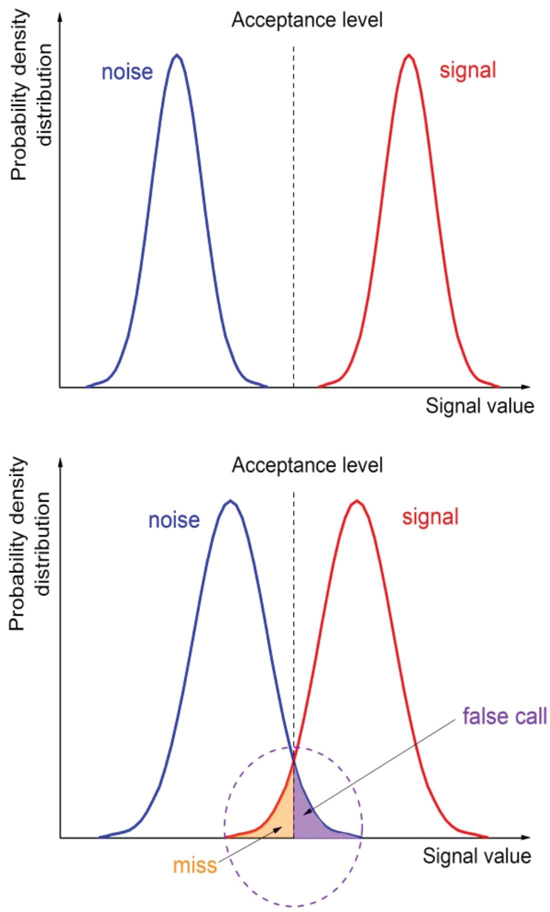


***Figure 3** Signal/noise ratio in applicable and non-applicable NDT systems*

### *3.2. REPRODUCIBILITY*

An NDT procedure is reproducible if the same result is ensured whoever carries out the inspection and wherever this is done. The keys for reproducibility are proper set up and calibration. For this, one-point calibration is not adequate; the calibration curve must be fitted to multiple points, see Fig. 4. On the left of Fig. 4 it can be seen that for one-point calibration there may be different responses. The multi-point calibration (on the right) ensures reproducibility.

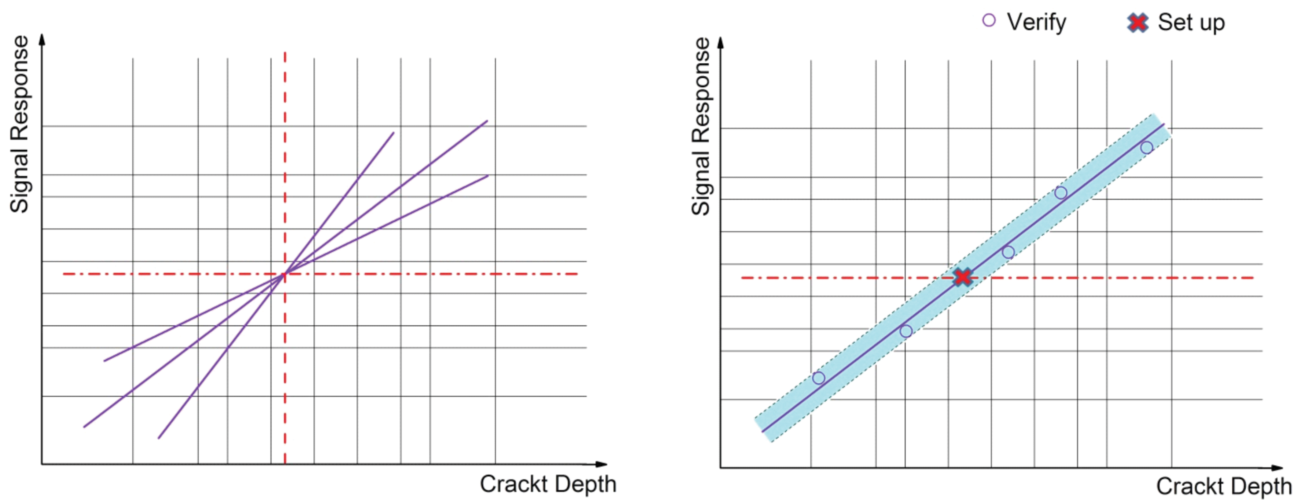


***Figure 4*** *Calibration curves fitted to one-point and multi-points*

### *3.3. REPEATABILITY*

Repeatability of a procedure is assessed by producing consistent measurement results for representative test artifacts, applied in the intended application environment. This assumes knowledge and registration of each element of the measurement process. Examples are verification of consistent signal levels from multiple, representative artifacts; measuring and documenting noise levels in locations where the NDT is intended to be used; documenting NDE threshold signal discrimination levels; and documenting signal and noise levels over the range of expected flaw sizes.

### *3.4. CAPABILITY*

NDT capability can be measured by the probability of detection (POD). POD is the fraction of detected flaws in the total number of flaws as a function of flaw size. POD was established to support NASA and other programs in 1970s and became the fundamental element of QNDE [4]. Today, the POD concept is an integrated part of engineering design, risk and lifetime assessment and prediction.

Fig. 5 shows a POD curve for a NASA space program where new points were generated from a limited number of original ones by a special simulation program, and thus it was possible to draw up the confidence interval as a function of crack size [5].

## *4. STRUCTURAL INTEGRITY*

Structural integrity assessment of engineering structures means evaluation of their resistance to strength and fracture. Since the energy requirement for ductile failure is far greater than that required for failure in the brittle mode, the basic tool of the structural integrity assessment is fracture mechanics. Fracture mechanics allows the calculation of the limit condition of the material, complete with intrinsic flaws (cracks) without unstable crack propagation. The assessment method can be deterministic or probabilistic; it is shown schematically in Fig. 6.

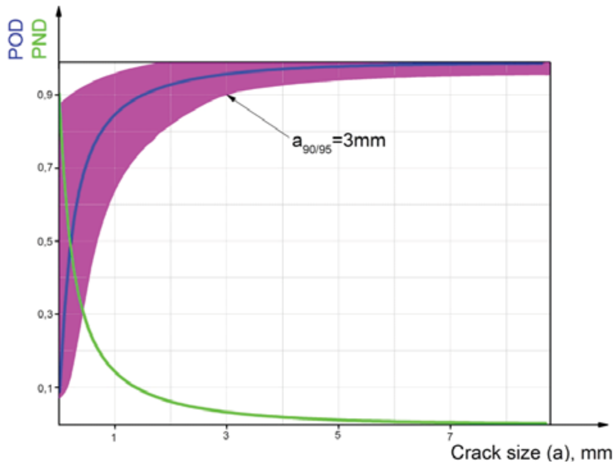


***Figure 5** POD curve as a function of crack size (for a=3mm: POD = 90%, confidence = 95%) [5]*

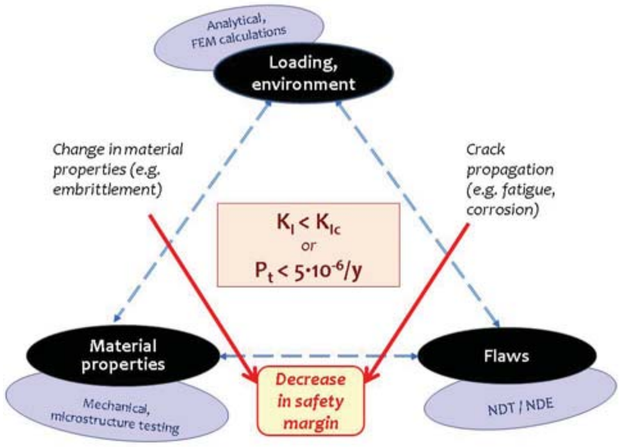


***Figure 6** Elements of structural integrity assessment and their interrelations*

It is clear from Fig. 6 that knowledge of the presence and locations of flaws, as well as their further characterization (size, orientation, and other features), are essential for the structural integrity assessment. Consequently, it is obvious that QNDE has been integrated into the assessment. As mentioned in section 2.1, this situation was created by the revolutionary changes in the design and operation practice of high risk industries. Fig. 6 is also valid for the structural integrity assessment of welded structures by extending the three main elements accordingly. For example, the residual stresses should be taken into consideration in “Loading, environment”, and the dendritic structure of weld metal and the heterogeneous structure of the heat-affected zone in “Material properties”. Special attention is needed for dissimilar metal welds. “Flaws” can contain all flaws which are typical for welding technologies (lack of fusions, non-metallic inclusions, hot cracks, cold cracks, etc.).

## 5. SUMMARY

This paper has shown the evolutionary development of non-destructive testing, and how QNDE was developed on the basis of QC-NDT. The characteristic features of both inspection types were presented, and the concept of FFS type NDT/NDE introduced.

The basic elements of NDT reliability were investigated; these are applicability, reproducibility, repeatability and capability. Finally, the role of NDT/NDE in the structural integrity assessment of engineering structures was briefly explained.

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