THE ROOTS OF IN-SERVICE NDT PERFORMANCE REQUIREMENTS

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INTRODUCTION

In the everyday activities we follow some kind of strategies as a general driving force of the human life. Our actions are mainly determined by the intellectual faculty and only in small part by intuitions. This general rule of the human body is acting when planning any non-destructive testing (NDT) activity as well. With regard to its objectives, NDT can be divided into two major fields: one is the quality control type NDT of industrial products; the second one is the fitness for service type NDT of structures and components in operation. The NDT methods applied in both cases are the same; however, in the way of thinking and the level of knowledge of the NDT personnel, in the presentation of the NDT results the two fields differ significantly from each other. In the case of quality control type NDT the goal is to decide on the conformance / non-conformance of a product. Usually it is enough to express the results in analogue signals (reference values) because the requirements are defined in the same language (an exception is the visual testing where the real flaw size can be provided).

In the case of in-service NDT of operating structures and components the most important outcome is the size (bounding rectangle or square) and the position of flaw detected. Allowable flaw sizes are calculated, in principle, from the following generic type equation:

$$[K_{Ic}]_i = C \cdot \sigma \cdot \sqrt{a_c}\ , \qquad (1)$$

where $[K_{Ic}]_i$ is an allowable value of fracture toughness for a given operating regime, C is a geometric factor, σ is a stress during the most severe regime, and a_c is the critical flaw size (normally through-wall-extension, TWE). Then, safety factors are used to obtain allowable size, usually $n_a = 2$, i.e. with respect to the flaw size.

What kind of strategy can be formulated in planning an NDT and determining its performance requirements?

- To detect the smallest flaw in the structure or component?
- To perform the NDT in the cheapest way?
- To invite the most accepted specialist in this field for drawing up an NDT procedure?
- To apply that procedure which is used by the competitor?

In the context of the paper performance mainly refers to probability of detection and sizing accuracy.

This paper intends to answer the questions above by presenting a scientifically proven concept.

SAFETY – RELIABILITY - RISK CONCEPT IN STRUCTURAL INTEGRITY ASSESSMENT

If we propose to find an absolutely clear way to find the strategy of planning an NDT procedure we have to return to the fundaments of engineering activities. These are based on the following terms: safety, reliability and risk. These terms are the driving forces for the activities made in privatized economic systems. The **safety** itself expresses the actual safety level of a system (structure, component) usually with a unit of percentage, i.e. it does not deal with investment and its cost items. In the expression of **reliability** the tools used for safety assessment (structural integrity assessment) are included, i.e. all knowledge, instruments, software, and cost of the experts. Against the investment we are able to consider the **risk** of the operating system, i.e. the probability of occurrence of failure (having no any unit) multiplied by the consequences, which can be expressed in cost figures.

If we speak about invested cost items (reliability) and operational risk we speak about the amount of money, which is both invested and risked. To define an optimum is the basic task looked for by the facility or plant owners. By this approach the principle of "minimum investment and maximum profit" is defined.

Relating to structural integrity assessment of engineering components the following are to be considered:

- degradation processes taking place in materials induced by the operation,
- existing discontinuities, flaws in the structures, and
- fields (stress-strain, temperature, magnetic, etc.) arising in the structures during operation and simulated operation conditions.

This is shown in Fig. 1.

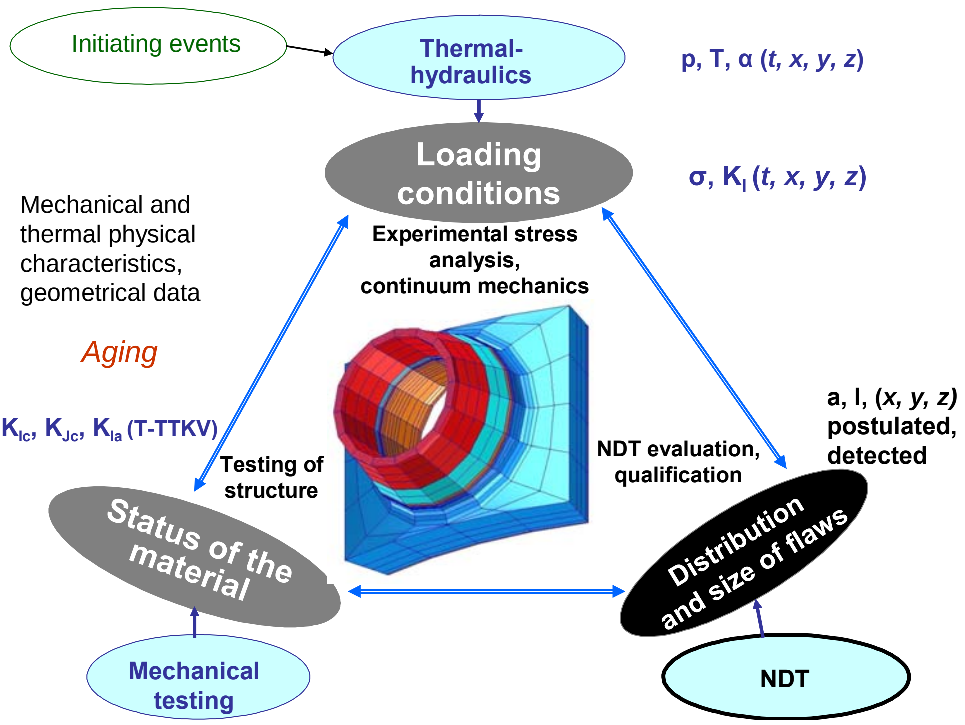

Fig. 1: Items of the reliability concept of the systems, structures and components

It is always important to know who is responsible for the reliability or the safety level of the systems: the economists or the engineers. In the recent decade or so it could be observed that the role and importance of the economists have significantly increased. This attitude has been strengthened in the privatization process especially in the newly joined EU countries since the new owners wanted to receive the profit of their investments as quickly as possible. The basic task is to find a common solution between economists and engineers without compromising safety.

The level of safety can be controlled by selecting a cost effective in-service inspection (ISI) and NDT strategy. In this case the following questions need to be answered:

- What kind of degradation process is active in the component inspected?
- In which part of the component does it take place?
- Which NDT method is able to detect it reliably?
- How often does it need to be inspected?
- What kind of capability demonstration (performance demonstration, inspection qualification) is required of the NDT system (equipment, procedure, personnel)?

These questions are summarized in Fig. 2 [1].

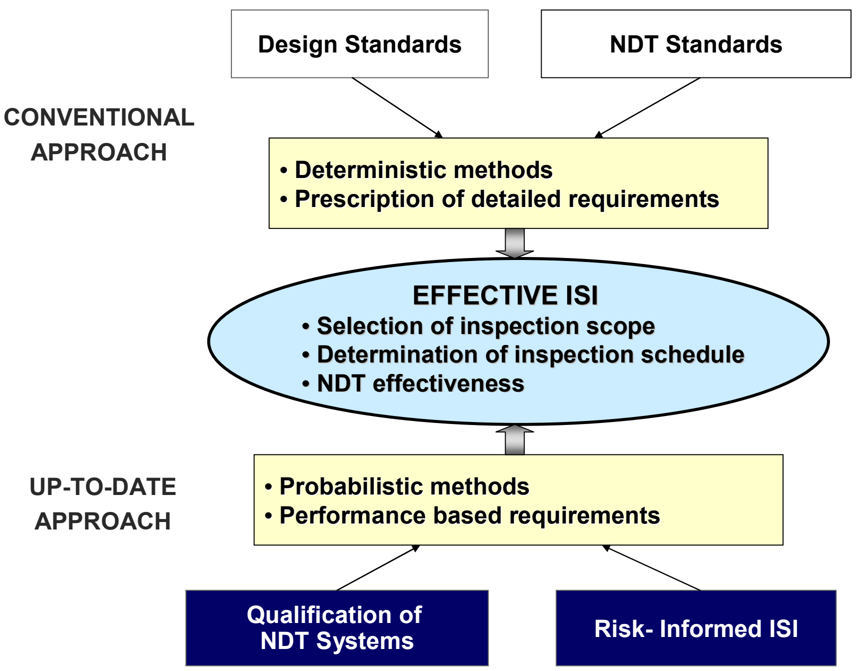

Fig. 2: Conventional and up-to-date approach of ISI / NDT

It is seen from the bottom part of Fig. 2 that rational of the questions mentioned before may have two aspects:

1. Type and size of flaws, accuracy of detection are determined by the safety and risk analysis of the structural elements.
2. Suitability of the NDT system (equipment, procedure, personnel) applied for detecting and sizing the defined flaws in a cost effective way.

CRACK PROPAGATION SENSITIVITY INDEX FOR QUASI-STATICALLY LOADED ELEMENTS

The questions can be answered only, if the reliability concept of the structures and components is based on fracture mechanics principles, i.e. if all the three determining factors illustrated in Fig 1. are taken into account. That is why the items Material - NDT - Loading Condition have to be considered at the same time. The last two items out of them may be expressed in term of *Crack Propagation Sensitivity Index (CPSI)* of the quasi-statically loaded structural component. This is a pure number without any unit, which characterizes the level of hazard of the detected flaw. Using this concept the hazard of different flaws can be compared by pure numbers, i.e. it can be said, for instance, that this flaw (defect) is three times more hazardous than that one. The introduction of CPSI of a structural element is fundamentally important because the **NDT finding - Loading conditions - Crack propagation resistance test results** are connected by applying fracture mechanics principles in reliability assessment of the components.

Using this definition the reliability of a structural element having crack like flaws (defects) and the reliability of the NDT results and determination of crack propagation resistance of the structural material create a „closed-loop system", i.e. their requirements are interconnected, see Fig. 1.

The CPSI of quasi-statically loaded structural elements is the derivative of the *K* stress intensity factor vs. *a* flaw size (TWE) function. Instead of the *K* stress intensity factor another invariant parameter of fracture mechanics can also be used (for instance the *J*-integral, or the strain energy density, etc.). Since the stress intensity factor or any other fracture mechanics parameter depends on the type of the structural element, on the loading conditions and the type, position and geometrical parameters of the crack-like flaw, the CPSI for a real structural element depends only on the flaw geometry. The simplest case is a planar crack the geometry of which can be characterized by *a*, the crack TWE. This is illustrated in Fig. 3.

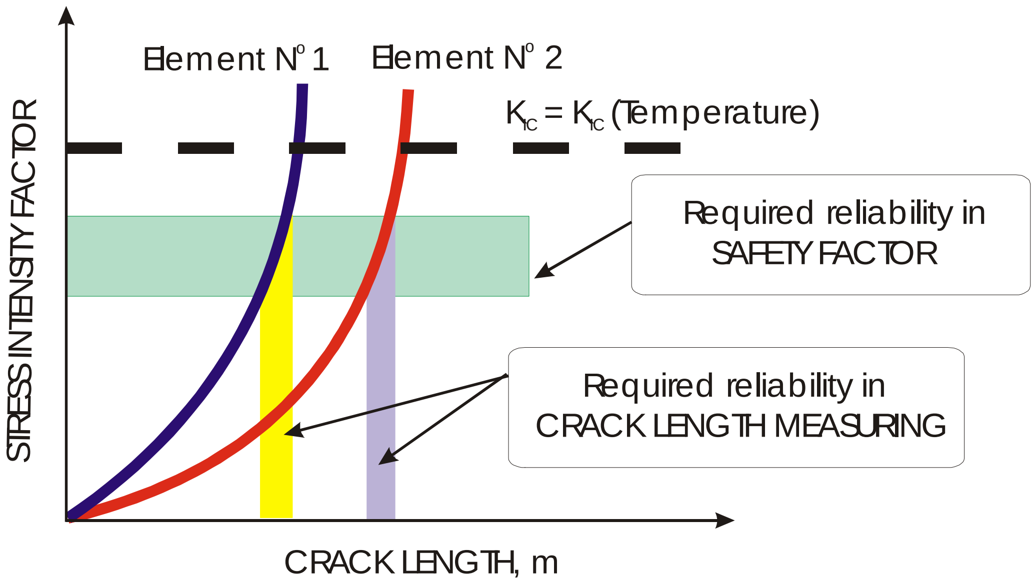

Fig. 3: The practical use of CPSI for determination of the required reliability of crack measuring for different structural elements

Fig. 3 clearly shows that at the same reliability expressed by the safety factor (i.e. at the same K_{Ic}/K_I values) of the element N° 1 and N° 2 the requirements of crack length measurement accuracy are quite different.

The solution for the stress intensity factors are collected either in different handbooks, papers [2-14] or in software [4] but the collection of their derivate does not exist yet in the literature. In the near future, one of the main tasks of the specialists working in this field is to prepare the collection of the derivate functions of the stress intensity factors for various structural elements, crack geometries and loading conditions.

EXAMPLES WORKED OUT

Let us to illustrate the CPSI concept by two very simple exemplars. Selecting a pipeline section, see Fig. 4, having an axial crack the stress intensity factor can be calculated by the equation of (2.a and 2.b.) [15].

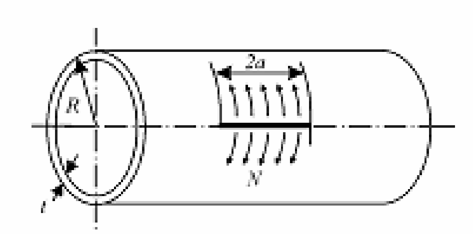

Fig. 4: Pipe with an axial crack

$$K_1^m = F^m \sigma_m \sqrt{a}, \quad K_1^b = \frac{3+\nu}{\sqrt{(1-\nu^2)/3}} F^b \sigma_m \sqrt{a}, \quad \sigma_m = \frac{N}{t}, \tag{2.a}$$

$$\lambda = \left[12\left(1-\nu^2\right)\right]^{1/4} a \big/ \sqrt{Rt} \tag{2.b}$$

The values of the F^m and F^b are detailed in the function of λ [15]. The derivate function has the following form (3.a. 3.b.):

$$\frac{\partial K_I^m}{\partial a} = \left(F^m(\lambda)\sigma_m\sqrt{a}\right)' = \sigma_m\left(\frac{\partial F^m(\lambda)}{\partial \lambda}\frac{\partial \lambda}{\partial a}\sqrt{a} + \frac{F^m(\lambda)}{2\sqrt{a}}\right) =$$

$$\frac{\partial K_I^m}{\partial a} = \left(F^m(\lambda)\sigma_m\sqrt{a}\right)' = \sigma_m\left(\frac{\partial F^m(\lambda)}{\partial \lambda}\frac{\partial \lambda}{\partial a}\sqrt{a} + \frac{F^m(\lambda)}{2\sqrt{a}}\right) = \tag{3.a}$$

$$= \sigma_m\left(\frac{\partial F^m(\lambda)}{\partial \lambda}\frac{\left[12\left(1-\nu^2\right)\right]^{1/4}}{\sqrt{Rt}}\sqrt{a} + \frac{F^m(\lambda)}{2\sqrt{a}}\right),$$

$$\frac{\partial K_I^b}{\partial a} = \frac{3+\nu}{\sqrt{(1-\nu^2)/3}}\left(F^b(\lambda)\sigma_m\sqrt{a}\right)' =$$

$$= \sigma_m \frac{3+\nu}{\sqrt{(1-\nu^2)/3}}\left(\frac{\partial F^b(\lambda)}{\partial \lambda}\frac{\partial \lambda}{\partial a}\sqrt{a} + \frac{F^b(\lambda)}{2\sqrt{a}}\right) = \tag{3.b}$$

$$= \sigma_m \frac{3+\nu}{\sqrt{(1-\nu^2)/3}}\left(\frac{\partial F^b(\lambda)}{\partial \lambda}\frac{\left[12\left(1-\nu^2\right)\right]^{1/4}}{\sqrt{Rt}}\sqrt{a} + \frac{F^b(\lambda)}{2\sqrt{a}}\right)$$

The CPSI for the pipe with a diameter of D = 610 mm, thickness of t =7.1 mm and an internal pressure of p = 64 bar can be seen in Fig. 5.

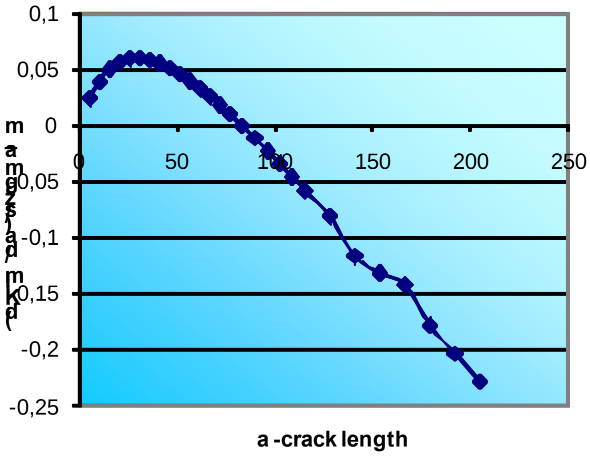

Fig. 5: Value of CPSI vs. crack length for a pipe with axial crack (D = 610 mm, t = 7.1 mm)

The same calculations can be performed for the pipe with a circumferential crack, which can be seen in Fig. 6 [15]. Ignoring the detailed steps the result is shown in Fig. 7.

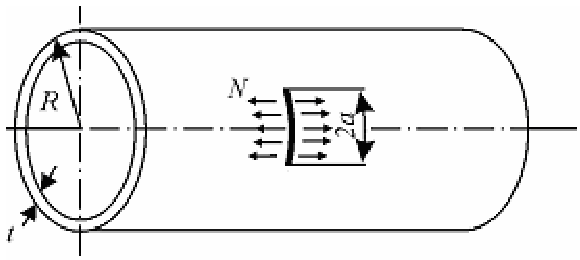

Fig. 6**:** Pipe with a circumferential crack

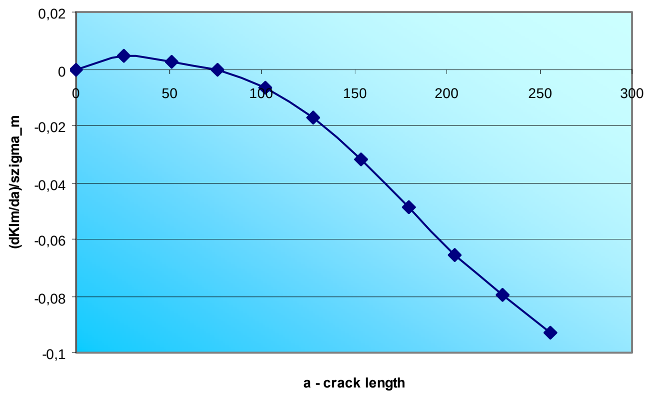

Fig. 7: Value of CPSI vs. crack length for a pipe with a circumferential crack (D = 610 mm, t = 7.1 mm)

Figures 5 and 7 exactly underline the following observations:

- the CPSI value depends on the type of structural element, crack configurations (through the stress intensity factor calculations),
- the CPSI values even at the selected examples depend on the crack length, i.e. the requirements for NDT depends on the crack length,
- the CPSI value is proportional to the degree of the local loading.

The CPSI value can contribute to determining the NDT requirements as well as requirements for the qualification of NDT systems. In the case of inspection qualification sizing accuracy is always an issue, and an unnecessary rigorousness may jeopardize the success of laboratory trials. On the other hand, if the CPSI value is high, than the requirements should be stronger in general compared with a lower CPSI value. It means that more efforts will be necessary to meet the requirements (more capable NDT equipment, more skilled NDT specialists, and more advanced NDT procedures) [15-17].

CONCLUSIONS

Considering the goal of this paper and the results presented, the following conclusions can be drawn:

- The reliability assessment of cracked structural components needs to be based on the co-operation of specialists working in the fields of NDT - Mechanical Testing - Fracture Mechanics.
- A system for characterisation of crack propagation sensitivity index of the structural elements for quasi-static loading conditions has been proposed. The CPSI serves a root for developing an NDT procedure or setting up ISI / NDT qualification objectives.
- The application of CPSI provides an opportunity to interlink the reliability assessment calculation and the reproducibility of the NDT or crack growth resistance test results.
- A compendium (and it's computer version) for *dK/da* calculation of different structural components with different crack configurations needs to be collected in the near future. It is already available for some 100 structural elements, including the application software as well. This compendium will be published soon.
- Having the above mentioned compendium the NDT and its qualification in the case of operating systems could be improved.

References

[1] Trampus, P.: Effective In-Service Inspection of Nuclear Power Plant Components, J. Materials Science and Technology, Vol. 16, 2008, No 3, p.163-172.

[2] Tada, H., Paris, P.C. and Irwin, G.R.: *The Stress Analysis of Cracks Handbook.* Del Research Corp., Hellertown, PA, USA, 1973.

[3] Rooke, D.P., Cartwright D.J.: *Compendium of Stress Intensity Factors.* Her Majesty's Stationery Office, London, 1976.

[4] *Stress Intensity Factors Handbook* (eds. Y. Murakami), Pergamon Press, 1987.

[5] Tóth, L.: "A computer aided assessment system of reliability cyclic loaded construction elements having flaws", in: *Proc.1st Int.Conf. on Computer-Aided Assessment and Control of Localized Damage,* Portsmouth, UK, 1990 (eds. M.H.Aliabadi, C.A.Brebbia, D.J.Cartwright), Springer-Verlag, Vol.1. p.39-53.

[6] Tóth L. *Reliability Assessment of Cracked Structural Elements under Cyclic Loading.* in Handbook of Fatigue Crack Propagation in Metallic Structures (eds. A. Carpinteri), Elsevier, 1994. p. 1643-1683.

[7] Carpinteri, A.: "Surface flaw under cyclic bending loading", in: *Proc.1st Int.Conf. on Computer-Aided Assessment and Control of Localized Damage*. Portsmouth, UK, (Edited by M.H.Aliabadi, C.A.Brebbia, D.J.Carrtwright), Springer-Verlag, 1990, Vol.1. p.147-158.

[8] Carpinteri, A.: "Fatigue growth of a surface crack in an elastic plate subjected to cyclic tensile loading", in: *Proc. 8th Cong. Mat. Test.*, 1982, Budapest, p. 327-331.

[9] Carpinteri, A.: Crack propagation under cyclic loading. *Fat. & Fract. of Eng.Mat. & Struct.* **15**, 1992. N°4. p. 265-376.

[10] Carpinteri, A.: Stress-intensity factors for semi-elliptical surface cracks under tension and bending, *Eng Fract. Mech.* **38**, N°4/5. 1991. p. 324-334.

[11] Carpinteri, A.: Elliptical-arc surface cracks in round bars, *Fat. & Fract. of Eng.Mat. & Struct.* **15**, N°11. 1992. p. 1141-1153.

[12] Savruk, M.P.: *Stress Intensity Factors of Bodies Having Cracks* (in Russian), in: Fracture Mechanics and Strength of Materials, Vol.2. (eds. V.V. Panasyuk), Naukova Dumka, Kiev, 1988.

[13] Pook, L.P.: Keyword scheme for proposed computer-based bibliography of stress intensity factor solution, *NEL Report N°704*, Department of Trade and Industry, 1986.

[14] Pook, L.P.: Unacceptable differences in published stress intensity factor solutions, *Fat. Fract. Eng. Mat. Struct.* N°1, 1989, p. 67-69.

[15] Dmytrakh, I.M., Vainaman, A.V., Statschhuk, M.H., Tóth, L.: *Reliability and durability of structural elements for heat-and power equipments* (in Ukrainian), Kyiv, 2005.

[16] Proc. 1st Int. Conf. NDE in Relation to Structural Integrity on Nuclear and Pressurized Components (eds. M. Bieth, J. Whittle), Woodhead Publishing Limited, 1999.

[17] Proc. 2nd Int. Conf. NDE in Relation to Structural Integrity on Nuclear and Pressurized Components, New Orleans, USA, 2000.

[18] Proc. 4th Int. Conf. NDE in Relation to Structural Integrity on Nuclear and Pressurized Components (eds. M. Bieth, J. Whittle), EUR 21871 EN, 2006.