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Non-destructive Testing and Fracture Mechanics: A Short Discussion

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Abstract. A short discussion is provided on the relationship between non-destructive testing and fracture mechanics. The basic tasks behind this are to guarantee the safety of a component at a potential hazard loading event, to specify inspection intervals or, alternatively, of demands on non-destructive testing for a fixed inspection regime, to plan accompanying actions for cases of temporary continued operation of structures in which cracks have been detected, and, finally, fatigue strength considerations which take into account initial defects.

INTRODUCTION

In many industrial applications, non-destructive testing (NDT) and fracture mechanics are individually applied each following its own rules with not so much interaction. Non-destructive testing is usually applied within a frame of what might be designated as a “good workmanship” philosophy, i.e., the product is aimed to be as defect-free as possible both during production and service. Note, however, that “defect-free” does not mean no defects exist, but that either they cannot be detected using the best suitable NDT procedure or they are present, but of a size smaller than proper acceptability levels. Fracture mechanics, on the other hand, is frequently restricted to “crisis intervention” when a defect is detected, especially if its size is not admissible according to conventional design rules.

The authors of this presentation are confident that the real potential of fracture mechanics is during the design stage, with respect to both quality control and the definition of acceptability levels for NDT procedures during production as well as for specifying proper NDT inspections during service. When, for example, a crack is detected in a railway axle during an inspection, it will be removed and replaced. Fracture mechanics, in such a case, should assist in specifying meaningful inspection intervals so that a potential crack would be detected before it grows to its critical size. To this aim, close cooperation between non-destructive testing and fracture mechanics is essential and indispensable. The intention here is to provide a discussion about how both disciplines can be applied in a complementary manner for ensuring the safe service of components.

TASKS OF NON-DESTRUCTIVE TESTING IN CONJUNCTION WITH FRACTURE MECHANICS

Overview

Table 1 provides a brief overview of applications of non-destructive testing and fracture mechanics side by side with respect to different issues of safe design and service. The various scenarios will be briefly discussed in the remaining part of the paper.

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TABLE 1. Complementary application of non-destructive testing and fracture mechanics.

Application	Requirements for non-destructive testing	Requirements for fracture mechanics
Excluding failure at hazard loading events	To exclude the existence of cracks of critical size at this loading	To correctly or conservatively determine crack driving force and fracture toughness
Specification of residual lifetime	To reliably detect an "initial crack" size during quality control operations	To correctly or conservatively simulate crack propagation and failure
Specification of inspection intervals	To assure a high probability of crack detection	To correctly or conservatively simulate crack propagation and failure
Specification of a minimum "Probability of Detection" for a given inspection interval	To specify "Probability of Detection" vs. crack size function and its influencing factors	To correctly or conservatively simulate crack propagation and failure
Limited further operation of a cracked structure	To correctly or conservatively size a crack	To correctly or conservatively simulate crack propagation and failure
Defect-corrected fatigue strength	To detect cracks and defects as small as possible	To simulate small crack propagation

Excluding Failure at Hazard Loading Events

One example of this kind of application refers to transport containers for dangerous goods. It has to be guaranteed they do not break during an accident, e.g., when they fall down during crane work or haulage [1]. Usually, only embedded defects below a certain size are permissible. When ultrasonic testing is used, crack sizing is commonly based on "equivalent reflectors" which tend to conservatively overestimate crack area compared to the real one. Since no guidance is used to be given on the permissible location of the embedded crack in the wall, this has to be assumed to be close to the wall surface with the consequence that the crack has to be re-characterized as a semi-elliptical surface crack. For critical positions, the crack driving force in terms of a dynamic J integral or K factor is determined, for example, by finite elements using a combination of global dynamic analyses, adequate for impact loading (the container falls down) of the structure without the crack, and a sub-model analysis containing the crack [1]. No fracture will occur as long as the crack driving force is smaller than the fracture toughness of the material.

Specification of Residual Lifetime

The knowledge of the residual lifetime is needed in the context of a damage tolerance analysis (see, e.g., [2]), whose essential objective is to establish NDT inspection intervals so that a crack is detected in due time, before causing failure. Any crack which potentially could escape detection is assumed as existing. The choice of the initial crack size, for fracture mechanics life predictions, is commonly based on the experience of the NDT worker, but this might be questioned for a number of reasons. Detecting defects such as cracks is an "inherently stochastic process" [3]. E.g., in manual testing, a crack might be found by one inspector, but missed by another one or even by the same at another trial. Therefore, the initial crack size is a statistical parameter rather than a deterministic one, although deterministic upper-bound values can usually be specified.

Specification of Inspection Intervals

The residual lifetime is one of the input parameters of a damage tolerance analysis. In order to specify inspection intervals, additional information from non-destructive testing is necessary. Sometimes, this is avoided by simply defining the inspection interval as a fraction of residual lifetime. If, e.g., it is chosen as half the residual lifetime, so to have two chances to detect the crack before failure, the rationale is to have another chance to detect the crack when it will be missed during the first inspection. However, this is a very premature statistics only. Complete statistical analyses are based on the so-called PoD-crack size curve, with PoD standing for "Probability of Detection". Such curves have first been introduced by NASA in the context of the Space Shuttle program. Following its first application field in aerospace (e.g. [4]), nowadays PoD data are generated for various branches such as nuclear energy, offshore structures, turbines, bridge structures and railway vehicles. An overview on PoD characteristics of railway axle cracks is provided in [5], see also [6]. As the result of a combined NDT-fracture mechanics analysis, the overall probability of detection PoD_{ov} (or non-detection $PoND_{ov}$) is determined as a function of the inspection interval. Note that $PoND_{ov}$ corresponds to the failure probability of the NDT procedure, i.e. it describes the probability that the crack becomes critical before it would be detected. It is also worth remarking this probability of failure does not correspond to that of the component because it does not include the probability that a crack really exists.

The determination of the PoD characteristics for a specific application is anything but a trivial task. It has to be distinguished between experimental determination and simulation.

Experimental Determination of PoD-crack Size Characteristics

The principle is straightforward. A statistical number of samples is prepared with artificial or natural flaws (even if the representation of natural flaws by artificial defects is questioned in the literature as explained later on). Then, experiments are carried out by various examiners using the same NDT procedure. For each defect, i.e. each crack size, the probability of detection is determined by suitable statistical elaborations. However, it is immediately clear that the experimental effort is immense, particularly for the smaller defects, since some statistical confidence is needed. From this point of view, it is worth remarking, also considering the connections with fracture mechanics, that the main aim of PoD curves is to allow estimating the largest defect that can be missed and not the smallest defect that can be detected.

In addition, the result will be affected by a large variety of influencing factors. The authors in [7] list as many as ten classes of potential errors including:

- the NDT technique itself
- the setting up and calibration of the equipment
- poorly written or even absent NDT procedures and the ability of the operator to follow them
- human factors such as fatigue during long shifts or un-adjusted shift work
- unspecified aims of the inspection (just to satisfy a regulation or specific suspicion)
- the inspectability of the component (access, surface quality, etc.)
- the defect characteristics with respect to those the chosen NDT method is designed for
- management issues such as clear information, communication, etc.
- data processing and classification
- data reporting

In [8], the authors point to the fact that it is not only the defect size but also its orientation which affects the PoD curve, e.g., in ultrasonic inspection. With respect to ultrasonic testing of railway axles, the authors in [5] emphasize artificial defects instead of natural cracks may constitute a problem. Frequently, the information is obtained on samples prepared with notches manufactured by electro discharge machining (EDM) or even saw cuts. Note that ultrasonic waves behave differently in such cases because the gap width affects the reflection/transmission behavior and thus the signal-to-noise ratio.

Theoretical or Numerical Simulation of PoD-crack Size Characteristics

Some of the problems listed above, particularly the operator-related ones, are overcome by automatic and mechanized inspections. Note, however, that, whilst it is certainly true that increased automation will reduce manual variation, there might also be shortcomings when the necessarily strongly formalized automated procedure is compared to the work of a highly specialized investigator. In addition, automated systems may also contain human behavior risks such as undetected coding errors or quality of maintenance of the automated systems [5]. Without dispute, an advantage of the suppression of subjective factors is that it allows to theoretically or numerically simulate PoD curves. For instance, dedicated software or general ones, such as finite elements, are commonly used to simulate ultrasonic signals for a specific test setup. In combination with a suited criterion, e.g. a certain signal-noise ratio, a hit/miss decision is possible. The theoretical PoD determination is not only much less expensive than the experimental method, it is also more flexible because, for example, modifications in the test setup can be captured much easier. An example for railway axles is provided in [9]. It remains reliable simulation results always require an experimental validation of the theoretical or numerical model and that a suitable mathematical model is today not available for all the problems listed above.

Specification of a Required Minimum Probability of Crack Detection for a Given Inspection Interval

Here, the principle described in section 2.4 is reversed because the inspection interval is fixed, e.g., in accordance with the maintenance scheme. There are two options:

(a) the "last chance" estimate, as the authors in [6] call it, it was proposed in [2]. Starting from the time (or number of loading cycles) to component failure obtained by fracture mechanics analysis, the crack size at one inspection interval before the failure is determined. Based on the PoD-crack size curve, the probability of detection (or non-detection) at this stage is consequently known;

(b) if this probability is not acceptable, another NDT method or test setup could be chosen, giving more satisfying results, and/or, instead of basing the assumption of just one inspection, more of them can be taken into account. In both cases, the result is a higher PoD. Note, however, that the number of inspections multiplied by the inspection interval must not exceed the residual lifetime and that too many inspection intervals can be economically not sustainable.

Limited Further Operation of a Cracked Structure

If a crack is detected, for example in a railway axle, no further operation is permissible. Nevertheless, there are other cases where the removal or replacement of a cracked component is not easily possible. Imagine, e.g., a bridge in which a crack is detected. In such a case, fracture mechanics can be used to gain time in combination with accompanying actions such as load reduction by suited traffic regulation. Starting with the dimensions of the detected crack, residual lifetime can be determined, which provides the maximum timeframe for final actions. In such a case, non-destructive testing has not only to detect the crack, but has also to provide its size. Note that crack sizing usually requires advanced methods such as "Time of flight diffraction" (TOFD), "Synthetic aperture focusing technique" (SAFT) or "Phased array technique" for ultrasonic testing and others.

Defect-corrected Fatigue Strength

The initial defect sizes used in a damage tolerance analysis (see section 2.3) could be applied to determine the fatigue limit of a cracked component. A railway example is the so-called "one million miles axle". Fracture mechanics calculations can be used for optimizing the design because, for example, the axle diameter could be increased so that the initial crack according to section 2.3 would not yield failure during a specified residual lifetime (the "one million miles") after which the axle has to be replaced by a new one [10].

Summary

Non-destructive testing and fracture mechanics are two mainstays for the safe design and operation of components for which the existence of crack-like defects cannot be excluded. The present paper provides a short discussion of their interrelationship in the contexts of different basic tasks, such as component safety under hazard loading, inspection intervals, temporary further operations of structures after cracks have been detected, and defect-influenced fatigue strengths. Some of these applications are already realized, others are upcoming or point to the future.

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