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Fracture Mechanics 2

Applied Reliability

Ammar Grous

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Preface

This book is intended for technicians, engineers, designers, students, and teachers working in the fields of engineering and vocational education. Our main objective is to provide an assessment of indicators of quality and reliability to aid in decision-making. To this end, we recommend an *intuitive* and practical approach, based on mathematical rigor.

The first part of this book shows the fundamental basis of data analysis in both quality control and in studying the mechanical reliability of materials and structures. Laboratory and workshop results are discussed in accordance with the technological procedures inherent to the subject matter. We also discuss and interpret the standardization of manufacturing processes as a causal link with geometric and dimensional specifications (GPS, or *Geometrical Product Specification*). This is moreover the educational novelty of this work, in comparison here with consulted praiseworthy publications.

We discuss many laboratory examples, thereby covering a new, industrial organization of work. We also use mechanical components from our own real mechanisms, which we built and designed at our production labs. Finite element modification is thus relevant to real machined pieces, controlled and soldered in a dimensional metrology laboratory.

We also discuss mechanical component reliability. Since statistics are common to both this field and quality control, we will simply mention reliability indices in the context of using the structure for which we are performing the calculations.

Scientists from specialized schools and corporations often take an interest in the quality of measurement, and thus in the measurement of uncertainties. The so-called cutting-edge endeavors such as aeronautics, automotive, and nuclear industries, to mention but a few, put an increasing emphasis on the *just measurement*. This text's educational content stands out due to the following:

1) The rigor of the probabilistic methods which support statistical–mathematical treatments of experimental or simulated data.

2) The presentation of varied lab models which are to come at the end of each of the following chapters: this should help the student to better understand how to:

- define and justify a quality and reliability control target;

- identify the appropriate tools to quantify reliability with respect to capabilities;

- interpret quality (capability) and reliability (reliability indices) indicators;

- choose the adequation test for the distribution (whether justified or used *a priori*);

- identify how trials can be accelerated and their limits;

- analyze the quality and reliability of materials and structures;

- size and *tolerance* (GPS) design structures and materials.

– What about uncertainty calculations in applied reliability?

The fracture behavior of structures is often characterized (in linear mechanics) by a local variation of the material's elastic properties. This inevitably leads to sizing calculations which seek to secure the structures derived from the materials. Much work has been, and still is, conducted in a wide range of disciplines from civil engineering to the different variants of mechanics. Here, we do not consider continuum mechanics, but rather probabilistic laws for cracking. Certain laws of statistical distributions are systematically repeated to better approach reliability.

Less severe adequation tests would confirm the fissure propagation hypothesis. In fields where safety is a priority, such as medicine (surgery and biomechanics), aviation and nuclear power plants, to mention but three, theorizing unverifiable concepts would be unacceptable. The relevant reliability calculations must therefore be as rigorous as possible.

Defining safety coefficients would be an important (or even major) element of structure sizing. This definition is costly, and does not really offer any real guarantee on safety previsions (unlike security previsions). Today, the interpretation and philosophy of these coefficients is reinforced by increasingly accurate probabilistic calculations. Well-developed computer tools largely contribute to the time and effort of calculations. Thus, we will use software commonly found in various schools

(Auto Desk Inventor Pro and ANSYS in modelization and design; MathCAD, GUM, and COSMOS in quality control, metrology, and uncertainty calculations).

Much work has been done to rationalize the concept of applied reliability; however, no "unified method" between the mechanical and statistical interpretations of rupture has yet been defined. Some of the many factors for this non-*consensus* are unpredictable events which randomly create the fault, its propagation, and the ensuing damage. Many researchers have worked on various random probabilistic and deterministic methods. This resulted in many simulation methods, the most common being the Monte Carlo simulation.

In this book, we present some documented applied cases to help teachers succinctly present probabilistic problems (reliability and/or degradation). The intuitive approach takes on an important part in our problem-solving methods, and among various points, the main goal of this book is to give this humble contribution. Many commendable works and books have talked about reliability, quality control, and uncertainty perfectly well, but as separate entities. However, our task here is to verify measurements and ensure that the measurand is well-taught. As Lord Kelvin said, "if you cannot measure it, you cannot improve it". Indeed, measuring identified quantities is an unavoidable part of laboratory life. Theoretical confirmation of physical phenomena must go through *measurement reliability* and its effects on the function are attributed to the material and/or structure, among other things.

Mechanical models (rupture criteria) of continuum mechanics discussed in Chapter 10 make up a reference pool of work used here and there in our case studies, such as the Paris–Erdogan law, the Manson–Coffin law, S-N curves (Wöhler curves), Weibull law (solid mechanics), etc. We could probably (and justly) wonder in what way is this chapter appropriate in works dedicated to reliability. The reason is that these criteria are deliberately targeted. We used them here to avoid the reader having to "digress" into specialized books.

Establishing *confidence* in our results is critical. Measuring a characteristic does not simply mean finding the value of the characteristic. We must also give it an *uncertainty* so as to show the measurement's *quality*. In this book, we will show educational laboratory examples of uncertainty (GUM: Guide to the Expression of Uncertainty in Measurement).

– Why then publish another book dedicated to quality control, uncertainties, and reliability?

Firstly, why publish a book which covers two seemingly distinct topics (quality control and reliability including uncertainties)? Because both these fields rely on probabilities, statistics, and a similar method in describing their hypothesis. In quality control, the process is often already known or appears to be under control beforehand, hence the intervention of capability indices (SPC: statistical process control). Furthermore, the goal is sometimes the competitiveness between manufactured products. Security is shown in secondary terms. Indeed, it is in terms of maintainability and durability that quality control joins reliability as a means to guarantee the functions attributed to a mechanism, component, or even the entire system.

When considering the mechanical reliability of materials and structures, the reliability index is inherently a *safety* indicator. It is often very costly in terms of computation time and very serious in matters of consequence. The common aspect between both fields is still the probabilistic approach. Probabilities and statistical–mathematical tools are necessary to supply theoretical justifications for the computational methods. Again, this book intends to be pragmatic and leaves reasonable room for the intuitive approach of the hypotheses stated here and there.

Finally, we provide a succinct glossary to smooth the understanding of dimensional analysis (IMV: International Metrology Vocabulary) and structural mechanical reliability. This educational method allows us to "*agree*" on the international language used to define the mesurand, reliability index, or a succinct definition of the capability indicators largely used in quality control.

In terms of safety, component reliability (for both materials and structures) is absolutely essential in the field of safety and performance.

The field of reliability is used in many fields of engineering, from civil engineering to mechanical and electrical engineering: it is thus manifold. It often aims at the estimation of the functions at various phases of the lifecycle of components, subject to study. Reliability users increasingly depend on reproducible software, though they struggle to determine whether the component is active or passive, the size of the experience return and its imperative validation, the phenomena which tend to decrease the likelihood of failure or the reliability index, etc.

This book uses some methods provided here and there to estimate operational or target reliabilities. The apparent controversy between frequential and Bayesian probabilistic approaches are irrelevant in our humble opinion if we know how to set the problem *a priori*. Setting boundaries for the likelihood of rupture (failure or even degradation) is worth doing. As for us, we prefer calculating rupture through the damage indicator integral, made explicit by Madsen's work.

Just as estimating reliability can allow us to understand the history to better anticipate the future, we must show pragmatism in measuring the factors responsible for the likely rupture. Since the measurement is always inherently flawed and uncertain, we must include uncertainty calculations in our reliability methods. Without such calculations, our results would lead to doubtfulness.

First, vocabulary: reliability has its own, specific terminology (see glossary) which, like for metrology, affects the decision's terms. Thus, we will abide by the EN 13306 standard (see Table A.45 of the Appendix of Volume 3). The definitions for reliability, durability, failure, and degradation can be found in the appendix and glossary.

Reliability data is necessary to:

– prioritize between components → occurrence rate of each mode (AMDEC);

– identify the degradation mechanism for a clear experience feedback;

– optimize preventative and corrective maintenance;

– gather data efficient for, and necessary to, the correct calculation of reliability parameters and especially their uncertainties.

Analysis and *validation* are done by analyzing the experience feedback with respect to critical failure criteria, such as failure modes, the mean time between failures (MTBF), probability of failure on demand (P_s) and its reliability index according to a "selected criterion", the repair and/or material unavailability time, the confidence intervals, or even the sample size.

We note that reliability is usually taken into account from design, based on the specifications. It is calculated and compared to the allocated reliability (reliability demand). It includes all phases of life (design, manufacture, and development trials).

During exploitation (operation), the planned reliability is calculated and compared to a threshold (e.g. rate of failure) such as physical calculations, with the intention to extend it beyond the lifespan (cycle) planned during design.

Reliability is mostly measured, therefore making its **metrology** a serious business; hence, the calculation of its uncertainties including instrument and measurement equipment calibration.

Among the diverse difficulties which are imperative upon the reliability function, we hold, among others, the type of component (repairable or not repairable, redundant active or passive) and even some controversial methods or model (*frequencial/Bayesian*).

The component can be active:

– various degradation mechanisms with different modes of failure,

– unknown or even complex physical modelization,

– classic reliability and Bayesian reliability (*if*) so sometimes adapted to the study case,

– incomplete or even truncated data,

– modelization using a Gaussian distribution, an exponential law, a two- or three-parameter Weibull law or especially a Birnbaum–Sanders law (as is often the case in cracking rupture: wear and tear in zone II of the Ritchie curve – see Figures 1.2 and 1.17).

The component can be active and passive:

– few degradation mechanisms;

– degradation type: slow or progressive;

– few failures (if any);

– physical modelization of degradation: fissure initiation and propagation;

– numerical methods (energetic methods, integral calculations, and finite elements);

– Bayesian approach for available failure data.

As we are a physicist, practical mathematician-statistician or engineer, sometimes, in many schools of thought, "controversies" appear in the method or model (ex. frequency/Bayesian) used. In our book, we will try to remain pragmatic and synthetize our opinions.

From a *physicist's* perspective, the experimental conditions of data-gathering are known, and their uncertainties well-bound. Its so-called frequential analysis is based only on objective data, because they were measured *correctly*. We know that measurements are costly and time-consuming. If the data from "our physicist's" experiments are insufficient and if the process turns out to be non-repetitive or the number of parameters to estimate is high, the frequential approach falsely introduces confirmation bias in the analysis. The paradox is that the calculations are correct, but they only answer to a logically mathematical demand. In other words, the mathematics are correct but are superficially stuck on an inappropriate case, hence a rejection of the solution and the birth of controversy…

The *engineering* approach is *attractive* due to its "applied arts and crafts" aspect (i.e. learning). Its analysis includes the knowledge that we must apply an "*a priori*" law, which must by definition be biased. Without rejecting the Bayesian approach, this is where we favor the *engineering* approach because it uses *decision-making* *tools* for which preferences are clearly expressed. At the end of this approach, the uncertainty function greatly helps make the decision…

Finally, it is important to specify and frame the problem well: its context, hypotheses, available data, etc. Simulations (using software) are a helpful educational tool, but they should not be treated as *replacements* for real experiments. Relying on *real data* from the *experiment feedback* of the collection conditions is more suitable. Indeed, experiments and “real” data are a strategic necessity in case of preemptive validation.

In this book, we show (see Chapters 1 and 2) the qualitative analysis elements preceding quantitative, deterministic, and probabilistic analysis. The laws and tests shown in the first two chapters of Volume 1 are required reading for any probabilistic study of physical phenomena, and it falls to us to be pragmatic.

Regardless of the approach used, we must analyze the sensibility of factors and always apply common sense. Among many other methods of analysis, reliability is a tool for understanding the past. For example, many failures, degradations, and ruptures or ruin (damage) cannot be explained by deterministic models such as aging, mechanisms of degradation, models and laws (see Chapter 1, “Fracture mechanisms by fatigue”), etc. Studying reliability allows us to find the components and subcomponents to critique, the important variables (initial faults, factor of intensity of constraint *f.i.c.*, etc.) for which uncertainties should be reduced, and so on through a sound knowledge of physical phenomena.

Reliability anticipates and prepares for the future in order to improve performance and safety by optimizing exploitation strategies.

However, reliability alone cannot replace an experimental understanding of physical phenomena.

A. GROUS
November 2012

Glossary

Abrasion resistance

Hard materials also show good abrasion resistance; in other words, they are not easily worn down by friction. In practice they are harder to grind down.

Acceptable risk

"*Acceptable risk*" describes the structural and non-structural measures to be put in place to reduce probable damage to a reference level. A risk scale is often associated with dangers in order to classify them in order of seriousness.

Availability

Is a (dimensionless) attribute of **dependability**. It is the capacity of a system to properly deliver the service (quality) when the user has need of it. Availability is a unitless measurement; it corresponds to the ratio of uptime to total execution time of the system.

Chance

Imaginary cause of something that occurs for no apparent or explicable reason (dictionary definition).

Conditional probability

(Bayesian) probability of a consequence when the causal event will definitely occur. If we suppose that a fracture has reached the limit suggested by a pre-established hypothesis, the probability of cracking is a conditional probability.

Corrective maintenance or restoration to a state of proper function

Maintenance performed when a breakdown is detected, aimed at *restoring* a product to a state where it can fulfill its required function.

Corrosion resistance

This denotes the ability of a material to withstand damage from the effects of the chemical reaction of oxygen with the metal. A ferrous metal which is resistant to corrosion does not rust.

Degradation

Irreversible evolution of one or more characteristics of a product related to time, to the duration of use or to an *external cause – alteration of function, constant phenomenon, physical aging*

Dependability

The property which enables users to justifiably place their faith in the service provided to them: *reliability, availability, safety, maintainability, security.*

Dilation and contraction

When a material is heated, it expands slightly; this is called dilation. Conversely, if it shrinks (clue to cold), this is a contraction. The level of dilation and contraction of a metal affects its weldability. The more the metal is expanded or contracted, the greater the risk of *cracks* or deformations appearing.

Distribution function

Integral function of the probability density (or cumulative probability function), calculated in order of ascending values of the random variable. It expresses the probability of the random variable assuming a value less than or equal to a given value.

Ductility

Represents the ability of a metal to be deformed without breaking. It can be stretched, elongated, or subjected to torsion forces. Ductile materials are difficult to break because the cracks or defects created by a deformation do not easily propagate.

Durability

The ability of a product to perform its required function, in given conditions of use and maintenance, until a critical state is reached.

Elasticity

Ability of a material to return to its original form after a deformation.

Failure

Alteration or suspension of the ability of a system to perform its required function(s) to the levels of performance defined in the technical specifications.

Fault (error) resistance

Fault resistance is implemented to detect and handle errors.

Fault tree

Logical diagram using a tree structure to represent the causes of failures and their combinations leading to a **feared state** (Bayes). Fault trees enable us to calculate the **unavailability** or the **reliability** of the system model.

FMECA – risk analysis

A method for systematic risk analysis of the causes and effects of failures that might affect the components of a system. FMECA analyzes the seriousness of each type of failure. It enables us to evaluate the impact of such failures on the reliability and safety of the system.

Frailty

Frailty describes the characteristic of a metal that breaks easily on impact or from a deformation. It deforms little or not at all, and is easily broken.

Hardness

The ability of a body to resist penetration by another body harder than it. It is also characterized by its scratch resistance.

Hazard

Describes any event, unpredictable phenomenon, or human activity which would result in the loss of human lives, or damages to commodities or the environment.

Heat-affected zone (HAZ)

The HAZ represents the heat affected region of the base metal that was not melted during welding process. Metallurgists define usually the HAZ as the area of base material which has had its microstructure and properties altered by welding or heat.

Maintainability

One of the aspects of **dependability**. The maintainability of a system expresses its capacity for repair and evolution, with maintenance supposedly completed under certain conditions with prescribed procedures and means.

Malleability

A characteristic which permits the metal to be molded. It is the relative resistance of a metal subjected to compression forces. The malleability of a material increases with increasing temperature.

Markov chains

Used to evaluate the *dependability* of systems in a quantitative manner, this technique is based on the hypothesis that failure and repair rates are constant and that the stochastic process modeling its behavior is Markovian (a memoryless process). When the space of the potential states of the system is a discreet set, the Markovian process is called a Markov chain.

Materialized measure

The measuring instrument which replicates or permanently provides different types of values during use, each with an assigned value.

Metrology

The science of measurements and its different applications, which encompasses all theoretical and practical aspects of measuring, regardless of the uncertainty of the measurement or the domain to which it relates.

Measurand

A value to be measured.

Measuring accuracy

Proximity between a measured value and the true value of a measurand.

NOTE:

The measurement of accuracy does not produce a value and is not expressed numerically. A measurement is sometimes considered accurate if it offers a smaller uncertainty.

Although linked to the concepts of correctness and fidelity, it is better not to use the term “measuring accuracy” for measuring correctness or the term measuring fidelity for measuring accuracy.

Measuring accuracy is occasionally associated with the proximity between the measured values attributed to the measurand.

Measuring instrument, measuring apparatus

Usually a device used for making *measurements*, on its own or possibly in conjunction with other devices.

Measuring repeatability

This is the measuring fidelity according to a set of repeatable conditions.

Measuring reproducibility[1]

This is the measuring fidelity according to a set of *reproducibility* conditions.

Measuring uncertainty

Non-negative parameter which characterizes the dispersion of values attributed to a measurand, arising from information used according to the method (e.g. A or B of the GUM).

NOTE:

Measuring uncertainty includes elements caused by systematic effects (associated with the corrections and the assigned benchmark values) as well as definitional uncertainty. Estimated systematic effects are not always corrected. Elements associated with uncertainty would be added. The parameter is often the standard uncertainty (from the standard deviation, σ) or the half range (U/2) of an interval with a determined coverage probability (e.g. k = 2 for 95% confidence). Certain elements are evaluated with the type-A GUM from the statistical distribution of measured values characterized by standard deviations. The evaluation using the type-B GUM is characterized by standard deviations of probability density functions based on experience, among other things.

Preliminary hazard analysis (PHA)

Method for identifying and evaluating hazards, their causes, their consequences and the seriousness of these consequences. The aim of this analysis is to determine

1 For statistical terminology refer to ISO 5725-1:1994 and ISO 5725-2:1994.

the appropriate methods and corrective actions to eliminate or control dangerous situations or potential accidents.

Preventive maintenance

To *avoid loss of function; thus, it is a probabilistic notion, one of anticipation and prediction.* Such maintenance is performed at predetermined intervals, in accordance with prescribed criteria, intended to reduce the probability of failure or degradation of the function of a product.

Probability

Statistical concept which can either express a degree of confidence or a measurement of uncertainty (subjective probability) or be taken as the limit of a relative frequency in an infinite series (statistical probability).

Probability density (or distribution function)

This is a function describing the *relative likelihood* of a random variable assuming a particular value. It assigns a probability to each value of a random variable.

Random

Process in which the result varies even if the input data set remains identical (a protocol leads to different results).

Reliability

The reliability of a system (work) is its aptitude to meet its design objectives over a specified period of time, in the environmental conditions to which it is subject. It is based on the probabilities used to evaluate it.

Reliability is one of the aspects of *dependability*. It corresponds to the continuity of service that the system must provide to its users, with the system being considered as irreparable. Any accidental failure is taken into account, regardless of its severity. Reliability measures the rate of failure, the inverse of the MTTF (*mean time to failure*).

Risk

Risk is "a more or less predictable potential danger", or in other words a drawback which is more or less probable to which we are exposed. The scientific definition of risk involves an aspect of hazard and an aspect of loss, both expressed as probabilities.

Risk analysis

System inevitably contains design errors, regardless of the amount of validation work done. The "zero error" criterion is not a realistic goal, in view of the development costs this would entail. Thus, it is important for so-called critical systems to evaluate the risks for the users of the following systems:

FMECA: failure mode, effects, and criticality analysis.

SEEA: software error effects analysis.

PHA: preliminary hazard analysis.

Risk assessment

Procedure to determine the probability of a hazard *occurring* and its possible consequences.

Safety case

This approach is mainly used in the oil, nuclear, and rail transport sectors. In practice, this procedure facilitates the monitoring of studies.

Security

We distinguish between safety and security. Thus:

Safety guards against catastrophic failures, for which the consequences are unacceptable in relation to the *risk*.

Security relates to the prevention of unauthorized access to information.

Software reliability

Software inevitably contains *design errors*, no matter how strict the rules of design and validation. The ability of a software suite to provide acceptable service in spite of its residual errors defines its *reliability*.

Stress intensity factor (s.i.f., ΔK)

s.i.f (ΔK) is a function of the stress, crack size and crack shape. Stress intensity factors do not have variability. They have uncertainty and modeling errors. The crack shape may be unknown and be approximated by a semicircle.

In Mode 1 (during a fatigue cycle, in mechanics of rupture) (s.i.f = ΔK) is a measure of the stress-field intensity near the tip of an ideal crack in a linear-elastic solid when the crack surfaces are displaced in the opening mode. Stress-intensity factor range **(**ΔK**)** in fatigue crack growth rate is the variation in a cycle, that is, Kmax – Kmin.

Tenacity

The ability of materials to resist shock without breaking or chipping.

Trend test

Trend tests are used in *reliability* to obtain indicators of reliability, from data on failures, and determine fluctuations in reliability over time.

Undesirable event

An event that should not occur or which should be improbable in view of the objectives in terms of *dependability*.

Unit (measuring)

Real scalar value defined and adopted by convention, to which we can compare any other similar value to express the ratio between the two values as a number.

Value

Property of a phenomenon, (body, length, weight) expressed quantitatively by a number and a reference.

Abbreviations

CITAC	Cooperation on International Traceability in Analytical Chemistry
CSA	Canadian Standardisation Association
EA	European Cooperation for Accreditation
Eurachem	Focus for Analytical Chemistry in Europe
EUROLAB	European Federation of National Associations of Measurements, Testing and Analytical Laboratories
GUM	Guide to the expression of Uncertainty in Measurement (the reference document recognized by the CSA, EUROLAB, Eurachem, and EA)
IEC	International Electrotechnical Commission
ILAC	International Laboratory Accreditation Cooperation
ISO	International Organization for Standardization
S (or σ)	Standard deviation
SAS	*Le Service d'Accréditation Suisse* (Swiss Accreditation Service)
U	Uncertainty
VIM	International Vocabulary of basic and general terms in Metrology