MECHANICAL RELIABILITY AND DESIGN

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MECHANICAL RELIABILITY AND DESIGN

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Preface

Following the publication of my earlier book in 1986 I lectured to a number of specialist courses, seminars and the like on various parts of its contents. Gradually, these lectures concentrated more and more on the design aspects of mechanical reliability, which many saw as the key area. Having retired from this activity, I have brought together the final form of these various lectures in a more developed format in this book. The background has been filled in more fully than was possible in the limited time for lectures, and continuity material has been added. The opportunity has been taken to dot a lot of i's and cross many t's of the supporting theory so as to produce a coherent picture of the role of reliability, particularly as a quantitative requirement, in the design of mechanical machines and components and, in particular, their constituent parts.

Like the lectures on which it is based, the book is aimed at practising mechanical engineers; but, like the lectures, it could be used in specialist courses and seminars. Additionally, parts of it could well be included in courses on mechanical design at first degree level. I do not see how the education of any mechanical engineer can be considered complete without some reference to quantified statistical reliability, and to the impact of specifications for such reliability on design.

The book makes full use of statistical reliability concepts, but crucial fundamental aspects are critically reviewed before use. In the event it was found that surprisingly little statistics is actually needed for a design methodology aimed to meet a quantified reliability, but it was found necessary to delve a little further into materials science than is customary. I hope that the reader, having read the book, will accept that a design methodology based on statistically defined input data to meet a quantified reliability specification is feasible, not too different from contemporary practice, and not difficult to implement. I hope too that he or she will be prepared eventually to say goodbye to all the uncertain empiricism that surrounds so much of contemporary design.

Finally, I wish to acknowledge my indebtedness to all those reliability workers who have carried out and reported stochastic test data on materials and components, both those quoted in this book and those consulted but not quoted.

Full reference has been given in the text to all quoted data, so that the reader may consult the original work. Obtaining worthwhile data is very time consuming and laborious, but those data are the bedrock of all our knowledge. My thanks to them all, especially to British Coal for permission to use previously unpublished data in the case study of Chapter 7.

A.D.S. Carter
Oxford 1996

Notation

A	Material constant (microstructurally short crack)
A_c	Empirical constant in creep rate equation
a	Crack length
B	Material constant (physically small crack)
C	Physically small crack threshold
c	Cost
c_i	Constants
D	Material constant (physically long crack)
d	Distance to barrier
d	Damage (Section 6.1)
E	Damage resistance threshold
$E_N(s)$	PDF of damage resistance at N load applications
$E(s)$	PDF of damage resistance threshold ($N \rightarrow \infty$)
$\bar{E}$	Mean value of $E(s)$
F	Cumulative probability of failure
$F(x)$	CDF of failure
$f(x)$	PDF of failure
G	Miner summation
g	Number of entanglements
$H(t)$	Cumulative hazard function
h	Hazard
$h(t)$	Hazard expressed in terms of t
$h(n)$	Hazard expressed in terms of n
I	Number of intervals
i	1,2,3, . . . , etc.
j	1,2,3, . . . , etc.
K	Scaling factor
k	Number of standard deviations from mean to worst case
L	Load
$L(s)$	PDF of failure-inducing stress due to load
$\bar{L}$	Mean value of $L(s)$
$L(p)$	PDF of load

$\bar{L}(p)$	Mean value of $L(p)$
LR	Loading roughness
l	Number of loads
M	Maintainability
MP	Mean probability (mean rank)
Mz	A Weibull function
m	Index in power relationship
N	Number of load applications to failure
n	Number of load applications
P	Probability
p	Force or other impressed phenomenon
Q	Total number of items in population
Q_c	Activation energy for creep
q	Number of items
R	Reliability (cumulative probability of no failure)
R	Universal gas constant (section 6.2.2)
$R(n)$	Reliability expressed in terms of n
$R(t)$	Reliability expressed in terms of t
$R(c)$	Rockwell – c scale
S	Strength
$S(s)$	PDF of strength at critical section
$\bar{S}$	Mean value of $S(s)$
SM	Safety margin
s	Stress
T	Time to failure
t	Time
Σt	Cumulative operating time
t'	Time from different origin
t_o	Weibull locating constant
U	Ultimate tensile strength
$\bar{U}$	Mean ultimate tensile strength
u	Cross-sectional area
$V(s)$	PDF of strength modification during manufacture
$\bar{V}$	Mean of $V(s)$
W	Number of breakdowns
ΣW	Cumulative breakdowns
X	General arbitrary material property
x	General arbitrary variable/variant
Y	Yield strength
Z	Attribute
z	$s_F - s_{50}$
α	Material constant (microstructurally short crack)
β	Material constant (physically small crack)
β	Weibull shaping parameter

γ	Coefficient of variation
ε	Strain
$\Delta\gamma_p$	Shear plastic strain range
ΔK	Stress intensity factor
ζ	s - N function
η	Characteristic life
θ	Number of tests
λ	Breakdown rate
μ	Mean value
ν	Duane index
σ	Standard deviation
τ	Temperature
ϕ	Factor of safety
ω	Maintenance cost index

Subscripts

a	Average
c	Refers to strength collapse
c	Value at confidence limit
d	Defects
E	Refers to damage resistance threshold
F	Value for $F\%$ failures
g	Refers to entanglements
i	Successive values 1,2,3, . . . , etc.
j	Successive values 1,2,3, . . . , etc.
l	Lower limit
L	Refers to load
m	Of mean
max	Maximum perceived value
min	Minimum perceived value
N	Value at N load applications
nom	Nominal value
O	Reference or arbitrary value
o	Original or initial value
op	Operational
p	Value for process
S	Refers to strength
SH	Refers to strain hardening
U	Refers to ultimate tensile strength
u	Upper limit
Y	Refers to yield strength
0	Lowest acceptable value
*	Minimum physically small crack

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* Specified value

Note: SI units are used throughout, except that original data have been quoted as such, i.e. in the originator's units. The SI equivalent is always given when the quantity could have general significance.

Glossary

assembly *See hierarchy of mechanical artefacts.*

break down To rupture the continuity of performing a given function. To disrupt or stop for a time.

breakdown rate The rate at which breakdowns occur.

component *See hierarchy of mechanical artefacts.*

damage A change in a material structure.

damage resistance The ability of a material to resist damage by a load or other hostile environment.

fail To become exhausted; to come to an end.

failure The termination of the ability to perform a required function. The inanimate equivalent of death.

failure rate Term not used in this book.

field 'In the field' or 'in service' implies that the product is in the hands of the intended user, and data so described refer solely to his/her/their use of the product. Tests or trials of any kind are specifically excluded.

hazard The non-dimensionalised rate at which failures occur in a non-maintained component or part. For the mathematical definition see section 3.5 (equation 3.36).

load Any hostile environment that can give rise to a failure. See Chapter 1 for a comprehensive definition.

hierarchy of mechanical artefacts There is no standardised terminology, but the following definitions apply to their usage in this book. (Given in hierarchical order, not alphabetical.)

system A combination of integral machines and components to achieve a specified output(s).

subsystem A convenient subset of a system made on various different criteria, such as providing one of several different inputs to the system, operating on an identifiable basis (e.g. hydraulic), contained as an integral package, provided by a given supplier, and so on, Can be extended to sub-subsystem, etc.

machine An integral assembly of components and parts to achieve a defined output or related series of outputs. The lowest subsystem level, but could well be a stand-alone artefact.

assembly A package of components and parts that comprises the machine. The package is usually determined by manufacturing or handling convenience rather than any functional attribute, though they may well coincide. Can be extended to sub-assembly, etc.

component An identifiable self-contained unit, to perform a given function, made up of several or many parts. The lowest assembly level. It may or may not be maintainable.

part The fundamental mechanical artefact, which cannot be dismantled. Essentially, it is completely defined by a detail working drawing – to use old nomenclature – or by a modern electronic record or hard copy. Hence often referred to as a ‘detail’ in the literature. The word ‘piece’ is also often used, especially for a part made specifically for test (testpiece). A part or piece is not maintainable except by replacement.

product Can be any of the above, but generally excluding systems. The final output of a manufacturer or manufacturing organisation.

item A single constituent of a statistical population on which an observation or measurement is made. Sometimes called ‘specimen’ in statistical literature.

machine *See hierarchy of mechanical artefacts.*

operational reliability The ability of a system/product to perform the required function under stated conditions of use and maintenance for a stated period of time.

part *See hierarchy of mechanical artefacts.*

population The totality of items possessing specified attributes. The whole product.

prototype The first or primary version of any product. It is used to establish the feasibility of the product and as a model for subsequent full production. There may be several prototypes.

product *See hierarchy of mechanical artefacts.*

reliability The ability of a system/product to perform the required function under stated conditions of use for a stated period of time.

ROCOF Acronym for the rate of occurrence of failures; equivalent of breakdown rate.

sample A subset of a population.

service *See field.*

standard s - N curve The s - N curve derived by contemporary conventional practices. It is truly neither the mean nor the median curve, but is closer to the latter.

strength The ability to resist a compatible load without failure at any given instant. A product may have several different strength attributes.

stress-rupture A failure mechanism in which failure, rupture, or fracture of the material may take place on application of a load, but if not the material structure remains unchanged.

system *See hierarchy of mechanical artefacts.*

threshold The limit state above which damage may be inflicted and below which no damage can be done.

variation A difference in a property of the items making up a population. It includes both the statistical variance (or standard deviation) and the shape of the distribution.

wear A failure mechanism in which no failure, rupture, or fracture necessarily takes place on the application of a load, but there is a change in the material structure (i.e. damage is done). Failure takes place when the cumulative damage reaches some critical value.

wear-out The period of time during which wear failures take place.