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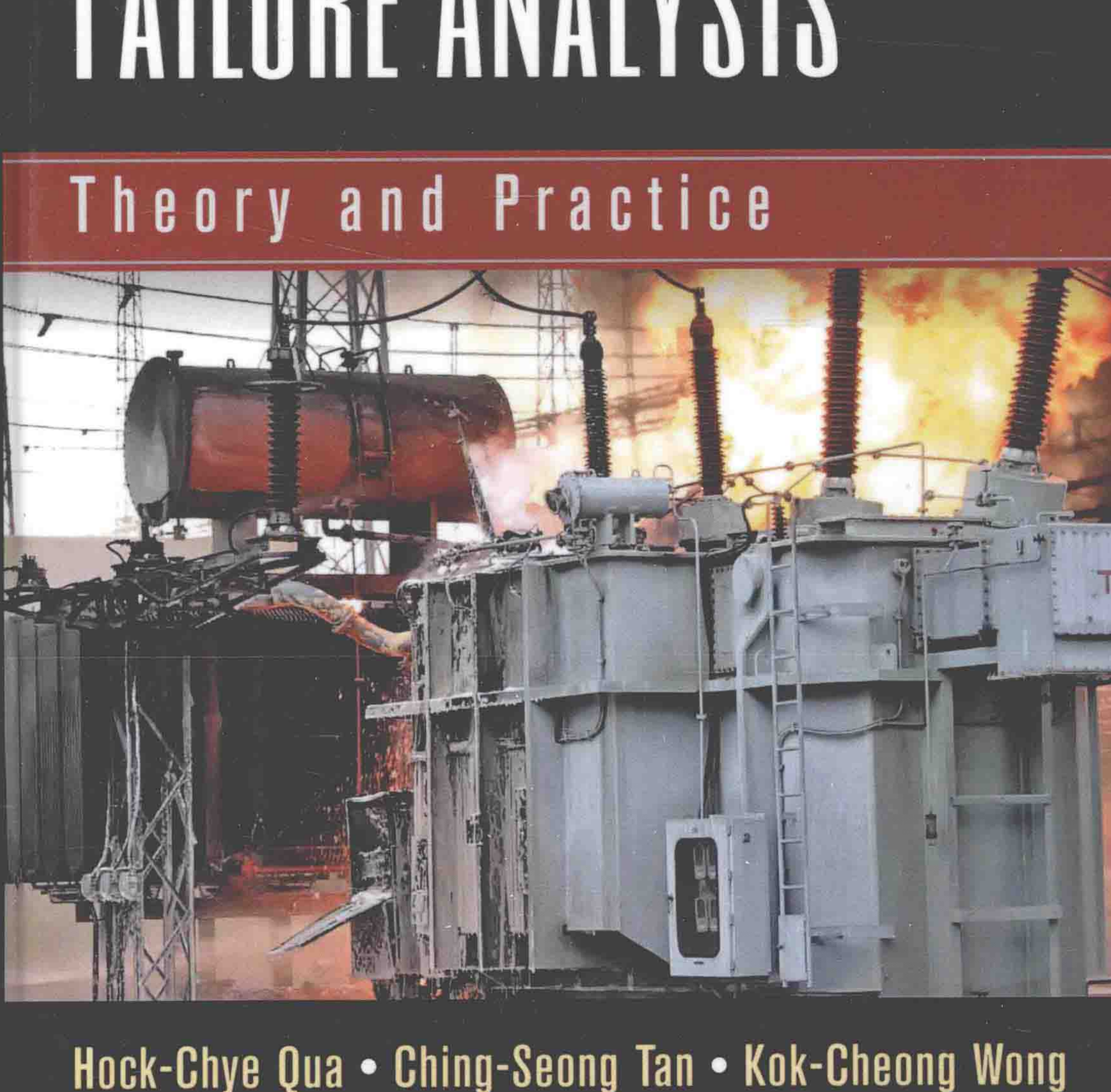
Applied Engineering Failure Analysis

Theory and Practice



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Foreword

It fills me with pride and pleasure to pen the foreword for this book. I must say I am privileged to be given this chance as I personally know some of the authors: Ir. Qua Hock Chye who was my lecturer during my undergraduate days and is now an International Collaborative Partner of Universiti Tunku Abdul Rahman and Dr. Tan Ching Seong who was my colleague at Multimedia University and Universiti Tunku Abdul Rahman. My heartiest congratulations to all the authors who have achieved this remarkable feat of having the book published. It is a testament of your passion and dedication to the area of failure analysis as the way forward towards better investigative research and engineering work.

Former British Prime Minister, Winston Churchill, once said, 'Success is based on going from failure to failure without losing eagerness.' While success is the ultimate power that hastens us en route to our goals, it is failure along the way that guides us towards further discovery and leads us to these goals. Science progresses by trying out ideas, disproving earlier conceptions, and gradually getting closer to the truth at the heart of the phenomenon being studied. Thomas Edison tried more than a thousand times before he produced a light bulb that worked. Failure is a wonderful tutor and an even better teacher for the discovery and prevention of future mishaps in all aspects.

The role of an engineer is to respond to a need by building a device, to plan or to create within a certain set of guidelines and specifications. Some designs will fail to perform their given function with a sought-after level of performance. Hence, engineers must struggle to design in such a way as to avoid failure, and most importantly, catastrophic failure that could result in loss of property, damage to the environment, and possible injury or loss of life. Through analysis of engineering disasters and failures, modern engineers learn what to avoid, how to create better designs, and to seek solutions to improve performance with less chance of future failures.

Therefore, I highly commend the authors of this book who have painstakingly researched and compiled a collection of cases on actual failure analysis which serve as valuable lessons for others to study and learn from. Such a generous sharing of knowledge, experiences, and findings augurs well for the future of the engineering industry and I hope that others will take this lead to do something similar for the advancement of knowledge.

May this book achieve its further goal of providing essential reference material and feedback on design processes and thereby contribute to the avoidance of applied engineering failures in the future.

Ir. Prof. Academician Dato' Dr. Chuah Hean Teik
President
Universiti Tunku Abdul Rahman

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FOREWORD

It is a well known adage that "*one learns more from failures than from successes*". It is also true that we learn from experience; as every experience adds more information to memory that in time reasoning becomes logical. Thus, it is necessary for us to document our experiences properly and derive lessons from them.

In spite of such efforts however, accidents will unfortunately continue to happen, often due to reasons beyond our control. Time and time again, structures and machines have failed without warning, and often with disastrous consequences.

The bottom line is failures are a fact of life. A failure-free system is more of a myth than a reality. When failures occur, it is important to conduct prompt investigation of these failures in order to ascertain their causes and take remedial action to prevent their recurrence.

Applied Engineering Failure Analysis: Theory and Practice seeks to develop awareness in engineers on the traditional failure analysis theories and the actual conducts of the failure cases. It provides a systematic analysis that can be implemented in the design works to prevent future failures.

The authors have meticulously compiled vast information and case studies on the subject. As a useful record of the experiences of failure analysis of over a 30-year period, this book is a good archive of information for failure analysts, practicing engineers, and students of engineering.

As President of The Institution of Engineers, Malaysia, a professional institution dedicated to promote the science and profession of engineering and to facilitate the exchange of information and ideas related to engineering, I am indeed proud to be associated with this publication.

I congratulate the authors for their professionalism and commitment that they brought to their work. To the authors, well done, and I wish you every success in your future endeavors.

Ir. Choo Kok Beng FASc
IEM President

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Hock-Chye Qua obtained a B.E. (Mech) and an M. Eng. Sc. from the Engineering Faculty of the University of Malaya, where he later served as an associate professor until his retirement in 1999. He was one of the pioneer failure investigators in Malaysia and has been active in failure/forensic investigations for more than 40 years on a large variety of cases within Asia, spanning the mechanical, metallurgical, structural steel, and electrical disciplines. He is a professional engineer and a Fellow of the Institution of Engineers Malaysia.

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List of Abbreviations

Chapter 1

a_c	Critical crack size (Equation 1.1)
ASME	American Society of Mechanical Engineers
BF	Brittle fracture
CP	Codes of practice
CUI	Corrosion under insulation
DD	Disruptive discharge
DF	Ductile fracture
EFA	Engineering failure analysis
K_{IC}	Plane strain fracture toughness (Equation 1.1)
LEFM	Linear elastic fracture mechanics
MIC	Microbiologically influenced corrosion
MVC	Microvoid coalescence
NDE	Non-destructive evaluation
PWHT	Post weld heat treatment
QA	Quality assurance
QC	Quality control
σ_c	Fracture stress (Equation 1.1)
SCC	Stress corrosion cracking
SEM	Scanning electron microscope
Y	Function of crack and stress configurations (Equation 1.1)

Chapter 2

a	Crack length (Equation 2.5)
AAS	Atomic absorption spectroscopy
AISI	American Iron and Steel Institute
API	American Petroleum Institute
APS-C	Advanced photo system type-C
BCC	Body centred cubic structure
BSE	Backscattered electrons
CCD	Charge-coupled device

EBSD-IPF	Electron backscattered diffraction—Inverse pole figure
EDS	Energy dispersive X-ray spectrometry
E	Elastic modulus (Equation 2.4)
FA	Failure analysis
FI	Failure investigator
FM	Fracture mechanics
HCF	High-cycle fatigue
ICP-AES	Inductively coupled plasma atomic emission spectroscopy
K	Stress intensity factor (Equation 2.5)
LCF	Low-cycle fatigue
n	Factor of safety (Equation 2.3)
N_f	Cycles to failure for completely reversed loading (Equation 2.4)
N	Cycle (Equation 2.5)
n_i	Number of cycles at a given stress σ_i (Equation 2.7)
N_i	Number of cycles to failure at a given stress σ_i (Equation 2.7)
NDT	Non-destructive testing
OES	Optical emission spectrometer
PMI	Positive material identification
σ_m	Mean stress (Equations 2.2 and 2.3)
σ_a	Variable stress (Equations 2.2 and 2.3)
S_e	Fully corrected fatigue strength at critical location of component (Equation 2.3)
ε_A	Strain amplitude (Equation 2.4)
SE	Secondary electrons
S-N Curve	Wöhler curve (cyclic stress versus logarithmic scale of cycles to failure)
S_y	Yield stress (Equations 2.1 and 2.3)
TEM	Transmission electron microscope
WDS	Wavelength dispersive X-ray spectrometer

Chapter 3

a	Crack size (Equation 3.2)
BS	British Standard
BRT	Bus rail transit
HB	Brinell hardness
HRC	Rockwell hardness
HV	Vickers hardness
LRT	Light rail transit
MRT	Mass rapid transit
I_{xx}	Moments of inertia
K_{Ic}	Fracture toughness

K_{Id} Dynamic fracture toughness
K_I Stress intensity factor
MPI Magnetic particle inspection
OD Outer diameter
σ_{Ic} Critical/fracture stress
TWJ Thermic weld joint
UT Ultrasonic test

Chapter 4

AGMA American Gear Manufacturers Association
API American Petroleum Institute
σ_c Calculated contact stress number (Equation A4.3)
BDF Below the drill floor
BS British Standard
b Face width (Equations A4.1 and A4.5)
b Face width of tooth (Equation A4.3)
C_p Coefficient depending on elastic properties of materials (Equation A4.3)
C_m Geometry factor (Equation A4.3)
C_f Surface condition factor (Equation A4.3)
C_s Size factor (Equation A4.3)
C_H Hardness ratio factor (Equation A4.4)
C_L Life factor (Equation A4.4)
C_T Temperature factor (Equation A4.4)
C_R Factor of safety (Equation A4.4)
C_o Overload factor (Equation A4.3)
C_v Dynamic factor (Equation A4.3)
d Pinion pitch diameter (Equation A4.3)
EDS Energy dispersive X-ray spectrometer
F_t Transmitted tangential load (Equation A4.3)
F_t Transmitted load (Equation A4.5)
HB Brinell hardness
HRC Rockwell hardness
HV Vickers hardness
I Geometry factor (Equation A4.3)
J Geometry factor (Equation A4.5)
LS Long string
MD Measured depth
P Diametral pitch (Equation A4.5)
K_c Overload correction factor (Equation A4.5)
K_s Size correction factor (Equation A4.5)

K_m Load distribution correction (Equation A4.5)
K_v Dynamic factor (Equation A4.5)
K_L Life factor (Equation A4.6)
K_R Factor of safety (Equation A4.6)
K_T Temperature factor (Equation A4.6)
σ_t Calculated stress at root (Equation A4.5)
S_{at} Allowable fatigue bending stress for material (Equation A4.6)
S_{ac} Allowable contact stress number (Equation A4.4)
S_{ad} Maximum allowable design stress (Equation A4.6)
S_c Surface stress factor of material (Equation A4.1)
S_b Bending stress factor for material (Equation A4.2)
SEM Scanning electron microscope
SS Short string
Xc Speed factor for wear (Equation A4.1)
X_b Speed factor for strength (Equation A4.2)
Y Strength factor (Equation A4.2)
Z Zone factor (Equation A4.1)

Chapter 5

Bph Blue phase
CB Circuit breaker
DE Drive end
DD Disruptive discharge
DGA Dissolved gas analysis
EDS Energy dispersive X-ray spectrometer
ELCB Earth leakage circuit breaker
EMF Electromotive force
ER End ring
FAT Factory acceptance test
FI Failure investigator
HV High voltage
H Heat loss
I Current
LV Low voltage
Megger Megaohm meter
MVC Microvoid coalescence
N-DE Non-drive end
NDT Non-destructive testing
OLTC On-load tap-changer
P Power
PLC Programmable logic controller

R	Electrical resistance
Rph	Red phase
SEM	Scanning electron microscope
SFRA	Sweep frequency response analysis
TRW	Transition resistor wire
Tx	Transformer
V	Voltage
WPI	Weather protected type I (motor enclosure)
XLPE	Cross-linked polyethylene
Yph	Yellow phase

Chapter 6

ASME	American Society of Mechanical Engineers
A3	Lower-temperature boundary of austenite region at low carbon content (phase diagram)
BS	British Standard
BTF	Boiler tube failures
HV	Vickers hardness
OD	Outer diameter

Chapter 7

ASTM	American Society of Mechanical Engineers
BS	British Standard
CUI	Corrosion under insulation
EDS	Energy dispersive X-ray spectrometer
JIS	Japanese Industrial Standard
PVC	Poly vinyl chloride
$\mathbf{RH_{av}}$	Average relative humidity (Equations 7.4 and 7.5)
$\mathbf{RT_{av}}$	Average temperature
R.C.	Conventional reinforced concrete
RH	Relative humidity
σ'	Effective stress (Equation 7.6)
σ	Total stress (Equation 7.6)
SPT	Standard penetration tests
T	Temperature
TBM	Temporary bench mark
W	Weight loss due to corrosion penetration (Equation 7.1)

t	Time of exposure in years (Equations 7.1 through 7.5)
u	Water pressure (Equation 7.6)
w	Water content (grams of water content in 1 kg of dry air)
W	Corrosion depth per surface (mm) (Equations 7.2 and 7.4)

Chapter 8

β_j	Phase function of a medium at the point of scattering (for crystalline)
CB	Conduction band
C_m	Specific heat of crystals (Equation 8.1)
C_p	Specific heat of particle (Equation 8.2)
D'	Material thickness (Equation 8.3)
DBD	Direct-backscattered-direct
E_c	Critical valence bonding strength (Equation 8.11)
E_i	Incident energy (Equation 8.9)
E_f	Final energy (Equation 8.9)
EM	Electromagnetic
F_c	Critical fluence (Equation 8.8)
FDTD	Finite difference time difference
FI	Failure investigator
I	Laser intensity (Equation 8.2)
ICNRP	International Commission on Non-Ionizing Radiation Protection
ISO	International Organization for Standardization
κ	Thermal diffusivity (Equation 8.1)
k_m	Thermal conductivity of crystals (Equation 8.1)
LID	Laser-induced damage
m	Neutron mass (Equation 8.11)
M	Target atom mass (Equation 8.11)
φ	Angle of particle movement before and after collision (Equation 8.11)
PKA	Primary knock-on atom
P_0	Incoming pulse (Equation 8.3)
Q_{abs}	Absorption efficiency factor (Equation 8.2)
ρ_m	Density of crystals (Equation 8.1)
ρ_p	Density of particle (Equation 8.2)
RID	Radiation-induced damage
R_j	Reflectance (Equation 8.3)
T_c	Critical temperature
t_j	First mean arriving time of photon group to layer *j* (Equation 8.3)
T_{ij}	Transmittance of a particular photon group (Kernal function)
τ_r	Rectangular pulse length (Equation 8.8)
UV	Ultra-violet

Contents