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Failure Analysis

Fundamentals and Applications in Mechanical Components

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Preface

When one reads a book, and cannot stop reading, it means that the book is pleasant and that, somehow, generates the expectation of the reader to continue reading compulsively until the end. The same happens with a play or a film. If the spectator begins to feel uncomfortable in his armchair, it is a signal that the play/film is decaying in interest. By the opposite, nobody moves, even in uncomfortable armchairs, and a spectator will keep his position until the end.

This happens with Jose Luis' book. Those of us that love Engineering and the resolution of its problems find in this work the right synthesis of what we always have looked for in books of the specialty. As mentioned in the prologue, this book answers why a failure occurred that jeopardized the integrity of a component or piece; the conditions that led to this failure and, finally, what we must do so that it does not repeat.

This book has been written by an education professional, also a successful researcher in this area as well as other areas of engineering, who has permanently performed consulting activities. In this book, the author pours all his experience in the prediction of damage, fitness for service, and reliability in concrete problems of professional life.

Therefore, this work that comes to light today covers all the expectations that are looked for to satisfy the high demand of specialized human resources in the selection, application, optimal operation, and service of industrial pieces and components. It will allow, in addition, forging highly enabled professionals, apt to work in projects in different economic sectors. I take for granted the success of this contribution by my colleague and friend of so many years.

Argentina, 2013 Raul H. Conde

Prologue

Back in the twelfth century, Bernard of Chartres said once that we are like dwarfs on the shoulders of giants. We can see beyond them, not because of any physical distinction, but because we are lifted up by their great height. Recapturing the idea, the famous seventeenth century English physicist Isaac Newton wrote in a letter to the scientist Robert Hooke: "if I have seen more is because I am on top of the shoulders of giants." We all are stepping on shoulders of giants that preceded us, in our continuous missions for whatever there is to be obtained beyond the horizon. The Holy Grail of engineering is the perfect design, something that always works exactly as envisioned and which never requires improvement. By all means, if we could obtain it, the perfect design would never fail.

In his seventeenth book, Henry Petroski explores something that he had already explored before: the inevitability of failure and the role it has had in the advance of technology. His last work is "To Forgive Design: Understanding Failure" (Harvard University Press). In his preface, the author defines this book as a sequel to his first book "To Engineer Is Human: The Role of Failure in Successful Design," published in 1985 and still available. The following fragment belongs to Chap. 2, "Things happen" or "Forgiving design":

It would not have to surprise us that failures exist. After all, the structures, the machines and the systems of the modern world can be exceedingly complicated in their design and operation. And the people who conceive, design, construct and interact with these complexities without a doubt can fail. Sometimes they use a defective logic, they transpose digits in a numerical calculation inadvertently, fit a bolt a screw of more or of less, they read a dial erroneously or they push hastily when they must throw. Also they can fail in concentrating themselves, anticipating and communicating at critical moments. In other occasions, the accidents can be due to people stopping being honest, ethical or professional.

For some reason, accidents happen and they invariably come from or lead to a failure by something or somebody. In fact, which would have to surprise us is not that failures happen, but that they do not happen more often. When they happen in our field, we tend to defend ourselves against accusations; we try to derive the failure. Failures are too often attributed to the things we design, we do, we sell and we operate, and not to the people who design them, do them, sell them and operate them.

In this book, we will start from a basis that is not shared by most other authors in the field: all causes related to a failure are exclusively human. From the philosophical point of view, this concept is clear. Still, those clearly physical causes, as is the case of a defective material, can be considered the result of a human error, although this error was committed at another moment (sometimes decades before) and in another company or country. Therefore, it is outside our analysis, and we can simply analyze the physical cause, the defect in the material, and forget that it is the result of a previous human fault.

The phrase "human error" commonly used in the journalistic media is tautological: only Humans have reasoning and freedom to choose between diverse alternatives, thus we are the only ones "enabled" to commit an error. Natural disasters (earthquakes, flooding, etc.), also called "Acts of God," cannot be considered as a human error. But the consequences of these natural events on the component that has failed are indeed due to human errors. Somebody did not consider adequately the probability of such event, or its intensity, and he/she did not make the necessary adjustments to the design and the construction of the component or structures.

But the previous statement does not mean that a person has to take the blame or be the cause of a failure. To look for guilt leads to the opposite direction of finding solutions. This will be seen specifically when we deal with the techniques of Root Cause Analysis. An axiom for lawyers, particularly for those involved in oral trials when they interrogate witnesses, these being friendly or hostile for the interest of his cause, is: never ask something if not sure of what the answer will be. This attitude, taken to other fields of the human activity, assures that the participation of a person will generate very little value added to the communitarian knowledge.

This phrase is attributed to Albert Einstein: "The man finds God behind each door that science manages to open. Chance does not exist; God does not play dices. The important thing is not to stop asking questions." Probably this has been said in different contexts. A failure analyst will have to assure that each member of the team makes at least all the necessary questions to arrive at true answers, that are not known a priori, and not regarding if these might not be considered suitable.

This book approaches failures of structural elements, that is, those components whose basic mission is to sustain mechanical loads. From this we can conclude that failure causes will be related to the incapacity of the components and materials to support operative loads, at some time of their life. We will not speak here of failures in functional components, where the fundamental utility of the component is referred to a specific capacity. Thus it is the case of failures in electronic and optical components, measurement and control systems, etc.

Construction technologies and use of structural components were refined by trial and error over thousands of years until the first age of metals. The use of metals was also refined by trial and error. The science of metals (and structural materials in general) is really as recent as the twentieth century. Of course, the use and engineering of these materials are much older. As components and systems become more complex, so do the mechanisms by which they fail. And because of this, understanding the causes of failures has never been more relevant. The modern methods for the analysis of real causes of failures respond to the need to interpret:

Why failures occur;
How failures occur;
How to avoid recurrence.

We live the way we do, and not another, because of the strengths, weaknesses, working costs, and difficulties of the materials and components we use. This book is not only for engineers and scientists, although most of the technicians in these disciplines would benefit from reading. Its real benefit is for the "lay" curious who want to know more, those who may face circumstantially the consequences of failures of systems or mechanical components. This book should also be useful for students, future scientists, or engineers.

One of the objectives of the professional activity of the author and collaborators has been the consolidation of experimental and numerical tools to address scientific research related to the main propagation mechanisms of mechanical damage in industrial components. The authors is a professor in the area of Mechanical Engineering, at the National University of Mar del Plata (UNMdP, Argentina). Dr. Otegui and some partners specialize in research, with activity in the Mechanics of Materials Division of INTEMA (Research Institute of Materials Science and Technology). This institute is funded by CONICET (National Scientific and Technical Research of Argentina) and is based in the Faculty of Engineering UNMdP. Contributors are from GIE SA, prestigious Engineering Consultancy firm with 20 years of experience in integrity assurance and life extension in the energy industries and hydrocarbon transportation and processing.

Experience in the evaluation of piping, vessels, rotating machinery, and other industrial components, allows the author to formalize this text, suitable for use as a professional reference book for those interested in how best to respond to failures and other incidents of mechanical origin. This text is intended as a self-contained source for those with different technical grades, who face the challenge of learning from the experience, often bitterly and at a great cost, of equipment failure, with the intention of reducing its likelihood of recurrence.

Acknowledgments

This book is dedicated to my most loved ones my wife Alejandra and my daughters Milagros and Victoria.

As it usually happens to us, I feel I should have spent more time with them. I wish I had known Alejandra years before. My daughters matured so soon! The rhythms of life are OK, I am not complaining. On the contrary, I find myself in a difficult situation for agnostics: I would like to thank, but I am not sure to whom. In any case, as my mother Chela says, I thank whoever is currently in charge of God's business in this world, recognizing that He probably does not exist. I thank Chela for helping me discover this and other secrets.

This book is the result of many training activities, in-house courses for companies, and particularly of lectures given during the last 10 years for Executive Corporate Training (pcernich@criteriocapacitacion.com). The author is grateful to Mr. Pablo Cernich, for his enthusiasm and professionalism in the pursuit of technical and pedagogical improvements in these conferences.

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The participation of colleagues and friends in the writing of this book is noteworthy. They contributed their opinions, efforts, and original material based on their own research:

- Mr. Aníbal Marquez amarques@fi.mdp.edu.ar, Professor and Researcher at INTEMA (UNMdP-CONICET). Aníbal is also consultant at GIE SA, leader in Failure Analysis of Rotating Machinery. He authored Chap. 8 of this book.
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About the Author

Dr. José Luis Otegui graduated in 1980 as the Mechanical Engineer UNMdP, Argentina. In 1988 he was awarded the academic degree of Doctor of Philosophy in Mechanical Engineering at the University of Waterloo, Canada. Since then he has been dedicated to the development of technologies in the area of mechanical modeling of metallic materials for structural use, and their application for the prediction of damage in industrial equipment. His articles are regularly published in scientific journals and conferences related to forensic engineering, pressure vessels, fatigue and fracture. He is currently Full Professor at the Faculty of Engineering of the University of Mar del Plata, and Researcher at CONICET (National Counsel for Scientific and Technological Research of Argentina).

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Chapter 1
Introduction

1.1 Historical Perspective

Technology has always been a risky business, but quantifying that risk is relatively a new phenomenon in the world of engineering and management. No matter what the technology, our best estimates of their success tend to be too optimistic. The history of mechanical constructions dates back to engine. The most successful in this field were the Romans. Roads and aqueducts developed by them were one of the pillars of strengthening their hegemony in the "known world" of the time. One of their most notable developments is the arch bridge, see Fig. 1.1a. It is based on transferring vertical loads due to vehicle weight by compression between the stones (Fig. 1.1b) to the embedding in pillar bases. Some historians take it as true that one of the keys to the success of this design was based on a practice, normal then as it is now: the pre-operational load test. Once the bridge was built, and before its entry into operation, a test was carried out with a dead weight much larger than the maximum expected in service. The peculiarity was that, in such event, the responsible for its design and construction should remain under the bridge... This system would ensure, on the one hand, a careful design and construction, and on the other, avoidance of repeating mistakes by incompetent engineers.

The need to reduce costs and longer spans between supports, and the availability of new materials and construction methods led to new designs, now based in tensile-loaded members and not only to compressive load transfer, see for example Fig. 1.2. This type of steel structure, which we call truss, was alongside the steam engine, one of the pillars of the European industrial revolution from the late eighteenth century. By then, Sir Isaac Newton had already laid the foundations of mechanics by introducing previous calculation as an auxiliary tool to the "genius," and reducing the importance of trial and error in the evolution of the designs.

Designs circumstantially exceeded capabilities of load calculation and prediction of material properties. In the period of greatest growth of the industrial revolution, there was no single week without a train accident attributable to defects in

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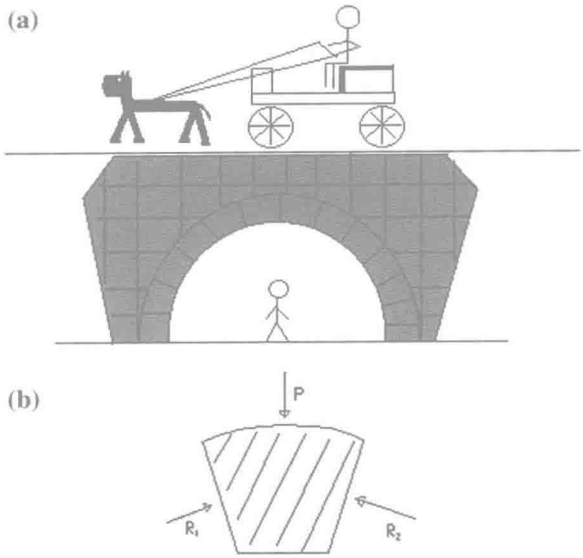

Fig. 1.1 **a** The arch bridge from Roman times, **b** load transfer by compression

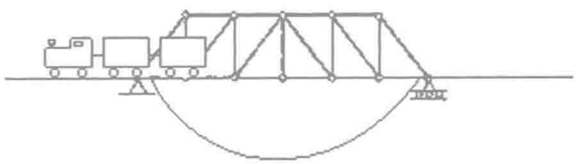

Fig. 1.2 The steel truss bridge and the industrial revolution

design or materials reported by British newspapers. The search for increasingly efficient structures generated the development of increasingly powerful design methods and materials with improved strength and reduced weight and cost.

1.2 Current Technology is Conditioned by our History

One of the most resounding failures, and thus more useful in the field of failure analysis, was the loss of the space shuttle Challenger. Failure analysis revealed not only deficiencies in design, but also serious organizational shortcomings. Understanding these shortcomings led, among other things, to the development of fault tree techniques (events, previous defects, and overcome barriers) for the determination of root causes. We will return to these issues in Chap. 7.

The American Space Shuttle used two SRB (Solid Rocket Booster) tanks that were manufactured by Thiokol in Utah. These long, thin tanks had to be built into sections. As discussed in some detail in Chap. 7, the failure of a joint was responsible for the Challenger disaster. Engineers perhaps would have preferred