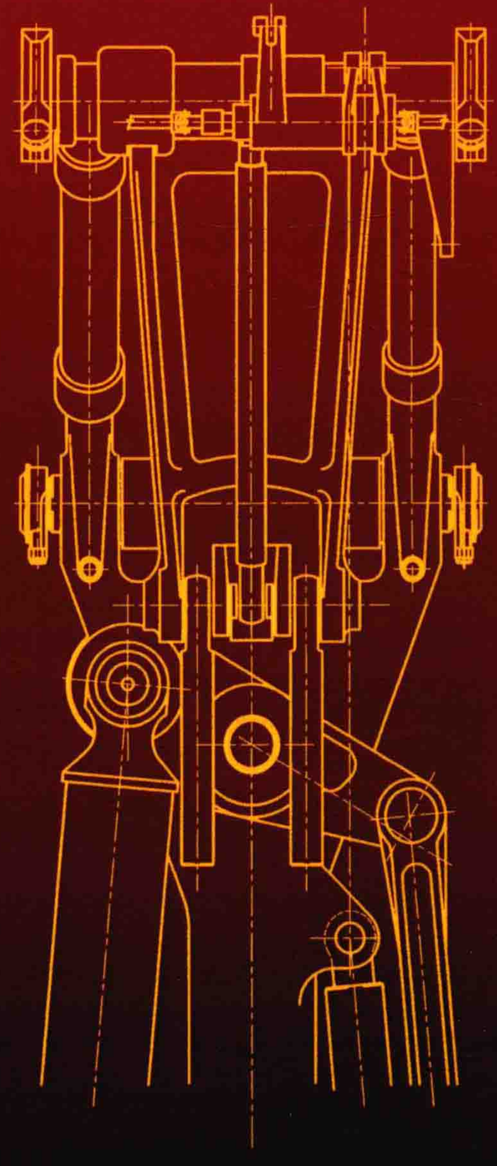
Design Engineer's Case Studies and Examples



Keith L. Richards

CRC Press
Taylor & Francis Group

Design Engineer's Case Studies and Examples

Keith L. Richards

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper
Version Date: 20130819

International Standard Book Number-13: 978-1-4665-9280-3 (Paperback)

Library of Congress Cataloging-in-Publication Data

Richards, Keith L.
Design engineer's case studies and examples / Keith L. Richards.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4665-9280-3 (pbk.)
1. Mechanical engineering--Problems, exercises, etc. 2. Machine design--Problems, exercises, etc.
I. Title.

TJ153.R48 2014
604.2--dc23 2013032503

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Design Engineer's Case Studies and Examples

Preface

Within the UK, the Engineering Council is the regulatory body for the engineering profession to which all engineering institutions are regulated and hold the register of all practicing engineers. There are three grades of membership: Engineering Technician (Eng.Tech.), Incorporated Engineer (I.Eng.) and Chartered Engineer (C.Eng.). The Incorporated Engineer requires an education to the equivalent of a degree; the Chartered requires a minimum of a master's degree.

In recent years many institutions, including the Institution of Mechanical Engineers, have seen a considerable increase in applications for Eng.Tech. registration. These applicants may be following a work-based learning program such as an apprenticeship and are enrolled in the institution of their choice as a student member. Individuals who do not have any formal qualifications may also apply for registration by demonstrating at an interview that they have the required experience and competence through substantial working experience and by showing that they have sufficient working knowledge and understanding of the technical issues relating to their area of work.

This book has been written with these young engineers in mind, who are contemplating taking this important step and moving towards registration. The subject matter is not confined to these student engineers; it is hoped that more senior practicing engineers who are not contemplating registration will also find the subject matter useful in their everyday work as a ready reference guide.

The contents have been selected on subjects that young engineers may be expected to cover in their professional careers, and the text gives solutions to typical problems that may arise in mechanical design.

Computers are now universally used in design offices, and designers often use software without really understanding its structure or limitations. They may accept the "answer" without question and not carry out any qualification testing to verify its accuracy. The importance of carrying out these checks is stressed to ensure that mistakes are minimised.

The design examples selected are mainly static problems, and the writer has tried to give as wide a selection as possible in the space available. It was deliberated whether to include a selection of fatigue related problems, and after careful reflection the subject was considered to be beyond the scope of this book.

The subjects covered include the following:

- Introduction to stress calculations
- Beam sections subject to bending
- Shaft design basics
- Keys and spline strength calculations
- Columns and struts
- Gearing
- Introduction to material selection
- Conversions and general tables

Chapter 13, Introduction to Material Selection, has been added so that young engineers will give some thought to the materials used in terms of physical and mechanical properties. It is recommended that a personal database be built up listing these properties; this has been found by the writer to be a great asset in his own career when searching for information on this subject.

The solutions used in this book have been checked using MathCAD, and every effort has been made to ensure that the units are also coherent.

Any errors that are found will be totally my responsibility, and therefore I apologise beforehand for any made. Where errors are found, the writer will be very grateful if you, the reader, can advise me of them so that future reprints will be corrected.

I have to thank Professor Richard Dippery for his helpful comments when reading the draft copy, and I take this opportunity to also thank my wife, Eileen, for all the help and support given while writing the manuscript and to whom this book is dedicated.

Keith L. Richards

About the Author

Keith Richards is a retired Chartered Mechanical Design Engineer who has worked in the design industry for over 55 years. Initially he served an engineering apprenticeship with B.S.A. Tools Ltd., which manufactured a wide range of machine tools, including the Acme Gridley, a multi-spindle automatic lathe built under licence, and the B.S.A. single spindle automatic lathe. These were used in Britain and widely exported around the world.

On leaving the B.S.A., for a number of years he served as a freelance Engineering Designer covering a wide range of industries, including aluminium rolling mill design for installation in a company in Yugoslavia, an industrial forklift truck for an American company that was manufactured in America and Europe, and the prototype Hutton tension leg platform, an offshore oil production platform using drill string technology to anchor it to the seabed. His responsibility on this project covered the design and engineering of the mooring system components of the platform and was answerable to the customer (Conoco) and Lloyds Inspectorate for all the engineering aspects to enable the platform operators to receive the licence to operate in the North Sea.

Other work covered experimental and analytical stress analysis, photo-elastic stress analysis, residual stress determinations, and electric strain gauge analysis. One aspect of this work involved the environmental testing of specialised camera support equipment for the European Space Agency (ESA) space probe Giotto. This work was contracted to British Aerospace, which designed the support. One major problem of working in space is the very high voltages developed, and concern had been expressed that if there was an insulation breakdown in the support, then the camera would be irreparably damaged and the mission would lose the opportunity of photographing the comet's head. The probe survived and went on to investigate a further comet, Grigg-Skjellerup.

He was also involved in the design of the chassis of a vehicle to carry a 50 ton nuclear waste container, transporting it from the reactor building to the cooling ponds at Berkeley Nuclear Power Station. The design brief was that the vehicle had to be electrical/hydraulic powered and reliable, as any breakdown would create a number of problems arising from radiation due to its contents.

Other work in the nuclear industry included working with a small team at Atomic Energy Research Establishment (AERE) (Harwell) designing a hydraulic powered robotic manipulator arm, Artisan, that was used for clearing away waste from inside the nuclear storage areas at various national and international nuclear power stations. This arm was fitted with a three dimensional camera to facilitate operation of the arm from a remote position.

Keith also designed a pipeline for conveying liquid carbon dioxide from a storage area across a roadway to a vaporiser used to cool the nuclear reactors at Hinkley Point B Nuclear Power Station. This work also included designing a bridge structure for supporting the pipeline crossing the roadway. The design brief included that the pipe bridge should withstand an impact from a truck travelling at 20 miles per hour without any damage being sustained by the pipeline. Any failure in the fluid supply would cause significant inconvenience to the site operators keeping the reactors cool.

Keith was also involved in the design and manufacture of a fully automated special purpose packaging line for handling radio-active medical isotopes; these were shipped to all parts of the world. The line was designed such that the isotopes were loaded at the start of the line and finished radiation proof packages were discharged at the end of the line complete with all the necessary attachments, etc., without any human intervention. Due to the high radiation levels, human operators were only allowed into the facility for a maximum of 2 hours; hence reliability had to be a high priority.

In recent years Keith became more involved in the aerospace industry, working on projects covering aircraft undercarriages, environmental control systems for military and commercial aircraft, and the A380 wing box and trailing edge panels.

Contents

1 Introduction to Stress and Strain

This chapter is written for student engineers with only a rudimentary understanding of stresses and strains and their application to design.

The reader will be introduced to the concepts of direct stress and strain. This includes tensile, compressive and shear strains, and also defines the modulus of elasticity and rigidity.

1.1 DIRECT STRESS

When a component has either a tensile or compressive force applied to it, the component will either stretch or be squashed, and the material is then said to be stressed. Stresses cannot be measured directly; they have to be deduced from strain measurements.

The following brief notes will give some explanation to the terms used in stress calculations.

1.2 TENSILE STRESS

Consider a circular solid bar having a cross-sectional area A subject to an applied tensile force F, as shown in Figure 1.1. This force is trying to extend the bar by the dimension δ.

$$\text{Stress } \sigma = \frac{F}{A} \text{ the symbol for stress is denoted by } \sigma. \tag{1.1}$$

$$\text{Strain } \varepsilon = \frac{\delta}{L} \text{ the symbol for strain is denoted by } \varepsilon. \tag{1.2}$$

$$\text{Stiffness } K = \frac{F}{\delta} \text{ the symbol for strain is denoted by K.} \tag{1.3}$$

1.3 COMPRESSIVE STRESS

Consider the same shaft as shown in Figure 1.1, but this time the force F is now compressing the bar as shown in Figure 1.2 and shortening the bar by the dimension δ.

The fundamental unit of stress in SI units is the Pascal. In the engineering field the Pascal ($1/m^2$) is generally considered a small quantity, and therefore multiples of kPa, MPa and GPa are used.

Areas may be calculated in mm^2, and here the units of stress measured in N/mm^2 are quite acceptable. As 1 N/mm^2 is equivalent to 1,000,000 N/m^2, then it will follow that 1 N/mm^2 is the same as 1 MPa.

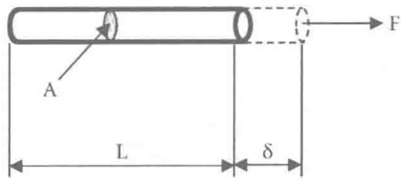


FIGURE 1.1 A circular solid bar under direct tension.

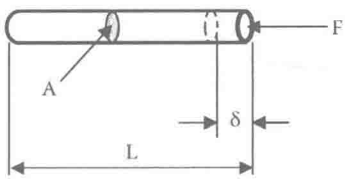


FIGURE 1.2 A circular solid bar under direct compression.

1.4 DIRECT STRAINS

In the above discussion on stress it was shown that the force F produces a deformation δ in the length of the component.

This change in length is referred to as *strain* and is defined as:

$= \frac{300}{100}$ The symbol for strain is ε (epsilon).

Strain has no units, as it is the ratio of the change in length to the original length, and the units therefore cancel out. Most engineering material has low strain values, as excessive strain will lead to extensive damage in the material. It will be found when studying the subject further that strain is generally written in the exponent of 10^{-6}, and this is usually written as με (micro-strain).

Example 1.1

Consider a metal rod 12.0 mm diameter and 2000 mm long subject to a tensile force of 250 N. The bar stretches 0.3 mm. Assuming the material is elastic, determine the following:

1. The stress in the rod.
2. The strain in the rod.

Solution:

Area of rod:

$$A = \frac{\pi d^2}{4}$$

$$= \frac{\pi \times 12.0^2}{4} \qquad (1.4)$$

$$\text{Area} = 113.097\ \text{mm}^2$$

1. The stress in the rod:

$$\sigma = \frac{F}{A} = \frac{250.0}{113.097} \quad (1.5)$$

$$\sigma = 2.210\ \text{N/mm}^2 (\text{or } 2.21\ \text{MPa})$$

2. The strain in the rod:

$$\varepsilon = \frac{\delta}{L} = \frac{0.30}{2000} = 0.00015\ (150\ \mu\varepsilon) \quad (1.6)$$

1.5 MODULUS OF ELASTICITY (E)

When an elastic material is stretched, it will always return back to its original shape when released. Figure 1.3 shows that the deformation of the material is directly proportional to the force causing the extension. This is known as Hooke's law.

$$\text{Stiffness} = \frac{F}{\delta} = k\frac{N}{m} \quad (1.7)$$

Different classes of materials will have different stiffnesses dependent upon the material and size. The size characteristic can be eliminated by using stress and strain values instead of force and deformation.

Force and deformation can be related to direct stress and strain:

$$F = \sigma \cdot A \quad (1.8)$$

$$\delta = \varepsilon \cdot L$$

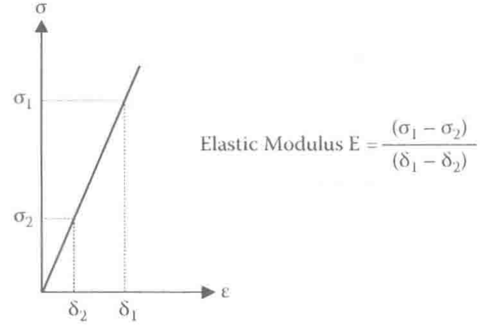


FIGURE 1.3 Relationship between stress and strain.

Therefore

$$\frac{F}{A} = \frac{\sigma A}{\varepsilon L} \tag{1.9}$$

and

$$\frac{F \cdot L}{A \cdot \delta} = \frac{\sigma}{\varepsilon} \tag{1.10}$$

The stiffness is in terms of stress and strain only, and this will be a constant. This constant is known as the *modulus of elasticity* and has the symbol E.

Hence:

$$E = \frac{F \cdot L}{A \cdot \delta} = \frac{\sigma}{\varepsilon} \tag{1.11}$$

Plotting stress against strain will give a straight line having a gradient of E (see Figure 1.3). The units of E are the same as stress.

1.6 ULTIMATE TENSILE STRESS

All materials, when stretched, will reach a point when the material has deemed to have failed. This failure may be when there is a catastrophic break. This stress level is known as the *ultimate tensile stress* (UTS). Different materials will have failure values dependent upon the material type.

Example 1.2

A tensile test carried out on a steel test specimen having a cross-sectional area of 150 mm^2 and a gauge length of 50 mm results in the elastic section having a gradient of 500×10^3 N/mm.

Determine the modulus of elasticity.

Solution:

From the ratio $\frac{F}{A}$ the gradient may be established, and this can be used to calculate E.

$$E = \frac{\sigma}{\varepsilon} = \frac{F}{\delta} \times \frac{L}{A}$$

$$= 500 \times 10^3 \times \frac{50}{100}$$

$$= 166.667 \text{ N/mm}^2 (166.667 \text{ MPa}).$$

1.7 SHEAR STRESS

When a force is applied transverse to the length of the component (i.e. sideways) the force is known as a shear force. Examples of this occur when a material is punched as in Figure 1.4, when a beam carries a transverse load as in Figure 1.5, or a pin is carrying a load as in Figure 1.6.

Shear stress is the force per unit area that is subject to the force as the cross-sectional area of the beam or the cross-sectional area of the pin. The unit for shear stress is τ (tau).

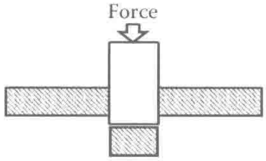


FIGURE 1.4 Material being punched.

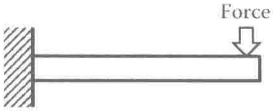


FIGURE 1.5 Beam subject to a transverse force.

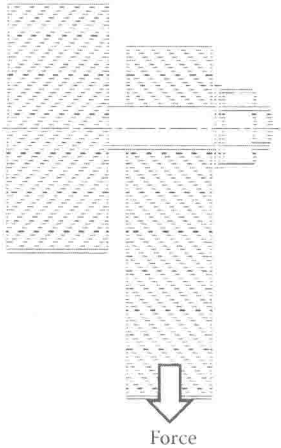


FIGURE 1.6 Pin subject to shear force.

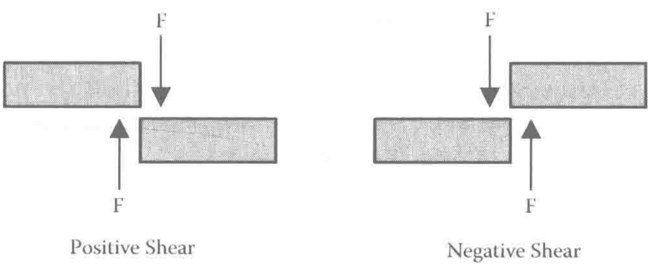


FIGURE 1.7 Direction of shear.

$$\text{Shear stress } \tau = \frac{F}{A} \tag{1.12}$$

The sign convention for shear force and shear stress is dependent upon how the material is being sheared. Figure 1.7 defines both positive shear and negative shear.

To understand the basic theory of the shear process, consider a block of rubber that is subject to a sideways force as shown in Figure 1.8

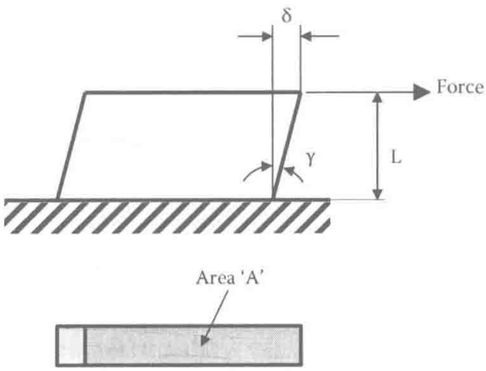


FIGURE 1.8 Block of rubber subject to sideways force.

where

F = sideways force
L = depth of section
δ = shear deflection

1.8 SHEAR STRAIN

As in Figure 1.8 the force F causes the block to deform. The shear strain is defined as the ratio of the height L to the distance deformed δ, i.e. δ/L.

It is also seen in Figure 1.8 that the end face rotates through an angle γ; as this is generally a very small angle, it can be considered that the distance δ is the length of an arc having a radius of L with an angle γ such that:

$$\gamma = \frac{\delta}{L} \tag{1.13}$$

The symbol for the shear strain is γ (gamma).

1.9 MODULUS OF RIGIDITY

Just as the modulus of elasticity, E, relates tensile stress to tensile strain, the modulus of rigidity, G, relates shear stress to shear strain, and a plot of this relationship will give a straight line as shown in Figure 1.9.

The gradient of the line is constant $\frac{F}{\delta}$, and this is the spring stiffness of the block of rubber in N/m. Other materials will display different spring stiffnesses.

If the force F is divided by the area A and δ by the height L, the relationship will still be a constant such that:

$$\frac{F}{A} \div \frac{\delta}{L} = \frac{F \cdot L}{A \cdot \delta} = \text{constant} \tag{1.14}$$

Now:

$$\frac{F}{A} = \tau \text{ and } \frac{\delta}{L} = \gamma \tag{1.15}$$

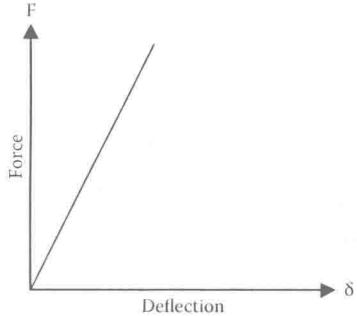


FIGURE 1.9 Modulus of rigidity.

Hence:

$$\frac{F \cdot L}{A \cdot \delta} = \frac{\tau}{\gamma} = \text{constant} \tag{1.16}$$

This constant is known as the *modulus of rigidity* and has the symbol G.

1.10 ULTIMATE SHEAR STRESS

Permanent deformation will occur in a material if the material is sheared beyond a certain limit and does not return back to its original shape. In this instance the elastic limit has been exceeded. When the material is stressed to the limit where the part fractures into two separate pieces, i.e. in a punching operation or a pin joint fails, the *ultimate shear stress* has been reached. The ultimate shear stress has the symbol τ_u.

Example 1.3

Calculate the force required to pierce a hole 20.0 mm diameter in a sheet 5.0 mm thick given that the ultimate shear stress is 50.0 MPa.

Solution:

The area to be pierced:

Circumference of cut:

$$\pi \cdot D = \pi \times 20.0 \text{ mm}$$

$$= 62.832 \text{ mm}$$

Area of cut:

$$= 62.832 \times 5.0 \text{ mm}^2$$

$$= 314.159 \text{ mm}^2$$

The ultimate shear strength = 50 N/mm^2:

$$\tau = \frac{F}{A} \therefore F = t \cdot A$$

Shear force required:

$$F = 1256.64 \text{ kN}$$