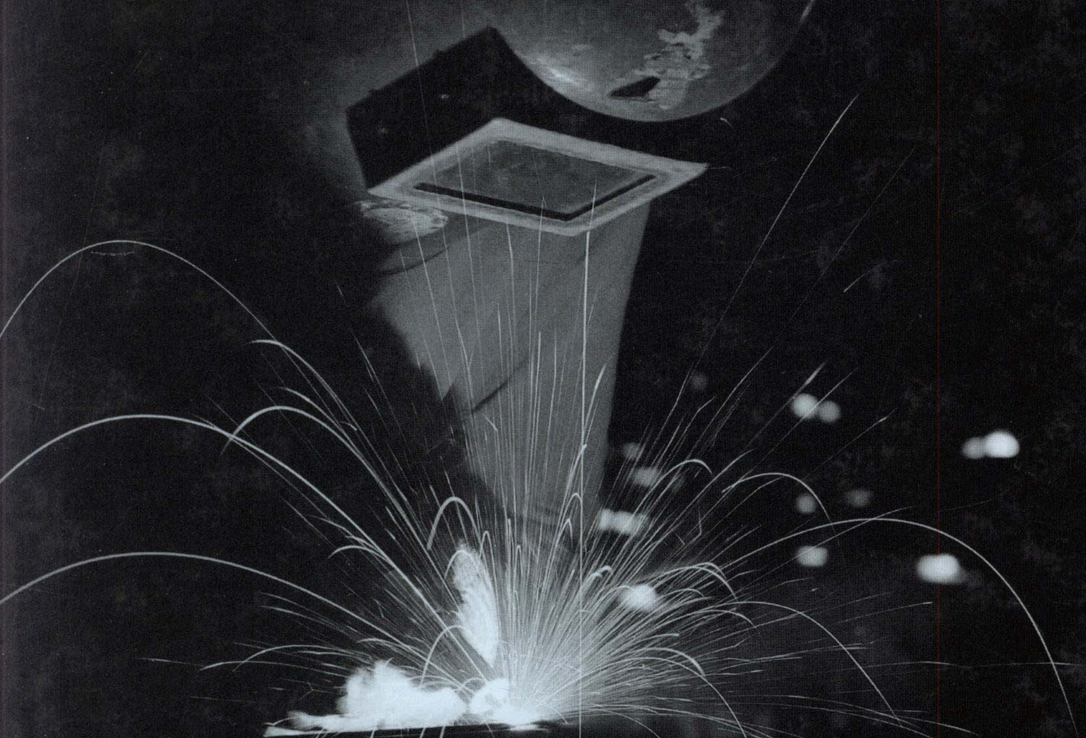

WELDED DESIGN

theory and practice

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William Andrew
publishing

ABINGTON PUBLISHING

Published by Abington Publishing
Woodhead Publishing Limited, Abington Hall,
Abington, Cambridge CB1 6AH, England
www.woodhead-publishing.com

Published in North and South America by William Andrew Inc.,
13 Eaton Avenue, Norwich, NY 13815, USA

First published 2001, Abington Publishing

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

ISBN 1 85573 537 7 (Woodhead Publishing Limited)
ISBN 0-8155-1474-3 (William Andrew Inc.)

Cover design by The ColourStudio
Typeset by BookEns Ltd, Royston, Herts
Printed by T J International, Cornwall, England

Preface

I have written this book for engineers of all disciplines, and this includes those welding engineers who do not have a background in matters of engineering design, as well as for others in all professions who may find this subject of interest. As might be expected, I have drawn heavily on my own experience. Not that I discovered any new principles or methods but because I had the privilege of firstly being associated with research into the behaviour of welded joints in service at its most active time in the 1960s and 1970s and secondly with the application of that research in a range of industries and particularly in structural design and fabrication which accompanied the extension of oil and gas production into deeper waters in the 1970s. The results of those developments rapidly spread into other fields of structural engineering and I hope that this book will be seen in part as a record of some of the intense activity which went on in that period, whether it was in analysing test results in a laboratory, writing standards, preparing a conceptual design or installing a many thousand tonne substructure on the ocean floor.

The position from which I write this book is one where, after being a structural engineer for five years, I became a specialist in welded design. In this role I have for many years worked with colleagues, clients and pupils who, without exception, have been and are a pleasure to work with; their mastery of their own disciplines and the responsibilities which they carry dwarfs my own efforts. I have also spent, I believe, sufficient periods in other occupations both inside and outside the engineering profession to give me an external perspective on my specialism. As a result I felt that it would be helpful to write a book setting out the subject of welded design in the context of the overall picture of engineering with some historical background. In presenting the subject in this way I hope that it will encourage teaching staff in universities and colleges to see welded joints and their behaviour as an integral part of engineering and that they will embed the subject in their courses instead of treating it as an add-on. It will also serve practising welding and other engineers wishing to extend their knowledge of the opportunities which welding offers and the constraints it imposes in their own work.

The subject of design for welding rests at a number of interfaces between the major engineering disciplines as well as the scientific disciplines of physics, chemistry and metallurgy. This position on the boundaries between traditional mainstream subjects may perhaps be the reason why it receives relatively little attention in university engineering courses at undergraduate level. My recent discussions with engineering institutions and academics reveals a situation, both in the UK and other countries, in which the appearance or otherwise of the subject in a curriculum seems to depend on whether or not there is a member of the teaching staff who has both a particular interest in the subject and can find the time in the timetable. This is not a new position; I have been teaching in specialist courses on design for welding at all academic and vocational levels since 1965 and little seems to have changed. Mr R P Newman, formerly Director of Education at The Welding Institute, writing in 1971,[1] quoted a reply to a questionnaire sent to industry:

> *Personnel entering a drawing office without much experience of welding, as many do today* (i.e. 1971), *can reach a reasonably senior position and still have only a 'stop-gap' knowledge, picked up on a general basis. This is fundamentally wrong and is the cause of many of our fabrication/design problems.*

There was then, and has been in the intervening years, no shortage of books and training courses on the subject of welded design but the matter never seems to enter or remain in many people's minds. In saying this I am not criticising the individual engineers who may have been led to believe that welded joint design and material selection are matters which are either not part of the designer's role or, if they are, they require no education in the subjects. Indeed, such was my own early experience in a design office and I look back with embarrassment at my first calculation of the suitability of welded joint design in an industry in which welding was not commonly used. It was an example of being so ignorant that I didn't know that I was ignorant. That first experience of a premature failure has stayed with me and gives me humility when assisting people who are in a similar position today. 'There, but for the grace of God, go I' should be on a banner above every specialist's desk. There are, of course many engineers who have, either because their work required it or because of a special interest, become competent in the subject. Either way, there is a point at which a specialist input is required which will depend upon the nature, novelty and complexity of the job set against the knowledge and experience of the engineer.

I have tried to put into this book as much as is useful and informative without including a vast amount of justification and detail; that can be found in the referenced more specialist works. However, I have tried to keep a balance in this because if too many matters are the subject of references the reader may become exasperated at continually having to seek other books, some of which will be found only in specialist libraries. For the most part I have avoided references to standards and codes of practice except in a historical context. Exceptions are where a standard is an example of basic design data or where it represents guidance on an industry wide agreed approach to an analytical process. I have adopted this position because across the world there are so many standards and they are continually being amended. In addition standards do not represent a source of fundamental knowledge although, unfortunately, some are often seen in that light. However I recognise their importance to the practical business of engineering and I devote a chapter to them.

I acknowledge with pleasure those who have kindly provided me with specialist comment on some parts of the book, namely Dr David Widgery of ESAB Group (UK) Ltd on welding processes and Mr Paul Bentley on metallurgy. Nonetheless I take full responsibility for what is written here. I am indebted to Mr Donald Dixon CBE for the illustration of the Cleveland Colossus North Sea platform concept which was designed when he was Managing Director of The Cleveland Bridge and Engineering Co Ltd. For the photographs of historic structures I am grateful to the Chambre de Commerce et d'Industrie de Nîmes, the Ironbridge Gorge Museum, and Purcell Miller Tritton and Partners. I also am pleased to acknowledge the assistance of TWI, in particular Mr Roy Smith, in giving me access to their immense photographic collection.

JOHN HICKS

Introduction

Many engineering students and practising engineers find materials and metallurgy complicated subjects which, perhaps amongst others, are rapidly forgotten when examinations are finished. This puts them at a disadvantage when they need to know something of the behaviour of materials for further professional qualifications or even their everyday work. The result of this position is that engineering decisions at the design stage which ought to take account of the properties of a material can be wrong, leading to failures and even catastrophes. This is clearly illustrated in an extract from *The Daily Telegraph* on 4 September 1999 in an article offering background to the possible cause of a fatal aircraft crash. ' "There is no fault in the design of the aircraft," the (manufacturer's) spokesman insisted. "It is a feature of the material which has shown it does not take the wear over a number of years..." ' This dismissal of the designer's responsibility for the performance of materials is very different in the case of concrete in which every civil engineer appears to have been schooled in its constituent raw materials, their source, storage, mixing, transport and pouring as well as the strength.

To emphasise the wider responsibility which the engineer has I give the background to some of the materials and the techniques which the engineer uses today and make the point that many of the design methods and data in common use are based on approximations and have limitations to their validity. A number of so-called rules have been derived on an empirical basis; they are valid only within certain limits. They are not true laws such as those of Newtonian mechanics which could be applied in all terrestrial and some universal circumstances and whose validity extends even beyond the vision of their author himself; albeit Newton's laws have been modified, if not superseded, by Einstein's even more fundamental laws.

The title of this book reflects this position for it has to be recognised that there is precious little theory in welded joint design but a lot of practice. There appear in this book formulae for the strength of fillet welds which look very theoretical whereas in fact they are empirically derived from large numbers of tests. Similarly there are graphs of fatigue life which look mathematically based but are statistically derived lines of the probability of failure of test specimens from hundreds of fatigue tests; subsequent theoretical work in the field of fracture mechanics has explained why the graphs have the slope which they do but we are a long way from being able to predict on sound scientific or mathematical grounds the fatigue life of a particular item as a commonplace design activity. Carbon equivalent formulae are attempts to quantify the weldability of steels in respect of hardenability of the heat affected zone and are examples of the empirical or arbitrary rules or formulae surrounding much of welding design and fabrication. Another example, not restricted to welding by any means, is in fracture mechanics which uses, albeit in a mathematical context, the physically meaningless unit $Nmm^{-3/2}$. Perhaps in the absence of anything better we should regard these devices as no worse than a necessary and respectable mathematical fudge – perhaps an analogy of the cosmologist's black hole.

A little history helps us to put things in perspective and often helps us to understand concepts which otherwise are difficult to grasp. The historical background to particular matters is important to the understanding of the engineer's contribution to society, the way in which developments take place and the reasons why failures occur. I have used the history of Britain as a background but this does not imply any belief on my part that history elsewhere has not been relevant. On one hand it is a practical matter because I am not writing a history book and my references to history are for perspective only and it is convenient to use that which I know best. On the other hand there is a certain rationale in using British history in that Britain was the country in which the modern industrial revolution began, eventually spreading through the European continent and elsewhere and we see that arc welding processes were the subject of development in a number of countries in the late nineteenth century. The last decade of the twentieth century saw the industrial base move away from the UK, and from other European countries, mainly to countries with lower wages. Many products designed in European countries and North America are now manufactured in Asia. However in some industries the opposite has happened when, for example, cars designed in Japan have been manufactured for some years in the UK and the USA. A more general movement has been to make use of manufacturing capacity and specialist processes wherever they are available. Components for some US aircraft are made in Australia, the UK and other countries; major components for some UK aircraft are made in Korea. These are only a few examples of a general trend in which manufacturing as well as trade is becoming global. This dispersion of industrial activity makes it important that an adequate understanding of the relevant technology exists across the globe and this must include welding and its associated activities.

Not all engineering projects have been successful if measured by conventional commercial objectives but some of those which have not met these objectives are superb achievements in a technical sense. The Concorde airliner and the Channel Tunnel are two which spring to mind. The Concorde is in service only because its early development costs were underwritten by the UK and French governments. The Channel Tunnel linking England and France by rail has had to be re-financed and its payback time rescheduled far beyond customary periods for returns on investment. Further, how do we rate the space programmes? Their payback time may run into decades, if not centuries, if at all. Ostensibly with a scientific purpose, the success of many space projects is more often measured not in scientific or even commercial terms but in their political effect. The scientific results could often have been acquired by less extravagant means. In defence equipment, effectiveness and reliability under combat conditions, possibly after lengthy periods in storage, are the prime requirements here although cost must also be taken into account.

There are many projects which have failed to achieve operational success through lack of commitment, poor performance, or through political interference. In general their human consequences have not been lasting. More sadly there are those failures which have caused death and injury. Most of such engineering catastrophes have their origins in the use of irrelevant or invalid methods of analysis, incomplete information or the lack of understanding of material behaviour, and, so often, lack of communication. Such catastrophes are relatively rare, although a tragedy for those involved.

What is written in this book shows that accumulated knowledge, derived over the years from research and practical experience in welded structures, has been incorporated into general design practice. Readers will not necessarily find herein all the answers but I hope that it will cause them to ask the right questions. The activity of engineering design calls on the knowledge of a variety of engineering disciplines many of which have a strong theoretical, scientific and intellectual background leavened with some rather arbitrary adjustments and assumptions. Bringing this knowledge to a useful purpose by using materials in an effective and economic way is one of the skills of the engineer which include making decisions on the need for and the positioning of joints, be they permanent or temporary, between similar or dissimilar materials which is the main theme of this book. However as in all walks of engineering the welding designer must be aware that having learned his stuff he cannot just lean back and produce designs based on that knowledge. The world has a habit of changing around us which leads not only to the need for us to recognise the need to face up to demands for new technology but also being aware that some of the old problems revisit us. Winston Churchill is quoted as having said that the further back you look the further forward you can see.

Contents

1 The engineer

1.1 Responsibility of the engineer

As we enter the third millennium *annis domini*, most of the world's population continues increasingly to rely on man-made and centralised systems for producing and distributing food and medicines and for converting energy into usable forms. Much of these systems relies on the, often unrecognised, work of engineers. The engineer's responsibility to society requires that not only does he keep up to date with the ever faster changing knowledge and practices but that he recognises the boundaries of his own knowledge. The engineer devises and makes structures and devices to perform duties or achieve results. In so doing he employs his knowledge of the natural world and the way in which it works as revealed by scientists, and he uses techniques of prediction and simulation developed by mathematicians. He has to know which materials are available to meet the requirements, their physical and chemical characteristics and how they can be fashioned to produce an artefact and what treatment they must be given to enable them to survive the environment.

The motivation and methods of working of the engineer are very different from those of a scientist or mathematician. A scientist makes observations of the natural world, offers hypotheses as to how it works and conducts experiments to test the validity of his hypothesis; thence he tries to derive an explanation of the composition, structure or mode of operation of the object or the mechanism. A mathematician starts from the opposite position and evolves theoretical concepts by means of which he may try to explain the behaviour of the natural world, or the universe whatever that may be held to be. Scientists and the mathematicians both aim to seek the truth without compromise and although they may publish results and conclusions as evidence of their findings their work can never be finished. In contrast the engineer has to achieve a result within a specified time and cost and rarely has the resources or the time to be able to identify and verify every possible piece of information about the environment in which the artefact has to operate or the response of the artefact to that environment. He has to work within a degree of uncertainty, expressed by the probability that the artefact will do what is expected of it at a defined cost and for a specified life. The engineer's circumstance is perhaps summarised best by the oft quoted request: 'I don't want it perfect, I want it Thursday!' Once the engineer's work is complete he cannot go back and change it without disproportionate consequences; it is there for all to see and use. The ancient Romans were particularly demanding of their bridge engineers; the engineer's name had to be carved on a stone in the bridge, not to praise the engineer but to know who to execute if the bridge should collapse in use!

People place their lives in the hands of engineers every day when they travel, an activity associated with which is a predictable probability of being killed or injured by the omissions of their fellow drivers, the mistakes of professional drivers and captains or the failings of the engineers who designed, manufactured and maintained the mode of transport. The engineer's role is to be seen not only in the vehicle itself, whether that be on land, sea or air, but also in the road, bridge, harbour or airport, and in the navigational aids which abound and now permit a person to know their position to within a few metres over and above a large part of the earth.

Human error is frequently quoted as the reason for a catastrophe and usually means an error on the part of a driver, a mariner or a pilot. Other causes are often lumped under the catch-all category of *mechanical failure* as if such events were beyond the hand of man; a naïve attribution, if ever there were one, for somewhere down the line people were involved in the conception, design, manufacture and maintenance of the device. It is therefore still human error which caused the problem even if not of those immediately involved. If we need to label the cause of the catastrophe, what we should really do is to place it in one of, say, four categories, all under the heading of human error, which would be failure in specification, design, operation or maintenance. An 'Act of God' so beloved by judges is a get-out. It usually means a circumstance or set of circumstances which a designer, operator or legislator ought to have been able to predict and allow for but chose to ignore. If this seems very harsh we have only to look at the number of lives lost in bulk carriers at sea in the past years. There still seems to be a culture in seafaring which accepts that there are unavoidable hazards and which are reflected in the nineteenth century hymn line '... for those in peril on the sea'. Even today there are cultures in some countries which do not see death or injury by man-made circumstances as preventable or even needing prevention; concepts of risk just do not exist in some places. That is not to say that any activity can be free of hazards; we are exposed to hazards throughout our life. What the engineer should be doing is to conduct activities in such a way that the probability of not surviving that hazard is known and set at an accepted level for the general public, leaving those who wish to indulge in high risk activities to do so on their own.

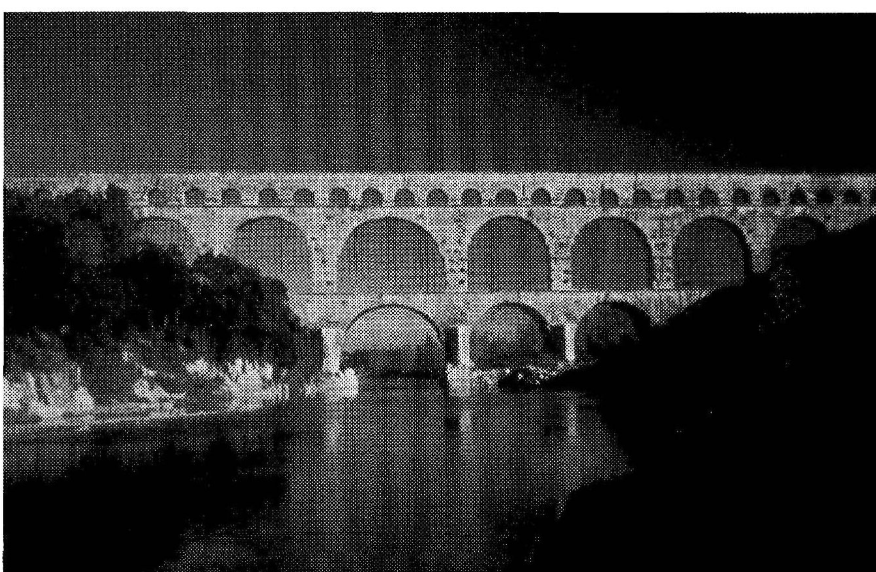
We place our lives in the hands of engineers in many more ways than these obvious ones. When we use domestic machines such as microwave ovens with their potentially injurious radiation, dishwashers and washing machines with a potentially lethal 240 V supplied to a machine running in water into which the operator can safely put his or her hands. Patients place their lives in the hands of engineers when they submit themselves to surgery requiring the substitution of their bodily functions by machines which temporarily take the place of their hearts, lungs and kidneys. Others survive on permanent replacements for their own bodily parts with man-made implants be they valves, joints or other objects. An eminent heart surgeon said on television recently that heart transplants were simple; although this was perhaps a throwaway remark one has to observe that if it is simple for him, which seems unlikely, it is only so because of developments in immunology, on post-operative critical care and on anaesthesia (not just the old fashioned gas but the whole substitution and maintenance of complete circulatory and pulmonary functions) which enables it to be so and which relies on complex machinery requiring a high level of engineering skill in design, manufacturing and maintenance. We place our livelihoods in the hands of engineers who make machinery whether it be for the factory or the office.

Businesses and individuals rely on telecommunications to communicate with others and for some it would seem that life without television and a mobile telephone would be at best meaningless and at worst intolerable. We rely on an available supply of energy to enable us to use all of this equipment, to keep ourselves warm and to cook our food. It is the engineer who converts the energy contained in and around the Earth and the Sun to produce this supply of usable energy to a remarkable level of reliability and consistency be it in the form of fossil fuels or electricity derived from them or nuclear reactions.

1.2 Achievements of the engineer

The achievements of the engineer during the second half of the twentieth century are perhaps most popularly recognised in the development of digital computers and other electronically based equipment through the exploitation of the discovery of semi-conductors, or transistors as they came to be known. The subsequent growth in the diversity of the use of computers could hardly have been expected to have taken place had we continued to rely on the thermionic valve invented by Sir Alexander Fleming in 1904, let alone the nineteenth century mechanical calculating engine of William Babbage. However let us not forget that at the beginning of the twenty-first century the visual displays of most computers and telecommunications equipment still rely on the technology of thermionic emission. The liquid crystal has occupied a small area of application and the light emitting diode has yet to reach its full potential.

The impact of electronic processing has been felt both in domestic and in business life across the world so that almost everybody can see the effect at first hand. Historically most other engineering achievements probably have had a less immediate and less personal impact than the semi-conductor but have been equally significant to the way in which trade and life in general was conducted. As far as life in the British Isles was concerned this process of accelerating change made possible by the engineer might perhaps have begun with the building of the road system, centrally heated villas and the setting up of industries by the Romans in the first few years AD. However their withdrawal 400 years later was accompanied by the collapse of civilisation in Britain. The invading Angles and Saxons enslaved or drove the indigenous population into the north and west; they plundered the former Roman towns and let them fall into ruin, preferring to live in small self-contained settlements. In other countries the Romans left a greater variety of features; not only roads and villas but mighty structures such as that magnificent aqueduct, the Pont du Gard in the south of France (Fig. 1.1). Hundreds of years were to pass before new types of structures were erected and of these perhaps the greatest were the cathedrals built by the Normans in the north of France and in England. The main structure of these comprised stone arches supported by external buttresses in between

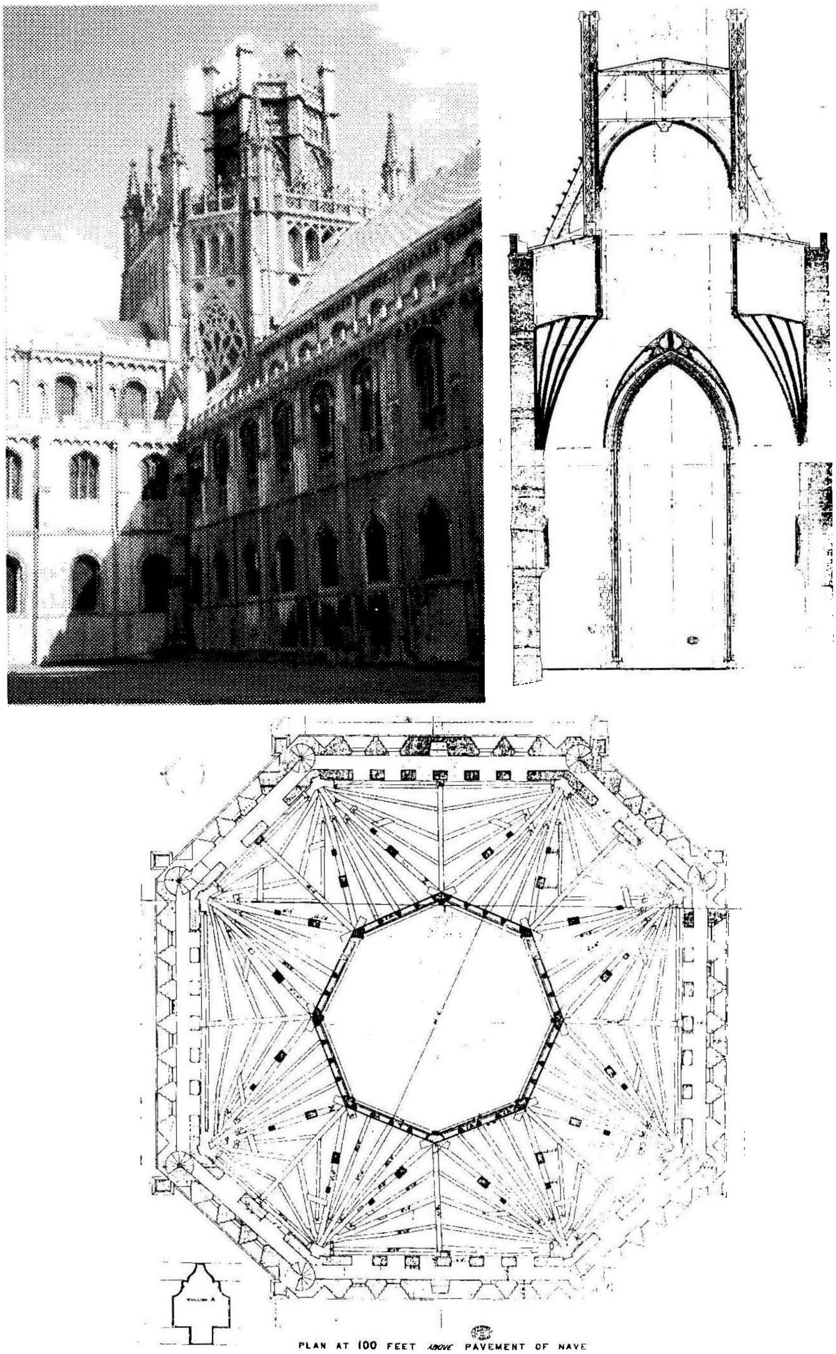


1.1 The Pont du Gard (photograph by Bernard Liegeois).

which were placed timber beams supporting the roof. Except for these beams all the material was in compression. The modern concept of a structure with separate members in tension, compression and shear which we now call chords, braces, ties, webs, etc. appears in examples such as Ely Cathedral in the east of England. The cathedral's central tower, built in the fourteenth century, is of an octagonal planform supported on only eight arches. This tower itself supports a timber framed structure called the lantern (Fig. 1.2). However let us not believe that the engineers of those days were always successful; this octagonal tower and lantern at Ely had been built to replace the Norman tower which collapsed in about 1322.

Except perhaps for the draining of the Fens, also in the east of England, which was commenced by the Dutch engineer, Cornelius Vermuyden, under King Charles I in 1630, nothing further in the modern sense of a regional or national infrastructure was developed in Britain until the building of canals in the eighteenth century. These were used for moving bulk materials needed to feed the burgeoning industrial revolution and the motive power was provided by the horse. Canals were followed by, and to a great extent superseded by, the railways of the nineteenth century powered by steam which served to carry both goods and passengers, eventually in numbers, speed and comfort which the roads could not offer. Alongside these came the emergence of the large oceangoing ship, also driven by steam, to serve the international trade in goods of all types. The contribution of the inventors and developers of the steam engine, initially used to pump water from mines, was therefore central to the growth of transport. Amongst them we acknowledge Savory, Newcomen, Trevithick, Watt and Stephenson. Alongside these developments necessarily grew the industries to build the means and to make the equipment for transport and which in turn provided a major reason for the existence of a transport system, namely the production of goods for domestic and, increasingly, overseas consumption.

Today steam is still a major means of transferring energy in both fossil fired and nuclear power stations as well as in large ships using turbines. Its earlier role in smaller stationary plant and in other transport applications was taken over by the internal combustion engine both in its piston and turbine forms. Subsequently the role of the stationary engine has been taken over almost entirely by the electric motor. In the second half of the twentieth century the freight carrying role of the railways became substantially subsumed by road vehicles resulting from the building of motorways and increasing the capacity of existing main roads (regardless of the wider issues of true cost and environmental damage). On a worldwide basis the development and construction of even larger ships for the cheap long distance carriage of bulk materials and of larger aircraft for providing cheap travel for the masses were two other achievements. Their use built up comparatively slowly in the second half of the century but their actual



1.2
The lantern of Ely Cathedral (photograph by Janet Hicks, drawings by courtesy of Purcell Miller Tritton and Partners).