The following guide to books on the history of construction and building engineering bibliography is compiled by Bill Addis and based on the bibliography in his book:

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It was compiled in 2006 and will be updated was soon as practically possible.

General introductions to building and civil engineering history

The history of construction and building engineering sits within the wider fields of the history of technology, the history of science and the history of civil engineering and the classic books in these fields not only provide an overview of our subject, but help set it in the wider context.

What is Construction History?

Until recently the history of construction has fallen between several stools – the histories of military and civil engineering, the history of science and technology, and the history of architecture. The large number of works in this bibliography that have been published in the last three or four years indicate that things are changing and a new discipline seems to be forming. In English it is generally called "Construction History". A periodical of that name has been published in Britain by the Construction History Society since 1985. In Spain, the first national congress on Construction History was held in 1996, and three others have followed (HUERTA, 1996, 1998, 2000, 2005). The first international congress on Construction History was held at Madrid in 2003 and its proceedings ran to over 2100 pages (HUERTA 2003); the second was held at Cambridge, England in 2006 (DUNKELD et at. 2006); the third is planned for 2009 in Cottbus, Germany. Previously disparate individuals and specialist groups are beginning to learn of each others' existence, and publications such as BECCHI, *et al.* (2002 & 2004) are facilitating this process.

History of civil engineering

The best overview of ***civil engineering*** history in English, which also deals extensively with buildings, is still the translation of the book written by the Swiss engineer, Hans Straub in the 1940s (STRAUB 1952) which has now reached its fourth edition in German (STRAUB 1992), Civil engineering, of course, embraces many disciplines, several of which touch on the construction and engineering of buildings, and each of these has its own literature. The recent twelve-volume series *Studies in Civil Engineering History* deals with all aspects of the subject including bridges, ports and harbours, dams, canals, railways and land drainage, as well as subjects closer to the engineering of buildings including water-supply and public health engineering (SMITH 1999), timber (YEOMANS 1999), iron (SUTHERLAND 1997 and THORNE 1999), concrete (NEWBY 2001) and design in civil and structural engineering (ADDIS 1999). Generally, however, civil engineering history, like military history, tends to be rather nationalistic, focusing on a particular country's achievements, for example WISELY (1974), SKEMPTON (1996), and DENNIS (2003).

History of building engineering

The **history of buildings** is dominated by books on the history of architecture, though these seldom address the question of how they were constructed or designed from the engineering point of view. Nevertheless, alongside histories of technology, science and civil engineering, histories of architecture provide a further context within which developments in building engineering can be set. Not least, they provide a helpful catalogue of what was being built in different countries and when the buildings were constructed. Of particular use are classic general works such as CHOISY (1899) and the many editions of Banister Fletcher's *History of architecture on the comparative method*. (FLETCHER 1996).

There are very few equivalent books devoted to the full range of **building engineering** disciplines over the last three thousand years or so – indeed, perhaps only the two volumes by COWAN (1977a & 1977b). A second contender (ELLIOTT 1992) deals predominantly with recent times, since the eighteenth century, and only covers developments in Britain and the USA.

Engineering disciplines

Structural engineering

The history of structural engineering has received more attention than other building engineering disciplines, both because it can be traced so far back into history and, significantly, because the science and mathematics of mechanics and forces were developed earlier than other sciences related to building. COWAN (1977a & 1977b), MAINSTONE (1998 & 1999), GRAEFE (1990), and JESBERG (1996) have all dealt with the entire history of structural engineering, from around 1000 BC to the last century. The pre-scientific era has been well-treated by MARK (1994) and MISLIN (1997) and the last three centuries have been covered by WERNER (1980), BILLINGTON (1985) RICKEN (1994) and PICON (1997). Developments by individual nations have been portrayed by many authors, for example, France (DESWARTE & LEMOINE 1980 and LEMOINE & MIMRAM 1995), Britain (COLLINS 1983), Italy (GUENZI 1992, BUCCARO & AGOSTINO 2003, and BUCCARO & MATTIA 2003)), and the USA (CONDIT 1960, 1961 *et al*.). Among many teachers of structural engineering who have used historical examples to illustrate structural principles Professor Mario Salvadori is perhaps the best known (SALVADORI 1990 and LEVY & SALVADORI 1992).

The process of designing building structures dates back to ancient times, long before modern mathematics and engineering sciences were first developed in the seventeenth and eighteenth centuries. Today's scientific design methods were preceded by a host of design rules whose origins have been traced in MAINSTONE (1968, 1988 & 1999) and ADDIS (1990 & 1999). Particular attention has been given to the design of the masonry structure of mediaeval cathedrals by ACKERMAN (1949), SHELBY (1977), SHELBY & MARK (1979), SANABRIA (1982) and HUERTA (2004). The development of design methods for the beams and columns in timber and iron, which form the basic elements of modern frame structures, has been addressed by YEOMANS (1987), SKEMPTON (1956), SUTHERLAND (1990) and SMITH (1992).

Since the first use of mathematics and science, or "theory" as it is often called, to help design buildings, there have been regular discussions of the relationship between such theory and the practice of building. This debate began in mediaeval times (VICTOR, 1979, ADDIS, 1990) and was largely resolved by RANKINE (1856), though the theme has been regularly revisited since that time, notably by CROSS (1952).

The greatest breakthrough in the development of structural design methods since the use of mathematics and science has been the use of ***scale models*** to predict the behaviour of full-size buildings. While this technique has its origins in mediaeval and even ancient times, its power has been fully exploited only since the 1930s (TORROJA 1958, NERVI 1956, COWAN *et al*. 1968, HOSSDORF 1974).

The nature of structural engineering design in recent times has become the frequent object of discussion and notable contributions have been made by HAPPOLD ET AL (1976) and PETROSKI (1985). A recent conference was the first to be devoted to *The conceptual design of structures* (HANGLEITER, 1996) and many publications use case studies as exemplars of good engineering design (e.g. SALVADORI 1990, ADDIS, 1994 & 2001).

The history of ***structural engineering science*** goes back to the earliest days of applying mathematics and science to solving practical engineering problems. The earliest surviving exposition of the classic questions in mechanics was by Aristotle in around 350 BC. His thirty-five questions were considered by many mediaeval philosophers, but the earliest evidence of genuine progress in answering them is found first in Leonardo's copious notes (TRUESDELL 1968b, MISLIN 1997, BECCHI 2004). Of greatest significance in the development of the modern science of strength of materials was Aristotle's Question 16 which asked why it is easier to break a long beam (or rod) than a short one of the same cross-section. This was the question that both BALDI (1621) and GALILEO (1638) went much further towards answering than Leonardo (BECCHI 2004). The strength and elasticity of beams has preoccupied structural scientists ever since and the definitive authority on this development is still TODHUNTER & PEARSON (1886-93). HEYMAN (1972) has given a condensed summary of the story and the key contribution made by Coulomb in his 1773 Essai. Of great practical significance was the work undertaken by William Fairbairn and Eaton Hodgkinson in the 1830s in developing the most economical cross section for iron beams (HODGKINSON, 1831).

The introduction of statics and the science of strength of materials into the world of the design engineer during the last three centuries has been thoroughly covered by many authors from many points of view. Comprehensive reviews have been written by TIMOSHENKO (1953), HEYMAN (1998), BENVENUTO (1991) and KURRER (2002). Good summaries of the key developments in structural theory are given by HAMILTON (1952), MAINSTONE (1968 & 1988), COWAN (1977b & 1977c) and CHARLTON (1982). This early work led in the early nineteenth century to the use of graphical methods to calculate forces in structures and, eventually, to the groundbreaking books by BOW (1851 & 1873) and CULMANN (1866) (see MAURER, 1998). The last few decades have seen the appearance of a growing number of specialist studies into the application of mechanics and statics to the design of buildings and structural elements (TRUESDELL 1968a, HEYMAN 1999, RADELET-DE GRAVE & BENVENUTO 1995, PASQUALE 1996, MAINSTONE 1999, HUERTA 2003 and BECCHI *et al*. 2003)

The first engineering text books that included engineering science that we would recognise were those of BÉLIDOR (1729 and 1750-82). The first devoted to structural science and the strength of materials were by EYTELWEIN (1801) and NAVIER (1820).

All large ***masonry structures*** built before the eighteenth century have inspired scholars to use their modern knowledge of structures to understand how these buildings work and, often, to consider how they might have been constructed. Such individual studies have led to a number of works which deal with the engineering of masonry structures (HEYMAN 1995 & 1996, BECCHI 2002, HUERTA 2004 and COWAN 1977d).

The development of the ***structural frame*** in the late eighteenth and early nineteenth century replaced masonry as the principal means of providing the structure of certain buildings. The use of timber beams (YEOMANS 1987) paved the way for making beams of cast iron (SKEMPTON 1956, SUTHERLAND 1990) and structural frames comprising cast and later wrought iron and steel (SKEMPTON & JOHNSON 1952, SKEMPTON 1959 & 1959-60 and WITTEK 1964). Later developments of the frame are covered in the development of high-rise buildings, below.

The development of ***roof trusses***, from their early days made of timber to their construction from wrought iron to cover engineering works, docks, railway stations and exhibition halls during the nineteenth century is covered by many authors, including

YEOMANS (1992), WITTEK (1964), LEMOINE (1986), SUTHERLAND (1988-89 and 1997), THORNE (2000) and MISLIN (2002).

In the twentieth century, the ***concrete shell*** provided a spectacular alternative to the roof truss and its early development in Germany, especially the Zeiss-Dywidag shell, is chronicled in KRAUS & DISCHINGER (1928) and BAUERSFELD (1957), JOEDICKE (1963). As the shell spread to other countries, its progress is best shown through the works of the three acknowledge masters of the art TORROJA (1956 & 1958), NERVI (1956 & 1966) and Candela (FABER 1963). This heroic era of concrete shells is celebrated by many authors including COWAN (1977d), BILLINGTON (1985) and SALVADORI (1990).

An interesting hybrid between masonry vault and concrete shell is the ***timbrel vault*** or *bóveda tabicada* made of tiles and used for centuries in a number of places on the Mediterranean coasts of Spain, France and Italy (TRUÑÓ 2004). Known also as the Catalan vault, it was exported to the USA in the late nineteenth century by Rafael Guastavino and used widely in New York as a form of fireproof floor construction (HUERTA 1999).

The use of ***tensile structures*** to form long-span roofs or canopies began in the nineteenth century (GRAEFE 1990b). The Russian engineer Vladimir Shuchov created several spectacular exhibition halls using woven strips of steel in the 1890s (GRAEFE 1990c). In the 1950s the German architect Frei Otto experimented with tensile roofs made with membranes and cables (ROLAND 1965, OTTO 1988) and both FORSTER (1994) and BERGER (1996) have charted the development of this type of structure during the late twentieth century.

Fire engineering

Throughout history an important influence on the construction of buildings has been the need to prevent them and their contents – both goods and people – from being damaged by fire. Today this aspect of building design is called ***fire engineering***, a term that dates only from the 1970s. A full history of fire protection and so-called 'fireproof construction' has yet to be written. A short review of these subjects, from the early days of theatres and multi-story buildings in the mid-eighteenth century, has been written by HAMILTON (1958). Fireproof construction began in earnest with the introduction of wrought and cast iron into building construction in the late eighteenth century (SKEMPTON & JOHNSON 1952, FALCONER 1993), a story which Sara Wermiel has taken into the nineteenth century, especially in Britain and the USA (WERMIEL 1993 & 2000). The contribution of Edwin O. Sachs, who organised the world's first International Fire Congress in London in 1903, is told in WILMORE (1998). For a detailed understanding of the situation in the late nineteenth century it is best to look at contemporary books, such as HAGN (1904) and FREITAG (1899).

Foundations, soil mechanics and earthquake engineering

Foundations

All buildings and bridges require firm ***foundations*** and practical methods for their construction were devised long before there was any useful understanding of the science underlying the curious and often capricious behaviour of the sand, soil and earth upon which foundations were constructed. The Roman engineer VITRUVIUS devoted several pages to his manual on building to the construction of foundations for temples (Book 3, Ch.4) and retaining walls (Book 6, Ch.8). ALBERTI too addresses the subjects on several occasions in his book on construction (1485). There is nothing like a public inquiry for revealing the current state of knowledge about an engineering subject and we are fortunate that the building of the new Rialto Bridge in Venice in the late 1580s was the subject of such an inquiry. The various and vivid arguments about the best construction for the foundations of the bridge were recorded *verbatim* and have been expertly summarised by PARSONS (1939).

Comprehensive histories of foundations and retaining wall design and construction have been written by KERISEL (1987 & 1993) and the use of concrete in foundations has been traced by CHRIMES (1996). Modern methods of constructing foundations were developed in Chicago in the late nineteenth century as engineers strove to support taller and taller buildings on the weak soil beneath the city. This dramatic period of progress has been told by PECK (1948).

Soil mechanics

Our success in building foundations today, and since the early twentieth century, depends entirely on our understanding of the properties of soils, the science known as ***soil mechanics***. This subject was first developed in France in the eighteenth century and by the Scottish engineer Rankine in the mid-nineteenth century. This period of history is covered by HEYMAN (1972) and SKEMPTON (1979). The breakthrough which transformed soil mechanics in the early twentieth century was due entirely to one man – the Czech engineer Karl Terzaghi. His experimental approach to studying the behaviour of soils, both in the laboratory and in the field, enabled him to understand how the presence of water affected the strength of soils (BJERRUM *et al*. 1960 & GOODMAN 1999).

Earthquake resistant structures

While the design of ***earthquake-resistant structures*** goes back to ancient times (KIRIKOV 1992) their quantitative design using estimates of the loads that act upon buildings in an earthquake began only in the late nineteenth century. The twentieth century history can be gleaned from the website of the Consortium of Universities for Research in Earthquake Engineering (www.curee.org). The contributions made by Lydik Jacobsen and his pupil John Blume are given on the website of the John Blume Earthquake Engineering Center (http://blume.stanford.edu).

Building services engineering

Heating and ventilation

As well as ***heating and ventilation***, the discipline now known as "building services engineering" embraces the supply of water, drainage, gas, electricity and telecommunications services as well as the provision of air conditioning, suitable natural and artificial lighting and a desirable acoustic performance of interior spaces. Such a range virtually defies comprehensive treatment, though one book has made an excellent attempt (BILLINGTON & ROBERTS 1982). The early development of central heating and forced ventilation in the late eighteenth and early nineteenth centuries has been reviewed by BRUEGEMANN (1978) and the story is continued into the early twentieth century, especially in the USA, by ELLIOTT (1992) and DONALDSON & NAGENGAST (1994). Developments in heating in the first half of the nineteenth century have been covered by FERGUSON (1976). BANHAM (1969) has written about the sometimes conflicting demands of achieving a good internal environment and creating good architecture.

Power

Before electricity, ***hydraulic power*** was used to drive various pieces of building equipment, especially lifts, and a history of this interesting technology, which survived in London into the 1970s, has been written by MCNEIL (1972). The recent interest in generating energy for use in buildings from renewable sources might suggest it is a new idea; but not so. BUTTI & PERLIN (1980) tell the story of using solar energy from its earliest use in ancient Greece.

Lighting

The provision of natural ***daylight*** inside a building became of great concern in the nineteenth century for two reasons. As new and taller buildings were built ever closer in cities it became important to establish whether a new building infringed the right to daylight of occupiers of an existing, adjacent building. Objective methods had to be devised for assessing the quality and quantity of daylight inside rooms (HAWKES 1970). The second stimulus was the growing belief, from the 1860s, that poor lighting would permanently affect the eyesight of schoolchildren and several scientists proposed assessing the intensity of light relative to normal daylight (KERR 1913, BILLINGTON & ROBERTS 1982). Before the development of electrical instruments to measure absolute light intensity, measurements in actual rooms and in scale-model rooms were made using 'relative photometry' (RUZICKA 1908, TROTTER 1921). Various attempts were made in the early 1900s to predict the movement of shadows throughout the day, in different seasons and at different latitudes. DUFTON & BECKETT (1931) devised their 'heliodon' to solve these calculations using a light source to simulate the sun's movement relative to a model building. ***Artificial lighting*** using coal gas began around 1800 (RUSSELL 1976, BILLINGTON & ROBERTS 1982) though, for the first few decades, gas lights were used as much to provide the motive power for forced ventilation as for providing light (BRUEGEMANN 1978).

Refrigeration and air-conditioning

Refrigeration and air-conditioning were first successfully accomplished in Europe in the mid-nineteenth century, but their widespread use including precise humidity control, first in industrial, then in commercial and domestic buildings, was a wholly American story that has been well-told by COOPER (1998) and ACKERMANN (2002). The so-called father of air-conditioning (though not its inventor or first practitioner in the USA) was Willis Carrier whose biography was compiled by one of his firm's employees (and one of the few women to feature in this book) Margaret INGLIS (1952). The grandfather of air-conditioning, David Reid, has been celebrated for the first time in a recent paper (STURROCK & LAWSON-SMITH 2006). The pre-history of domestic refrigeration – the ice house – is thoroughly covered in BEAMON & ROAF (1990).

Acoustics

The ***acoustics*** of both open-air theatres and enclosed spaces was a subject of great interest to the scientists of ancient Greece (c.500BC) and some of their ideas on the science of harmonics and theatre design are presented by the Roman engineer VITRUVIUS (Book 5 Chaps. 2-8). Several nineteenth century books on ventilation and heating also addressed room acoustics and how best to achieve suitable results, though they admitted it was not a precise or predictable art (e.g. INMAN 1836, REID 1844). In America and Europe alike, acoustics remained a mystery to building designers through most of the nineteenth century (THOMPSON 1992). The father of the modern science of acoustics was the Scottish physicist Lord Rayleigh (J.J. Thompson) though he did not concern himself with building design (BEYER 1999). The first acoustician to apply a scientific approach to assessing the acoustic qualities of lecture rooms, concert halls and churches was Wallace SABINE who described his experiments in a series of ground-breaking papers (SABINE 1922). His ideas were soon being applied by building designers (BEYER 1999, THOMSON 1992 & 2002). The acoustic design of concert halls only lost much of its unpredictability with the introduction of model testing to study the otherwise-incalculable behaviour of sound waves inside complex shapes. This approach was first studied in the 1930s (SPANDÖCK 1934) and developed to an (almost) exact science in the 1950s, especially by the Danish acoustician Vilhelm Jordan whose most well-known commission was the Sydney Opera House (JORDAN 1980).

Façade engineering

The specialist design of the building envelope has only recently acquired the name of ***façade engineering*** and dates from the introduction of curtain walling systems in the 1930s, although some would argue that the Crystal Palace (1851), Sheerness Boat store (1858) and the many steel-framed buildings in New York and Chicago from the 1890s deserve credit as early "façades" (FREITAG 1909. YEOMANS (1998) and BANHAM (1969) have looked at these early days and SULZER (1999) has made a detailed study of the work of Jean Prouvé who developed curtain walls in France in the 1930s. The intricacies of the modern, fully-glazed façade are best studied in RICE & DUTTON (1990) who describe how they developed one of the first such façades at La Villette in Paris.

Construction materials

The history of ***construction materials*** is often addressed alongside studies of the craft skills involved in building such as DAVEY (1961), ADAM (1994), FITCHEN (1986) HARVEY (1975), and GUILLERME (1995). Engineering in today's construction industry tends to be divided according to material simply because there exist different design codes of practice for timber, steel, masonry and concrete. General histories of recent times tend to follow the same demarcation (e.g. ELLIOTT 1992, YEOMANS 1997). The revolution in ***materials science*** in the early twentieth century, which led to an understanding of *why* materials are as strong (or weak) as they are, has been well told by GORDON (1968).

Measuring the structural properties of materials progressed in the seventeenth and eighteenth centuries alongside the development of the theoretical concepts of stress, strain, strength and stiffness (TIMOSHENKO, 1953). This early work grew into the larger activity known as ***structural testing*** which has been so important in enabling designers to specify material properties and hence make assessments and predictions of ***structural safety*** (PUGSLEY, 1944, BLOCKLEY, 1980).

The history of building materials is also dealt with in a wide range of publications dealing with the repair and refurbishment of old buildings – part of the growing heritage industry. Such works are generally outside the scope of this review.

Masonry

Masonry construction is covered in the general works mentioned above, in the section on structural elements and in the notes below dealing with the construction of mediaeval cathedrals. CAMPBELL & PRYCE (2003) have written a history of using ***brick*** in construction.

Timber

Timber engineering is dealt with in many books on vernacular building as well as a few that focus on engineering (e.g. YEOMANS, 1992 & 1999).

Glass

The use of ***glass*** in buildings from the eighteenth century is covered in ELLIOTT (1992) and many early iron and glass buildings are featured in HIX (1996). The modern, highly-engineered use of glass is described in RICE & DUTTON (1990) and several case studies of such buildings are given in HOLGATE (1997) and ADDIS (2001).

Aluminium

After the Second World War, when it was produced in large quantities for aircraft, ***aluminium*** had a short-lived period of popularity as a structural material in building construction, as well as its use in building façades, which continues until today. Shortly before the downturn in its use, America's largest producer of aluminium, Reynolds Metals, published two fine books on its use in construction (PETERS, 1956 & WEIDLINGER, 1956).

Iron and steel

The use of ***wrought iron*** from ancient times in the form of tie-bars and cramps is covered in general works on construction materials mentioned above. Its use for compression elements in bridge construction was taken up from the 1790s by Thomas Telford. Telford and others used wrought iron chains for suspension bridges from the early 1800s. The heyday of wrought iron arrived with the coming of the railways in the 1820s and soon railway stations and bridges of ever-increasing spans were needed. Most spectacular of all was the Britannia railway bridge (1845-50) over the Menai Straits in North Wales (ROSENBERG & VICENTI 1978). Wrought iron became widely used for building from the mid-nineteenth century (STEINER 1978, LEMOINE 1986, SUTHERLAND 1997, THORNE 2000).

The use of cast iron in buildings is covered under the sections on structural engineering (above) and industrial and high-rise buildings (below). William Fairbairn was one of the most prominent iron masters in Britain and wrote the first manual on using both cast and wrought iron in buildings (FAIRBAIRN 1854, POLE 1887). A number of key papers on the use of iron are collected in SUTHERLAND (1997) and THORNE (1999). The historical introduction to HART, HENN & SONNTAG (1985) provides a good review of the evolution of steel-framed buildings and complements a number of similar reviews (SKEMPTON 1959, STEINER, 1978, LEMOINE 1986, MARREY 1989 and WITTEK 1964). BANNISTER 1956 & 1957, WERNER & SEIDEL 1992) look at the early use of iron in the USA and SHANKLAND (1897) and BYLANDER (1937) were both structural engineers who described their own experience on many large steel-framed buildings.

Concrete

The making and use of ***Roman concrete*** is discussed by VITRUVIUS (c.25BC) and reviewed by many modern writers including DAVEY (1961), ADAM (1994), DELAINE (1997) and TAYLOR (2003).

Mass concrete was in use for foundations, in both bridges and buildings, from the late eighteenth century (MORDAUNT-CROOK 1965, GUILLERME 1986 & 1995, CHRIMES 1996). By the 1860s many hundreds of houses had been built entirely of mass concrete with no reinforcement (STANLEY 1979).

The development of ***reinforced concrete*** and its engineering use are covered by DE COURCY (1987), HUBERTI (1962), NEWBY (2001) and SUTHERLAND (2001) as well as the general books on materials mentioned above. For the impact of reinforced concrete on architecture, see LE CORBUSIER (1923), COLLINS (1958), COTTAM (1986) and BANHAM (1986). More than is the case for other materials, the history of reinforced concrete consists of a number of national stories which need to be read in parallel, so to speak. Some examples include the following: *France* - GUILLERME 1986, SIMONNET 1992, BOSC *et al*. 2001, GROTE & MARREY 2000; *Germany* - HÄGERMANN, HUBERTI & MÖLL 1962-65 and KRAUS & DISCHINGER 1928; *UK* - HAMILTON 1956, BROWN 1966; *USA* – CONDIT 1960 & 1961 and NEWLON 1976; SWITZERLAND - BILLINGTON 1979; *Italy* – NERVI 1945 & 1956, IORI 2001, LEVI 2002; *Spain* - TORROJA 1958 & 1967.

Building types

Cathedrals

The construction of ***cathedrals*** and large churches has probably attracted more interest than any other type of building built before 1900. Of the many works mentioned above, under structural engineering and below, under the different eras covered by individual chapters, the following provide a good cross-section: HART 1965, ACLAND 1972, BINDING & NUßBAUM 1978, COENEN 1990, CONRAD 1990, BINDING 1993, HEYMAN (1996), ERLANDE-BRANDENBURG (1995), COURTENAY (1997), SMITH (2001-02) and HUERTA (2004).

Fortifications and castles

The construction of ***fortifications and castles*** is also covered by a large bibliography through all periods of history (e.g. MESQUI 1995).As might be expected in military history, books often treat their subject along nationalistic lines. Several of the earliest works on engineering dealt with the design of fortifications (KEYSER c.1405, FRANCESCO DI GIORGIO 1470s, PARSONS 1939, GILLE 1966). Biographies of famous military engineers or architects such as Leonardo, various members of the Sangallo family and Michelangelo discuss the design of fortifications they designed. The French engineer Vauban has justly received considerable attention from historians of fortifications (ASSOCIATION 1984).

Industrial buildings

Although they seldom get favourable treatment in histories of architecture, ***industrial buildings*** contributed more to progress in structural engineering in the nineteenth century than any other building type. The pioneering work, especially in cast iron, occurred in Britain between about 1770 and 1860. The story is told in BANNISTER (1950), FITZGERALD (1988), SUTHERLAND (1988-89), SKEMPTON & JOHNSON (1952), SKEMPTON (1956 & 1959-60), GILES & GOODALL (1998) and HAY & STELL (1986). More general studies of the development of factories and engineering works are found in TANN (1970), ACKERMANN (1991) and MISLIN (2002).

High-rise buildings

The modern ***high-rise building*** owes its success to the use of riveted wrought-iron construction which was developed not only in engineering works but in other buildings that demanded wide-spans, especially railway stations, theatres, exhibition buildings and department stores (WITTEK 1964, LEMOINE 1986 and SCHULZE 1928). The story of high-rise building from around 1870 is largely an American one. The first half century is covered by CONDIT (1964), LANDAU & CONDIT (1996), SHANKLAND (1897), MUJICA (1930), BYLANDER (1937) and LAWRENCE (1990). A fascinating first-hand report of constructing the Empire State Building is reprinted in facsimile in WILLIS (1998) and an equally vivid, blow-by-blow account of designing and constructing Worldwide Plaza in New York in the 1980s is given in SABBAGH (1990). Developments in Chicago since the 1930s are given by CONDIT (1974). The nature of the creative genius that lies behind the best skyscrapers is provided by the biography of their greatest exponent, Fazlur Khan (ALI 2001).

Prisons, hospitals, theatres

The development of both ventilation and central heating for buildings was largely a consequence of constructing the first buildings to house large numbers of the public, namely ***prisons*** (BRODIE, 2002.and BRUEGEMANN, 1978), ***hospitals*** (TAYLOR, 1977, RICHARDSON, 1998 and STEVENSON, 2000) and ***theatres*** (LEACROFT, 1984). Theatres also played important part in the development of modern fire engineering (WILMORE, 1998) and, together with concert halls, the development of acoustic engineering (JORDAN, 1980).

Philosophy of engineering

The nature of engineering

Throughout the nineteenth century most people were constantly aware of the impact that civil, building, mechanical and electrical engineering had on their lives. The latest achievements in these fields were subjects of popular interest, both in the press and in books, in the way that the latest digital cameras and mobile phones are today. People regularly attended evening lectures on engineering subjects, not only to become more highly qualified, but simply out of interest. The English writer Rudyard Kipling wrote several stories that touched on engineering matters, including one in which he personified the iron plates and rivets of a ship, and the pistons and the steam in its engines, by way of conveying to his readers how they all contributed to a safe journey across the Atlantic (KIPLING, 1908).

Today the engineer's work, especially that of the building and civil engineer, tends to be taken for granted and building engineers have seldom made the effort to describe for others the nature of what they do. LEONHARDT (1981) has written a rare overview of the nature of civil and building engineers' work and, more recently, the firm of consulting engineers founded by Ove Arup has published an excellent overview of its activities to help raise understanding of what its engineers do (DUNSTER, c.1996). There is no better summary of the scope of modern engineering of the built environment. The present book can be considered as the story of how mankind got to the state summarised in Arup's book.

Writing mainly about the aircraft industry, but equally relevant to buildings, VICENTI has written on '*What engineers know and how they know it*' (1990). The best insights into the nature of structural engineering design come from the pens of those few engineers who have written about their own work, for example NERVI (1956), TORROJA (1967), RICE (1993), and HOSSDORF (2003).

The nature of engineering is also reflected in the birth of the modern professional engineering institutions that were created in nearly every country to define and protect the professional status of engineers, and to ensure their distinctness from one another and, especially, from the profession of architect (PICON 1988 & 1992, BUCHANAN 1989 and RICKEN 1994). The education of engineers has played an essential role establishing and maintaining the highest qualities in the profession (MCGIVERN 1960, EMMERSON 1973, PFAMMATTER 1992, GRAYSON 1993, BUCCARO & AGOSTINO 2003, BUCCARO & MATTIA 2003).

Philosophy of engineering design

A number of authors have addressed the ***philosophy of engineering design*** and process by which engineering design progresses (PACEY 1974, ROSENBERG & VICENTI 1978, BLOCKLEY 1980, BLOCKLEY & HENDERSON 1980, PETERS 1981 & 1996, and ADDIS 1990 & 1999.

The engineer's tools

Drawings

Like the mason's hammer and chisel and carpenter's saw and plane, design engineers have needed their own 'tools of the trade' – drawing and calculating. The Renaissance engineers Brunelleschi, Francesco di Giorgio and especially Leonardo illustrate the earliest days of using drawings as a means of visualising, developing and communicating engineering designs (GILLE 1966). Formal engineering drawings were developed in France in the eighteenth century to show not only the size and appearance of the finished artefact but often also its method of construction (PICON & YVON 1989). The technique of orthographic projection for representing three-dimensional space on paper (e.g. today's third-angle projection) was developed by Gaspard MONGE (1799). The broader history of the development of engineering drawing is told by NEDOLUHA (1960), BAYNES & PUGH (1981), BELOFSKY (1991), BOOKER (1979), and FERGUSON (1992).

Scale models used in design

The most important development in understanding the engineering behaviour of buildings and in designing unprecedented buildings has been the use of ***scale models*** to predict the behaviour of full-size buildings. While this technique has its origins in ancient and mediaeval times its use grew when engineers began in the mid eighteenth century to make use of science to enhance their understanding of problems (e.g. SKEMPTON 1981, ROSENBERG & VICENTI 1978). The full power of scale model testing was exploited first in the late nineteenth and early twentieth centuries in the fields of hydraulics and aerodynamics before being applied in civil and building engineering, for structures (BEGGS 1922, TORROJA 1958, NERVI 1956, COKER & FILON 1957, COWAN *et al*. 1968, OTTO 1973, HOSSDORF 1974, BACH *et al*. 1988, CHILTON 2000, KAWAGUCHI 2004, SAITOH 2004, MOTRO 2004, ADDIS 2005), wind loading (FLACHSBART 1928), lighting (RUZICKA 1908, KERR 1913, HAWKES 1970), acoustics (SPANDÖCK 1934, JORDAN 1980).

Calculation methods and tools

General histories of mathematics tell how man's ability to make ***calculations*** developed using geometry, number, trigonometry, algebra, logarithms and calculus (e.g. CAJORI, 1928-29, ASPRAY, 1990). The use of geometry in cathedral design is discussed by SHELBY (1972) and VICTOR (1979). Before the age of electronic calculators and computers, engineers used three devices for calculating - graphical charts, slide rules, and mechanical calculators. Many enthusiastic collectors of the latter two maintain interesting websites. The history of the slide rule is told in a classic work by CAJORI (1909), now available in facsimile form on the web. Graphical calculation methods, including nomography, were developed in France, especially by LALANNE (1846) and D'OCAGNE (1899). They have not attracted the enthusiasm of collectors but, as they were still in regular use into the 1960s, they can be studied in any of the hundreds of books on such techniques written for professional engineers (e.g. LIPKA, 1918, HEWES & SEWARD, 1923, ROSE, 1947).

The work of the design engineer involves both art and science and requires intimate collaboration with many other professions, especially architects, builders, contract lawyers and those concerned with finance and profit. The work of each profession has significant impacts on the work of the others, and many writers have addressed these issues (e.g. GIEDION, 1954, BOWLEY, 1966, STRIKE, 1991, PETERS, 1981 & 1991, NISBET, 1993 & 1997 and POWELL, 1996.

National histories of construction

History is often a highly nationalistic activity, though this is probably less pronounced in engineering history than in economic, social, political and military history. Many writers have a tendency to concentrate on those aspects of engineering history that have featured most prominently in their own country's development. This may, of course, simply reflect an author's linguistic skills and the stock of even the best libraries in all countries. The following are some examples of books providing particular insight into the history of building engineering in individual countries:

France

ACHE (1970), STEINER (1978), PICON (1992);

Germany

MISLIN (2002);

Italy

GUENZI (1981), CASCIATO (1990), DELLE TORRE (1994);

Russia

Many books referred to in FEDEROV (2006);

U.K.

COLLINS (1983);

U.S.A.

CONDIT (1960, 1961, and 1968), PETERSON (1976), GRAYSON (1993), BERGERON et al. (2000).

Biographies of eminent engineers

There are relatively few engineers and engineering scientists whose work related to buildings has attracted the attention of biographers. Before the twentieth century, engineers and scientists from many disciplines contributed to building design and their biographies are often to be found in other disciplines. From ancient times until the eighteenth century, most engineers were, for at least part of their career, military engineers concerned equally with fortifications, weapons, earthworks and hydraulic engineering; they generally devoted their energies to civil construction only in times of peace (VASARI 1550, GILLE 1966, PARSONS 1939, HARVEY 1972). Since the eighteenth century, many engineers engaged on buildings were also civil or mechanical engineers which makes their biographies easier to find (e.g. SMILES 1874-1900 and SKEMPTON, 2002). A few modern collections of building engineers' biographies have been published (e.g. HARTIG 1966, STIGLAT 2003). Several of the books dealing with the history of building science and engineering also contain short biographies of the key individuals (e.g. TIMOSHENKO 1953, DONALDSON & NAGENGAST 1994 and KURRER 2002). Biographies of many engineers and engineering scientists (from about 800BC), reporting their mathematical achievements, can be found on the excellent website of the mathematics department of St Andrews University in Scotland (MACTUTOR).

The following list indicates sources of biographical material about some of the most eminent building design engineers and some engineering scientists.

Apollodorus of Damascus – LEON 1961; HEILMEYER 1975; MACDONALD 1982; ANDERSON 1997

Ove Arup – ICE 1995

Bernardino Baldi – BECCHI 2004

Bogardus – BANNISTER 1956 & 1957

Filippo Brunelleschi – VASARI 1550; PASQUALE 2002; KING 2000

Felix Candela – FABER 1963

Willis Carrier – INGLIS 1952

Matthew Clark – FEDEROV 1992

Charlees Auguste Coulomb – GILLMOOR 1971; HEYMAN 1972

Karl Culmann – MAURER 1998

Eladio Dieste – PEDRESCHI 2001, ANDERSON 2004

Franz Dischinger – GÜNSCHEL 1966, SPECHT 1987

Gustave Eiffel – LEMOINE 1986

William Fairbairn – POLE 1877

Ulrich Finsterwalder – GÜNSCHEL 1966

Francesco di Giorgio – GILLE 1966

Robert Hooke – JARDINE 2003; ADDIS 2002

Anthony Hunt – MACDONALD 2000

Heinz Isler – CHILTON 2000

Fazlur Khan – ALI 2001

Leonardo – PARSONS 1939; TRUESDELL 1968; GILLE 1966; MISLIN 1997

Robert Maillart – BILL 1949, GÜNSCHEL 1966, BILLINGTON 1979,

Pier Luigi Nervi – NERVI 1956; DESIDERI *et al.* 1979

Frei Otto – ROLAND 1965, NERDINGER 2005

Jean Prouvé – SULZER 1999, 2000, 2002

W.J.M. Rankine – CHANNELL 1975

David Reid – STURROCK & LAWSON-SMITH 2006

Peter Rice – RICE 1994, BROWN 2001

Edwin O. Sachs – WILMORE 1998

Felix Samuely – HIGGS 1960

Jörg Schlaich – HOLGATE 1997

John Smeaton – SKEMPTON 1981

William Strutt – FITTON & WADSWORTH 1958

Vladimir Suchov – GRAEFE 1990c

Karl Terzaghi – BJERRUM et al.1960; GOODMAN 1999

Eduardo Torroja – TORROJA 1958

Wilhelm von Traitteur – FEDEROV 1992

Thomas Tredgold – BOOTH 1979/80

Vauban – BLANCHARD 1996

Owen Williams – COTTAM 1986, YEOMANS & COTTAM 2001

Christopher Wren – HAMILTON 1933/34; ADDIS 2002

Historical periods

Ancient times (before 500)

A number of works on military engineering have survived from Graeco-Rroman times, notably Heron and Philon (MARSDEN, 1971) and VITRUVIUS (c.25BC), which are often informative and tantalising in equal measure because of what they do not contain. Of the many dozens of works on building engineering and architecture we know were written in ancient times, the only one that survives is that of Vitruvius. He provides us with invaluable insight not only into the Roman building and engineering practices of his own day, but the work of Greek builders, architects and scientists from four or five centuries earlier. However, translations of his Latin text into modern languages have been done mainly by non-engineers whose lack of engineering understanding is often a source of confusion (rare exceptions are the translations into French by the engineer Jean Rondelet in 1812-17, and architect Auguste Choisy (CHOISY, 1909). There are many glimpses of the activity of the Roman construction industry in the writings of Roman historians, especially the elder and younger Pliny. There are many good general studies of Greek and Roman science and technology (e.g. WHITE, 1984) though these do not usually deal well with engineering and the issues that faced engineering designers. For this, the best sources are histories written by engineers (SPRAGUE DE CAMP, 1963, STRAUB, 1952) or by historians who have made studies of engineering (MARSDEN, 1971a & b, LANDELS, 2000).

Although now superseded by more recent scholarship, the classic nineteenth-century studies of building in ancient times by Choisy and Durm are still valuable sources of information and ideas (CHOISY, 1873, 1883 & 1904; DURM, 1892 & 1905). The best general study of the problems facing the designer of buildings in Classical Greek times is COULTON (1977) and there are many detailed studies of the design and construction of prominent buildings such as the Parthenon. The Roman building industry is well described in ADAM (1994) and TAYLOR (2003) and many books on Roman architecture deal with issues facing building designers, whether we think of them as engineers or architects (e.g. ANDERSON, 1997, MACDONALD, 1982, WARD-PERKINS, 1981, WHEELER, 1964 and WILSON-JONES, 2000). Particularly rewarding is Janet DeLaine’s study of the Baths of the Emperor Caracalla (DELAINE, 1997) which explores nearly every aspect of the construction of this remarkable building. Although there are studies of the work of Trajan’s chief engineer Apollodorus of Damascus (LEON, 1961; HEILMEYER, 1975; MACDONALD, 1982; ANDERSON, 1997), we still await a large-scale study of his enormous contribution to structural engineering history.

The mediaeval period (500-1400)

From the early mediaeval period, the church of Hagia Sophia in Constantinople (mid-sixth century) has been the object of much attention (e.g. MAINSTONE, 1988). The period between about 500 and 1000 is still often referred to as the ‘dark ages’, as if nothing of interest happened between the decline of the Roman empire and ‘Gothic’ cathedrals. In fact, a great deal was happening and the misnomer is gradually being eroded by good studies of technological and engineering progress, both in general works (e.g. SINGER, 1954-58) and specialist studies such as the seminal work by Lynn WHITE (1962). From this period, the architectural and engineering significance of the cathedral at Aachen (early-ninth century) has attracted the attention of many authors (e.g. MISLIN 1997).

Although no written equivalent of Vitruvius' book is known from the mediaeval period, a great many illustrations from around 1100 onwards have survived. These include illustrations in manuscripts, a number of designs for fortifications, castles and cathedrals. The skills used in constructing magnificent masonry cathedrals were generally developed first for the construction of fortifications and castles. Throughout this period (and arguably, throughout history) large-scale civic and religious construction took place only when construction engineers were not occupied on military projects (MESQUI 1995).

Mediaeval cathedrals have probably received more attention than any other type of building (for discussion of this phenomenon, see SMITH, 2001-02). For this period one relatively complete sketchbook has survived, that of Villard de Honnecourt dating from around 1200, which is now available in facsimile version on the web and has been the object of much analysis and comment (BOWIE 1959). In the late mediaeval period (overlapping with the Renaissance) there appeared the first manuals on geometry and its use by masons in designing cathedrals (ACKERMAN 1949, SHELBY 1972 & 1977, VICTOR 1979, SHELBY & MARK 1979, SANABRIA 1982 and HUERTA 2004).

The classic studies of cathedrals dealing with general design and construction issues are SIMSON (1956), FRANKL (1960), HARVEY (1972 & 1975) and JAMES (1982). These are complemented by many excellent books ranging from those intended for children (e.g. MACAULAY, 1974) and general interest readers (e.g. ERLANDE-BRANDENBURG, 1995, GIMPEL 1983) to mainstream works of scholarship (e.g. WILLIS, 1842, FITCHEN, 1961 & 1986, BINDING & NUßBAUM, 1978, COENEN, 1990, CONRAD, 1990, BINDING, 1993, COURTENAY, 1997,). Studies generally approach the subject in two ways – studies by modern engineers of how cathedrals work as engineering structures and historical studies of contemporary ideas about their design and construction (SMITH, 2001-02). Most general histories of building and engineering provide a good overview the structural engineering of cathedrals (e.g. STRAUB, 1952, COWAN, 1977, MARK, 1994, JESBERG, 1996 & MISLIN, 1997). Comprehensive analytical studies have been undertaken by HART 1965, ACLAND 1972, HEYMAN (1995 & 1996) and HUERTA (2004). Structural design methods for masonry structures have also been discussed by ADDIS (1990 & 1999) and MAINSTONE (1968, 1988 & 1999).

The Renaissance (1400-1630)

It is during the Renaissance that we find the first modern manuals on engineering matters – mainly military engineering and, until the birth of moveable type printing in the 1450s, in manuscript form only. Two of the earliest were Conrad KYESER (c.1405) and FRANCESCO DI GIORGIO MARTINI (1470s). Many pages of Leonardo's copious notebooks (1470s-1520s) have been published in facsimile versions, especially his mechanical inventions. The earliest printed works showing a large number of military and non-military devices are AGRICOLA (1556) and ZONCA (1607). These and other works have been well covered by KELLER (1964) and GILLE (1966).

From the early fifteenth century copies of a few drawings by the Florentine engineer and architect Fillipo Brunelleschi have survived and from the year 1485 we have the book on building by the Florentine gentleman architect ALBERTI. We are indebted to VASARI (1550) for biographies of these men and many other Renaissance engineers, architects and artists, though their engineering work, especially their military engineering and architecture, is seldom mentioned either by Vasari or most modern biographers of these 'Renaissance men'.

For a thorough overview of Renaissance engineers and engineering, much of which concerns buildings and civil engineering projects, there is no better work than that of the engineer William Barclay PARSONS (1939). DURM (1914) gives a thorough review of the practical art of building in the Renaissance.

One building achievement from the Renaissance overshadows all others – the dome of Florence cathedral designed and engineered by Brunelleschi in the early 1400s. Its remarkable design and the vivid story of its construction is told in all general histories of building engineering and in more detail by MAINSTONE (1969-70), SAALMAN (1980), KING (2000) and PASQUALE (2002). Several authors have compared Brunelleschi's dome with the equally large dome of St Peter's in Rome (built 1588-1626), designed and constructed by a number of architects and engineers, but in essence by Michelangelo, Della Porta and Domenico Fontana (DURM 1914, COWAN 1977d, MAINSTONE 1999).

In Leonardo's notebooks we find the earliest sketches that indicate a theoretical and generalised understanding of many ideas we now call mechanics or statics. These are covered in some detail by PARSONS (1939), MISLIN (1987) and TRUESDELL (1968). Nevertheless, there is still no comprehensive work collecting together all his sketches and notes concerning civil and building engineering. The pioneering work in the theory of structural behaviour by Bernadino BALDI in the late sixteenth century, published posthumously in 1621, is assessed by BECCHI (2004). TIMOSHENKO (1953) and STRAUB 1952) have discussed the contribution of the other early pioneer of statics, Simon Stevin.

In parallel with the very earliest developments in statics, building designers were developing further the design methods that had been established in the late mediaeval era (SHELBY 1972, SHELBY & MARK 1979, SANABRIA 1982, MAINSTONE 1968, BECCHI & FOCE 2002 and HUERTA 2004).

17th and 18th centuries (1630-1800)

The seventeenth and eighteenth centuries saw the scientific revolution which gave birth to the modern concept of *force* in astronomy and mechanics and paved the way for the modern sciences of statics and strength of materials (GALILEO 1638, STRAUB 1952, TIMOSHENKO 1953, TRUESDELL 1968; KURRER 2002, BECCHI 2004, HUERTA 2004). This work was developed by a great many French scientists, including especially, Coulomb (GILLMOOR 1971, HEYMAN 1972).

The two building designers who first exploited their understanding of mechanics and statics were Christopher Wren and Robert Hooke who, as leading scientists themselves, were well placed to do so (HAMILTON 1933-34, TIMOSHENKO 1953, JARDINE 2003; ADDIS 2002).

The eighteenth century also saw the birth of modern chemistry, thermodynamics and human biology which quickly came to influence building design by identifying the importance of ventilation in preventing the creation and spread of 'foul' and 'miasmic' air leading to discomfort and the spread of diseases in hospitals, prisons, theatres and other public buildings (BRUEGEMANN 1978, BILLINGTON & ROBERTS 1982, TAYLOR 1977, RICHARDSON 1998, STEVENSON 2000, and BRODIE 2002,)

The eighteenth century saw the birth of the profession of civil engineering (including much we now call building engineering) not only in the work of individual engineers such as John Smeaton (SKEMPTON 1981), but also the creation of the first polytechnic colleges devoted to non-military engineering in France and German-speaking countries of continental Europe (PICON 1988 & 1992, PFAMMATTER 1992, KURRER 2002), and the first moves towards the formation of the professional engineering institutions (BUCHANAN 1989).

As the demand for what later were called civil, mechanical and structural engineers grew, so began the appearance of the first text books summarising the knowledge that such engineers needed to know, and the engineering science that provided the intellectual foundation of the new art of engineering (e.g. BÉLIDOR 1729 & 1750-82)

Meanwhile, building construction was beginning to change as new types of buildings began to appear such as theatres (LEACROFT 1984) and factories (TANN 1970, FITZGERALD 1988, CALLADINE 1993, MISLIN 2002), and the new construction material – cast iron – made its impact on buildings (BANNISTER, 1950, SKEMPTON & JOHNSON, 1952, FITZGERALD, 1988 and SUTHERLAND, 1997).

19th century (1800-1920)

During the first half of the nineteenth century engineers in every field of civil and building engineering learned and consolidated how to make effective use of mathematics and various branches of science. They learned how to reduce the quantities of materials they needed, while also increasing the confidence with which they could predict the behaviour and performance of their structures and buildings before construction began. Following the pattern set by Bélidor's first scientific textbooks on engineering (BÉLIDOR 1729 & 1754-80), a number of lecturers at the first continental European engineering polytechnics began publishing books of their own lecture courses, most notably EYTELWEIN (1801) in Berlin and MONGE (1799) RONDELET (1812-17) and NAVIER (1820) in France. The theory of statically-determinate structures (especially roof trusses) and the elastic behaviour of structural elements developed rapidly during this period (TIMOSHENKO 1953, CHARLTON 1982, BENVENUTO 1991, KURRER 2002) and, if anything, gave the impression to many engineers that the gap between 'theory' and 'practice' was widening not narrowing. Rankine helped bridge this gap by redefining the use of the established 'factor of safety' to serve as the means of reconciling precise mathematical predictions with the known variability in the properties and behaviour of real materials and structures (RANKINE 1856 & 1858). This firmly established the role of the design engineer, intermediate between the scientist and the contractor.

As the behaviour of fluids and heat became better understood, so the design of heating, ventilation and water supply began to develop from purely empirical methods in 1800 to methods based on scientific understanding and experimentation by the 1850s (FERGUSON 1976, BRUEGEMANN 1978, BILLINGTON & ROBERTS 1982, DONALDSON & NAGENGAST 1994). Gas lighting was introduced into factories from around 1800 (BILLINGTON & ROBERTS 1982, RUSSELL 1976) and for several decades was used equally as the motive power for forced ventilation (BRUEGEMANN 1978). There still remains much to research in this rich field of building design history and the earliest manuals on the subject are full of interest (for example, HALES 1758, WYMAN 1804, CHABANNES 1818, SYLVESTER 1819, TREDGOLD 1824, INMAN 1836, and REID 1844).

The development of building structures during the first half of the nineteenth century consists largely of the growth and spread of cast and wrought iron as fireproof construction materials, especially in Britain (SKEMPTON & JOHNSON 1952, FITZGERALD 1988, SUTHERLAND 1997), France (LEMOINE 1986, MARREY 1989, LEMOINE & MIMRAM 1995), Russia (FEDEROV 1992, 1996 & 1997) and Germany (MEHRTENS 1903-23, JESBERG 1996, LORENZ & ROHDE 2001, MISLIN 2002). Iron began to be used in the USA in the 1850s for fireproof construction, both for building façades and load-bearing elements (BANNISTER 1956 & 1957, CONDIT 1960, WERMIEL 1993 & 2000, PETERSON 1976). One of the first spectacular structures in cast iron in the USA was the dome of the Capitol, built in the late 1850s in the manner of the iron dome of St Isaac's cathedral in St Petersberg in Russia, constructed in the 1830s (CAMPIOLI 1976, FEDEROV 1996).

It should not be forgotten that during this period concrete was also being established as a construction material both for building foundations (MORDAUNT-CROOK 1965, GUILLERME 1986 & 1995, CHRIMES, 1996) and for a great many houses built of mass concrete (STANLEY 1979). The first significant use of iron reinforcement in concrete was in the 1850s (BROWN 1966, COURCY 1987, SIMONNET 1992, NEWBY 2001).

The late nineteenth century and early twentieth saw the fully scientific approach spread to all aspects of building design. For structures this meant the development of graphical statics (CULMANN 1866, BOW 1873, MAURER 1998) and integrating elastic behaviour into the statical treatment of structures to allow the design of statically indeterminate structures (MEHRTENS 1903-23, TIMOSHENKO 1953, CHARLTON 1982, BENVENUTO 1991, KURRER 2002). For the first time engineers tackled the analysis of genuinely three-dimensional frameworks, shells and tensile structures (FÖPPL 1892, KRAUS & DISCHINGER 1928, GRAEFE 1990c). For heating and ventilation it meant the integration of thermodynamics into design methods (RIETSCHEL 1894, BILLINGTON & ROBERTS 1982). In the 1910s Wallace Sabine introduced the idea of reverberation time into acoustic design (SABINE 1922).

Wrought iron quickly replaced cast iron for the construction of large buildings in the 1850s and 1860s (LEMOINE, 1986, MARREY 1989, THORNE 1999), especially for utilitarian industrial buildings (TANN 1970, MISLIN 1997). Steel made its impact on building construction from the 1880s (SKEMPTON 1959, WERNER 1980), and its greatest impact was in the development of the high-rise commercial buildings in New York and Chicago (CONDIT 1964 et al., LANDAU & CONDIT 1996, FRIEDMAN 1995).

Although reinforced concrete made its first appearance in the 1850s, it had little impact on mainstream building construction until the 1890s when it was taken up quickly in both Europe and America (NEWBY 2001, SUTHERLAND 2001; *France* - SIMONNET 1992; *Germany* - HÄGERMANN, HUBERTI & MÖLL 1962-65 and KRAUS &

DISCHINGER 1928; *UK* - HAMILTON 1956; *USA* – CONDIT 1961 and NEWLON 1976; *Italy* – IORI 2001, LEVI 2002; see also references for concrete, above).

20th century (1920 - today)

The late nineteenth century had seen great progress in experimental physics and chemistry leading, most importantly, to an understanding of the atomic structure of matter. This was of enormous significance for the construction industry as it became possible to explain the mechanical properties of materials and use the scientific experimental approach to improving these properties (TIMOSHENKO 1953, GORDON 1968). Few of the major developments in building construction in the twentieth century would have occurred without this better understanding of materials and the better and more reliable prediction of their structural properties (for example, soils - BJERRUM 1960, GOODMAN 1999; concrete - ABRAMS 1918; steel - HART, HENN & SONNTAG 1985; glass - GORDON 1968). No less significant was how the improved understanding of the properties of materials led to their more efficient and more imaginative use by building designers and contractors (STRIKE 1991, RICE 1994, RICE & DUTTON 1995, ROBBIN 1996, YEOMANS 1997).

The experimental methods developed by scientists in the nineteenth century were soon put to use by engineers to predict the behaviour of full-size structures and buildings using tests conducted on scale models. (See COWAN 1968 and other references cited above under The nature of engineering). This technique led to rapid progress in every field of building engineering and was the essential forerunner of using computers, beginning in the late 1950s, to model the engineering behaviour of buildings.

The gradual introduction of scientific methods and experimental science into the construction industry can be traced through the many research institutes dedicated to building science and engineering that have been established in most countries, either in books (e.g. LEA 1959 & 1971) or, nowadays through these institutes' web sites.

The progress of building construction during the twentieth century can be traced along four, relatively independent lines.

Reinforced concrete has been a favourite material among engineers and architects wanting to create new building forms, especially thin shells and highly sculptural forms reflecting the casting technique by which concrete structures are made (LE CORBUSIER 1923, COLLINS 1958, BANHAM 1986, TORROJA (various), NERVI (various), KRAUS & DISCHINGER 1928, FABER 1963, DESIDERI 1979, CONDIT 1961). The second main strand of development has been the continuing development of high rise buildings (MUJICA, 1930, RANDALL, 1949, CONDIT, 1960, et al., HART, HENN & SONNTAG, 1985, SABBAGH, 1990, WILLIS, 1998, ALI, 2001).

In parallel with relatively conventional building structures, the last century saw a growing interest in structures that shun the rectilinear and orthogonal constraints of framed structures, and clearly work in three-dimensions. As well as many concrete shells there has developed a large family of dramatic structures using tensile cables and membranes suspended from steel struts (ROLAND, 1965, OTTO, 1973, GRAEFE, 1990c, FORSTER, 1994, RICE, 1994, ROBBIN, 1996, BERGER, 1996, HOLGATE, 1997, NERDINGER, 2005).

The fourth main strand of development in the twentieth century was the engineering of the internal environment of buildings and the full control of humidity and temperature in buildings – what we now call air-conditioning. This was achieved by using thermodynamics in design calculations and an experimental approach to testing and improving the effectiveness of installed systems. Many engineers succeeded in these aims (COOPER 1998, ACKERMANN 2002) but none was commercially more successful than Willis Carrier who led the air-conditioning revolution in America. This spread from weaving and other factories in the early 1900s to theatres and cinemas in the 1920s and commercial offices in the 1930s (INGLIS 1952). The rest of the world followed around twenty years later (BANHAM 1969).

Other specialist fields of building engineering, such as fire, façade, earthquake and acoustic engineering, are still too young to have had their histories charted. A few key works have been mentioned above under the discipline headings. Their development can be traced both in the literature written for professionals in their fields and through the professional and research institutes that have been established to promote the disciplines and to encourage research into their technical development.

The technical, professional literature of engineering disciplines is, however, rather unapproachable for the non-professional. A number of authors have written books specifically to convey the nature of the work of the modern engineer in the building industry, with both students and non-engineering professionals such as architects in mind (e.g. DUNSTER 1998, ADDIS 1994 & 2001). There has also been some good analysis of the work of the modern engineer in studies of how the industry progresses (e.g. BOWLEY 1966) and, especially, the relationship between engineer and architect in design buildings (e.g. GIEDION 1954, BUILDING ARTS FORUM 1991, RICE 1994).