

GREAT MODERN STRUCTURES

100 YEARS OF
ENGINEERING
GENIUS

DAVID LITTLEFIELD AND WILL JONES

FOREWORDS BY SARAH BUCK
PRESIDENT OF THE INSTITUTE OF STRUCTURAL ENGINEERS
2007-2008

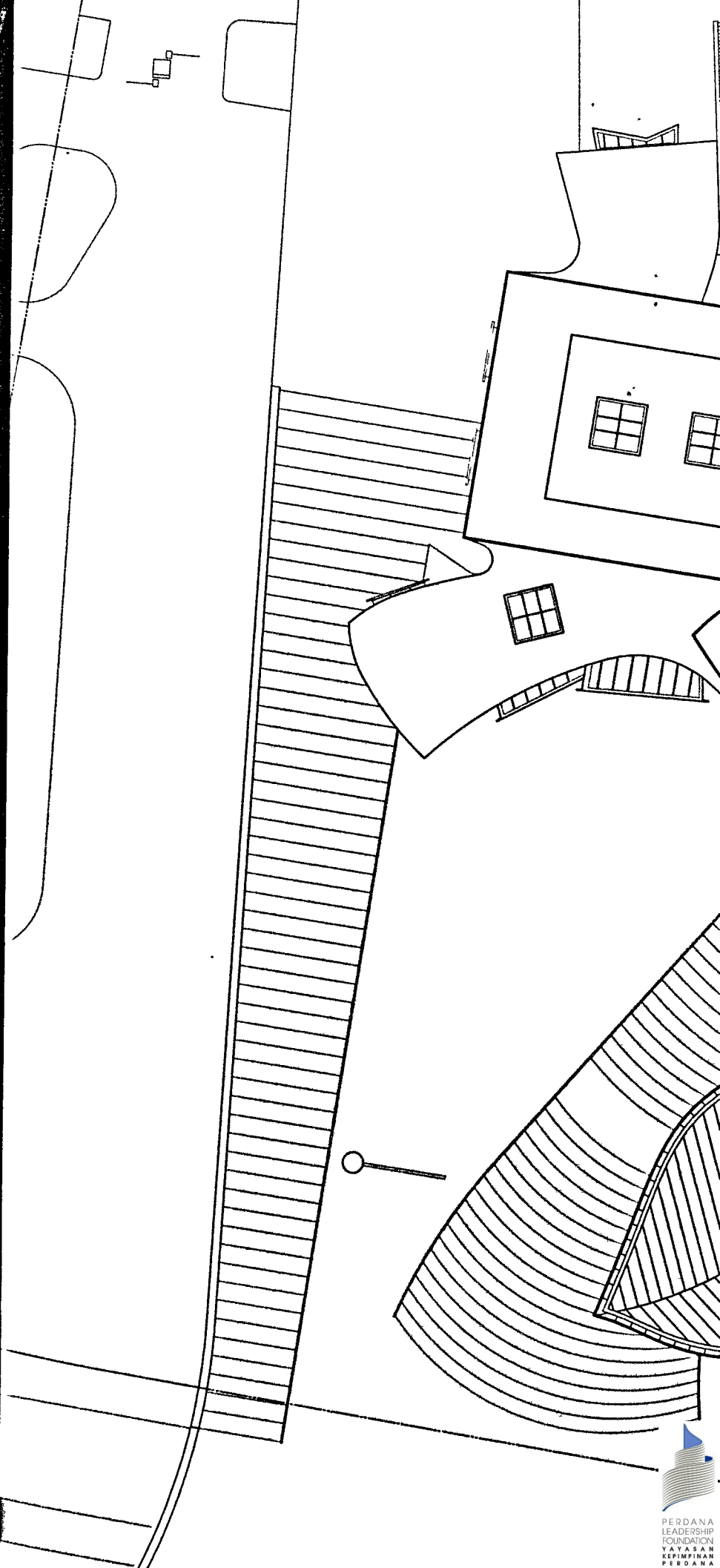
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2007-2009

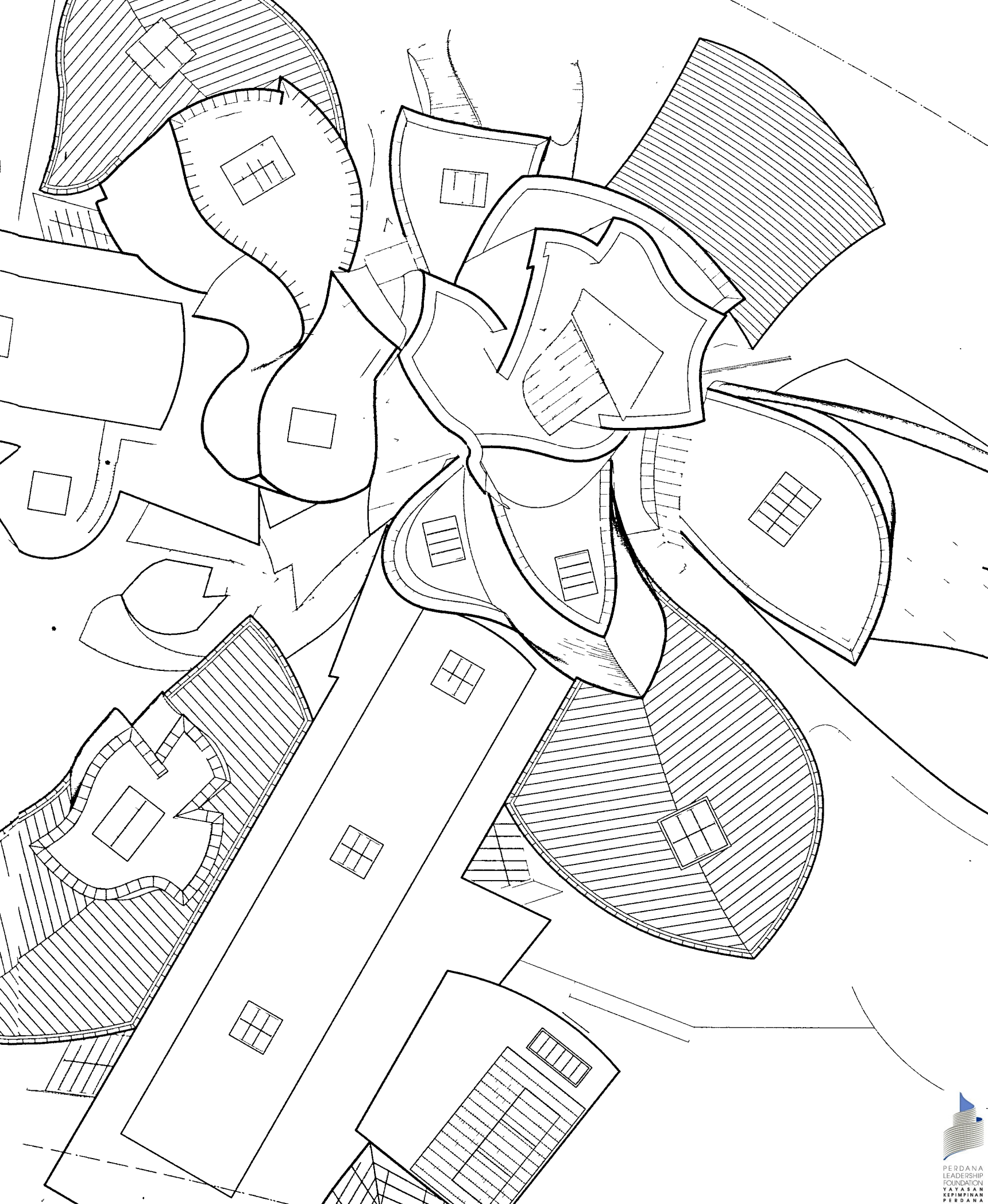
Great Modern Structures profiles more than sixty of the world's most impressive engineered structures built between 1900 and the present day. Many of those featured in this new edition are record breakers within their respective categories – Height, Span, Volume, Surface or Power – while others have more modest but equally significant reasons for inclusion, such as complexity, beauty or sheer inventiveness.

Alongside towers such as the Burj Khalifa in Dubai, bridges ranging from Sydney Harbour in Australia to the Millau Viaduct in southern France, and the contrasting Olympic stadiums of Beijing and London, David Littlefield and Will Jones also discuss less obvious, non-architectural structures that have tested the resourcefulness of designers and builders, for instance the Troll A Gas Platform in the North Sea. For each of these varied entries, they explore the complexity of the design of the featured structure, the challenges faced in its construction, and how it fits into the wider context of the history of architecture and engineering, shedding light on the skill and ingenuity of the engineers, architects and builders involved. From concept to reality, the strengths and qualities of each project are amply illustrated with drawings, plans and striking photographs.

Featuring the work of many major architects and engineers, including such luminaries as Norman Foster, Frank Gehry, Zaha Hadid, Renzo Piano, Richard Rogers, Eero Saarinen, Mies van der Rohe and Frank Lloyd Wright, *Great Modern Structures* is an authoritative yet accessible guide to the made-made wonders of engineering that have come to represent the modern world.

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GREAT MODERN STRUCTURES

NOTE

This book contains over 60 structures, each of which is characterized by dozens of weights, measures, dates and other pieces of data. This book, therefore, contains many hundreds of "facts". We have endeavoured to get them all right.

However, in researching this book it has often been difficult to find sources that agree on what would appear to be simple, incontrovertible truths. One would imagine it is relatively easy to find out how tall or long a structure is, or when it was completed, or how much it weighs. But it is not so simple. There can be considerable time lags between the practical completion of a structure, its "fitting out" and its official opening. The height of a building can be measured from ground level, from basement level or from the top of a "plinth"; it can be measured to the altitude of its roof or the tip of its antenna, or merely to the height of the highest inhabited floor. In recording the length of a bridge, do you measure the gap that is spanned or the distance between one end of the structure and the other (for example the anchor points of a suspension structure)? Does the weight of a structure include its foundation or the weight of a building's contents? Surprisingly, it has even been difficult pinning down how many storeys a tall building contains – do the figures include uninhabited levels, such as machinery zones and basement car parks? We have often encountered conflicting "facts" in relation to the simplest of enquiries and it is not unusual to find wholly reliable sources using different data. We have endeavoured, however, to check our facts with as many sources as possible and make a judgment about which are the most reliable or meaningful.

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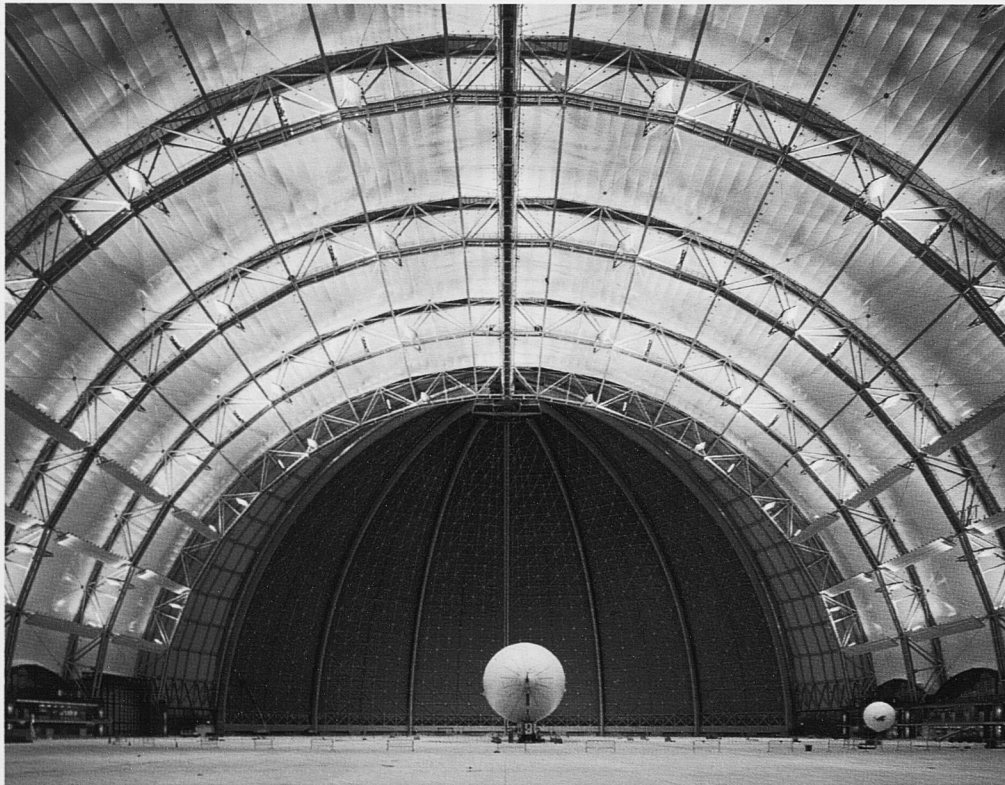
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TUN DR. MAHATHIR MOHAMAD

GREAT MODERN STRUCTURES

100 YEARS OF ENGINEERING GENIUS



DAVID LITTLEFIELD & WILL JONES

PUSTAKA PERDANA



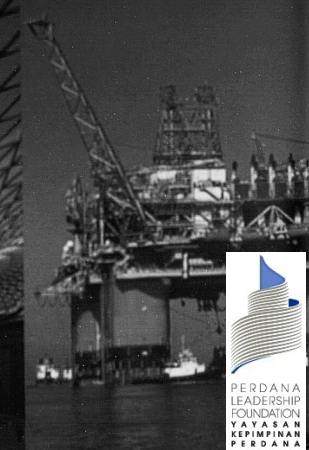
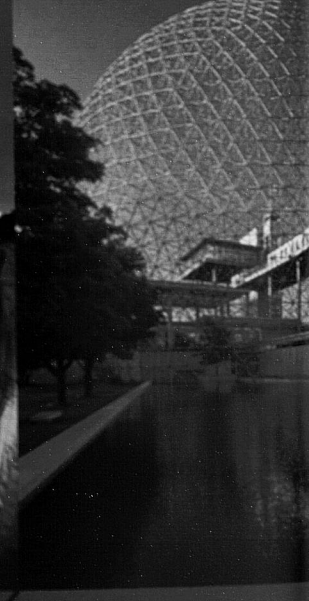
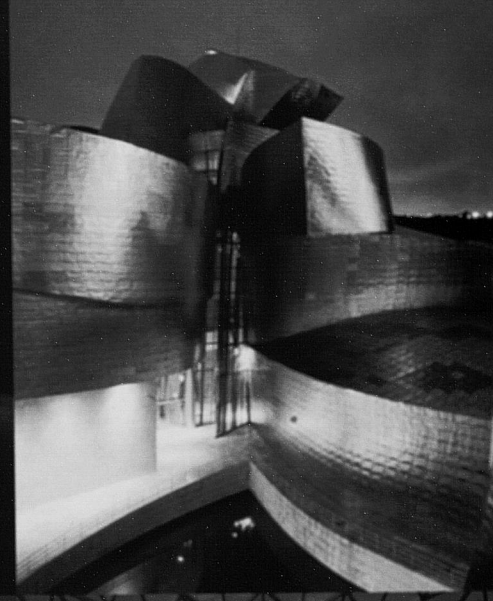
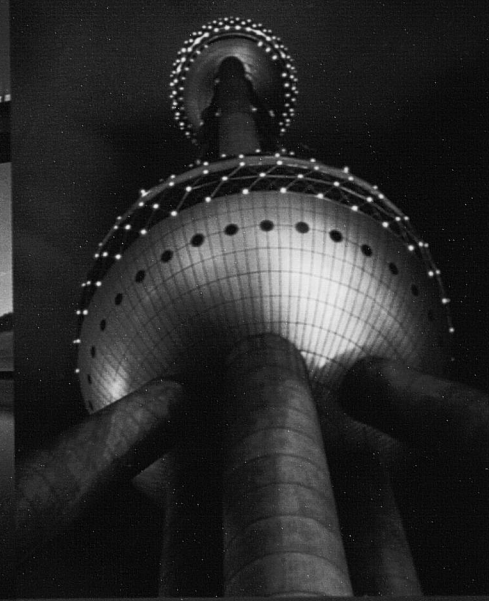
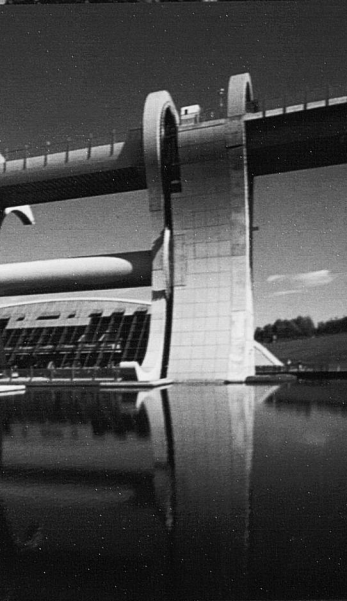
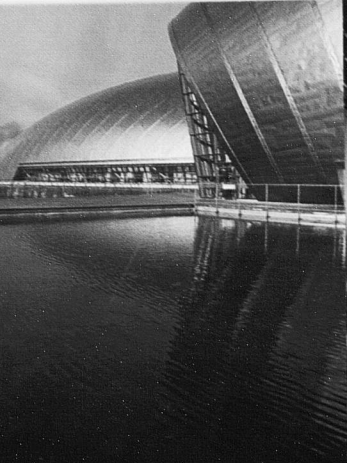
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FOREWORD

SARAH BUCK, ISTRUCTE PRESIDENT 2007–2008

As President of the Institution of Structural Engineers during the celebrations of its centenary year, I feel very privileged to be asked to write a foreword for this magnificent book, which celebrates the best of modern man-made structures throughout the world.

In most people's minds famous locations are defined by their structures. Sometimes these structures are formed by nature, such as Mount Everest, the Grand Canyon or Uluru (Ayers Rock), but more often the allusion is to something man-made. And for perhaps as long as man has been able to write or remember lists, there have been lists of "wonders". These lists indicate an enduring curiosity about remarkable structures. For example, Byzantine mathematician and traveller Philon listed the Seven Wonders of the Ancient World in 150 BC. Even more remarkably, the Great Pyramid was 2,000 years old then, and some 2,000 years later it still impresses. *Great Modern Structures* follows a proud tradition of listing wondrous structures.

David Littlefield and Will Jones have organized the structures under a number of categories: Height, Span, Volume, Surface and Power. In doing so they have recorded how structural engineers have pushed the boundaries of the possible and have developed form and materials to build higher, longer and with more complexity than ever before. This book not only describes and illustrates the structures, but it also explains how key developments made the advances possible. Steel frames enabled buildings to go higher; lifts allowed people to use the buildings; intricate damping systems permitted higher and longer structures to be built in earthquake areas; and finite element analysis and complex graphic packages have enabled very complex shapes to be analysed with confidence.

For many of the illustrated structures, structural engineers showed great ingenuity, beyond innovative design, to enable the construction to take place. For example, the London Eye required careful lifting arrangements while the 850-tonne (940-ton) Gateshead Millennium Bridge was floated up the River Tyne and lifted into place by one of the largest cranes in the world.

Most of the structures required effective teamwork to bring the projects to fruition. The collaboration of the structural engineer and architect is well illustrated

in the Surface section. The complex organic shapes of the Guggenheim in Bilbao and the seemingly random structure of London's 2002 Serpentine Pavilion all required such teamwork. To achieve the vision, careful and complex structural modelling was required to prove the adequacy of the structural form and to ensure that the structures could be built.

A considerable number of the structures take their essence from nature. Structural engineers and architects have been joined on many of the projects by sculptors to assist in the design. The geodesic domes at Eden, the timber gridshell at Downland, the Beijing National Stadium and the Atomium in Brussels all illustrate the influence of nature in design. The combination of these talents has created structures that sit comfortably in the landscape and have a natural feel to them.

Two main elements of modern focus are safety and sustainability. It is sobering to read that in building the Panama Canal, which opened in 1914, an estimated 25,000 people lost their lives. When the Golden Gate Bridge was built in 1937, nets were erected below deck level to catch anyone who should fall. Nineteen were saved in this way, but still a total of 11 died during construction. Safety has now become integrated into the design and construction of modern structures, and these days any loss of life is rightly viewed as unacceptable. Sustainability is also of vital importance as society reviews its collective environmental impact. Water will be harvested and recycled, there will be a waste management system and pollution will be controlled. This is a trend which will continue and is likely to make the biggest impact on construction in the near future.

This book strikes the right balance. There is enough detail for the professional, yet it is written plainly and it is beautifully illustrated for the general audience. Above all it celebrates those visions that have become solid realities which stir the imaginations of all that see them. I can thoroughly recommend this book to the reader.

SARAH BUCK



FOREWORD

SUNAND PRASAD, RIBA PRESIDENT 2007–2009

There is a Russian tradition, probably mythical, whereby at the exact time the first vehicles cross a newly-built bridge, its engineers have to take up position directly underneath it. Mythical or not, the notion vividly captures the visceral thrill of the moment when a structure, entirely reliant on the human mind for its existence, is first fully tested by physical forces. Not all the fascinating structures in this book are about suspending weight in such a way, but all have this in common: they were conceived by extraordinary feats of the imagination, shaped through a fusion of science and art, and constructed with will and daring. That must be one of the reasons for the enduring power of great structures to excite and move us, but perhaps there is something more fundamental. We are children of nature and in awe of its expanse, its might and its beauty. Spans that cross seas, towers higher than clouds, interiors as large as caverns, dams that create new lakes and surfaces with the captivating intricacy and sensuality of leaves and crystals – they make us feel more significant; they suggest that we have the measure of the world.

These structures have more than just a visual presence. Some of them are almost hidden, like the tunnels or the submerged gates of flood defences. Unlike the Øresund Bridge which connects Denmark and Sweden, we cannot actually see the Channel Tunnel which joins France and England from above ground; but we can somehow feel it, and the construction of the tunnel has profoundly altered the geographical relationship between Britain and continental Europe.

These structures move us, but they are also hard-working. Climate change is compelling us to rethink how to obtain the energy we need but for the time being our lifestyles depend on power stations and oil rigs. Skyscrapers, and skyscraper clusters, make it possible for large numbers of people to work in close proximity, generating the intense transaction of knowledge and information on which modern cities rely. Large halls bring people together in another way and bridges and tunnels in yet another.

And often thousands of people have to work together in order to design and build them: engineers, architects, constructors and finance experts. They are triumphs of human collaboration, no less than of knowledge and imagination.

We see in most of these structures a unity of purpose and appearance. Their amazing forms are logical solutions to both their function and their constructional challenges. Sometimes the starting point was economy, which one might think of as being far removed from the achievement of beauty, let alone magnificence.

So many of the examples in this book, such as the Empire State Building, Sydney Opera House and the Bilbao Guggenheim Museum, have become symbols of their cities, in the long tradition of the Acropolis, Taj Mahal and Eiffel Tower. As a boy I built model bridges and cranes with Meccano kits. I was drawn to architecture because it combined art and science to improve people's lives and to expand possibilities. The structures illustrated in these pages suggest that the possibilities are endless.

SUNAND PRASAD

Opposite: Neue Nationalgalerie, Berlin, Germany

Below: Øresund Bridge, Denmark to Sweden



INTRODUCTION

The defining characteristic of human beings is their ability to reshape the world. It is within our power to change the course of mighty rivers, to create vast artificial lakes, to build towers of immense height and to cross large expanses of water without getting our feet wet. This book is a celebration of some of the man-made structures that have come to define the modern world. All of the structures featured demonstrate, in some way, the ingenuity, skill and, very often, the sheer courage of which engineers, architects and builders are capable.

But this is not an exhaustive list. There are enough staggeringly large and beautiful bridges alone to fill a book of this size. The same can be said of tall buildings and even dams. The structures in this book provide a snapshot of what engineers have achieved over the last 100 years, not only in terms of their completed works but also in terms of the techniques that have been developed to achieve their aims. The development of pre-stressed concrete and the steel frame; the invention of computers and the emergence of digital design; the advent of the global positioning system and many other similar advances have all enabled us to build higher, span further and dig deeper than ever before. We can also build increasingly fast because of technological and engineering advances and, as a result, vast structural undertakings like Taiwan's Taipei 101 tower (page 30), the Millau Viaduct (page 104) and even Dubai's Burj Khalifa (page 72) can be delivered in the space of a few years rather than generations.

The structures within the book are split into five chapters – Height, Span, Volume, Surface and Power. The first two are relatively self-explanatory, with only the odd “curve ball” thrown in: a collection of some of the world's tallest structures and a chapter featuring bridges and tunnels. These are the engineering equivalent of “A-list” stars, the headline grabbers. However, the Volume, Surface and Power chapters contain structures that are no less ambitious, and it is here that we can begin to appreciate the scope of the engineer's work. From the sheer size of buildings such as the Millennium Dome (page 166) to the complexity of the Osaka Maritime Museum (page 154) and the scale of the Hoover Dam (page 270) or ingenuity of the Falkirk Wheel (page 254), engineers have played a crucial role in every structure.

Another link between all of these structures is that they are all expressions of power in one way or another. They fulfil a social, economic or political need. Some were controversial at the time. Others, like the Three Gorges Dam in China (page 278), are still provoking protest and praise in equal measure. A few of them were built as demonstrations of technological ability, others as expressions of cultural ambition. In all cases, the architects and engineers pushed the boundaries of what was considered possible in order to deliver structures that are simultaneously mesmerizing and highly functional.

A good number of the structures featured here will be familiar to readers. The Pompidou Centre (page 202), for example, the Empire State Building

(page 46) and the London Eye (page 64) – each of these is instantly recognizable because the extraordinary achievement of their creation is lodged deep in the public consciousness. Other structures will be less familiar: the Stanford Linear Accelerator in California (page 276) or the Bodegas Protos winery in Spain (page 128), for example, but we have found a place for them in this book because they are, nonetheless, clever and often unique, ground-breaking structures.

Not every case study within this book is “iconic” – some will never be and others are yet to be completed, after which they may or may not go on to become globally recognized. However, every structure embodies a certain beauty, because of the effectiveness with which it fulfils its particular function. And there is no end to mankind's engineering ambition: before this book is more than a few years old, taller skyscrapers, longer bridges and exciting new “power structures” will be growing before our eyes.

As a species, we are driven to strive for the next step, the as yet unattainable goal. Often people attribute this fierce competitive spirit to sportsmen and women, or business leaders, but take one look at the phenomenal built achievements in the world and you'll see that some of our greatest accomplishments can often be measured in bricks and mortar, steel or concrete.

DAVID LITTLEFIELD AND WILL JONES

Right: Akashi Kaiyō Bridge, Akashi Strait, Japan





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PERGANT



HEIGHT is undoubtedly the defining characteristic of modern structural accomplishment. The ability to span considerable distances or construct large volumes is well established, but the ability to build high with a relatively small “footprint” is a very recent phenomenon. The possibilities of steel framing, enhanced by the advent of the elevator, generated such excitement that an entirely new architectural term was coined – “skyscraper”. Indeed, the first true skyscrapers, such as the towers of 1920s and '30s Manhattan, were of such astonishing dimensions that they are still among tallest structures on the planet. New York’s Empire State Building, built in 1931, still towers over anything in Europe and, although no longer the world’s tallest building, it still retains its iconic position in the popular imagination.



PETRONAS TOWERS KUALA LUMPUR, MALAYSIA

Claiming the accolade “tallest building of the twentieth century”, the Petronas Towers in Kuala Lumpur, Malaysia are considered among the architectural wonders of the modern world. Designed by US architect Cesar Pelli & Associates, who also designed London’s One Canada Square, better known as Canary Wharf Tower, and the World Financial Center in New York, these twin towers are 452 metres (1,483 feet) tall.

The story of their rapid development and frenetic construction highlights the impassioned desire of the East to create architectural history. However, the result is not the gigantic eyesore that it could have been, rather a modern monument demonstrating man’s ability to build both big and beautiful.

Pelli won the commission to design the towers in a competition in 1991, which he and other renowned skyscraper architects were invited to enter. The client, a conglomerate called Kuala Lumpur City Centre Berhad, which incorporated the Petronas corporation, had laid down instructions that the designs had to be “identifiably Malaysian and of world-class standards that the Malaysian people could be proud of”. Pelli’s answer was to design a scheme that envisioned two slim 88-storey towers, each with a 44-storey annex. The towers’ circumference gradually decreases, giving the impression

of two elegant buildings spiralling heavenwards and, cleverly, when viewed from above, the floor pattern is based on an Islamic eight-pointed star—two overlapping squares symbolizing the interlocking of heaven and earth.

Strengthening the Malaysian feel, Pelli specified local materials and designs to adorn the interior of the two towers. However, the winning feature of his competition design may well have been the Skybridge linking the two buildings; this serves to link the towers for evacuation purposes and for day-to-day access of shared facilities, such as the executive dining room and Surau (prayer room). However, according to Eastern philosophy, the enclosed space created between the bridge and the two towers can be seen as a spiritual portal or open doorway to infinity or the future.

Each of the Petronas Towers houses 88 storeys of occupiable space, plus an additional architectural point, to complete the towers’ gradual structural narrowing, before finally a tall spire reaches to 452 metres (1,483 feet) high. In the beginning, there were no plans to upstage the Sears Tower in Chicago (see page 34), then the world’s tallest building at 442 metres (1,450 feet). The original design was 15 metres (49 feet) short of Sears, at 427 metres (1,401 feet). Detailed designs were already well underway when the potential to create the highest building in the world was realized.

Pelli redesigned the building, extending the height of the architectural point and spire. After checking the new design in a wind tunnel to verify its stability, he announced that the race was on for the world’s tallest building. Even after Pelli had completed his designs, the project management team spent eight months figuring out the logistical details, right down to the position of the cranes on the site.

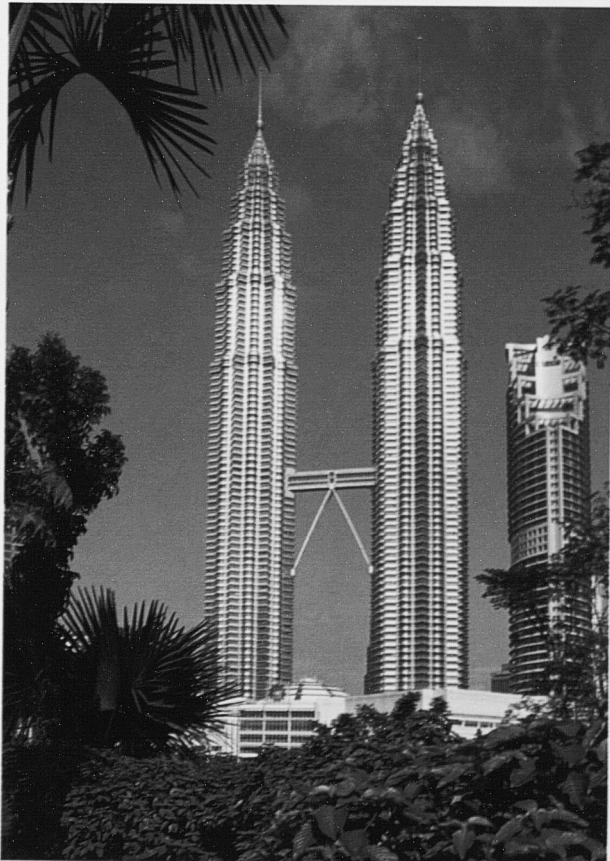
Construction of this mammoth project began in earnest in 1993. Built on soil substrata, the Petronas Towers are anchored to the earth via a forest of deep concrete friction piles that sink up to 120 metres (394 feet) below ground. These piles transfer the load of the buildings out through the ground by means of the cohesion between the soil and the embedded surface of the pile. On top of these is a huge reinforced-concrete pad foundation on which the towers sit.

The towers themselves are also largely concrete, of which each tower contains some 80,000 cubic metres (2.83 million cubic feet). A structure of high-strength reinforced-concrete core walls and columns was chosen because, in Malaysia, local contractors are more familiar and comfortable working with concrete than with steel. The 23-by-23-metre (75-by-75-foot) concrete cores and an outer ring of widely spaced super-columns support the towers. This allows for a slender profile and provides 1,300–2,000 square metres (13,993–21,528 square feet) of column-free space per floor; in total there are 74,322 square metres (800,000 square feet) of office space. Concrete also provides better stability to dampen the sway of the towers in winds, and minimizes vibration.

Construction was fast and furious, with the two towers racing skywards. It was quite literally a race as the construction of each tower had been contracted to separate companies, and each wanted to beat the other to the top. Eventually, Samsung Engineering and Construction, the builders of Tower 2, won the race, despite starting a month behind Tower 1, which was built by Hazama Corporation. Tower 1 had run into problems when surveyors discovered that

Left: Rising higher than any other building in Malaysia, the twin spires of the Petronas Towers dwarf even large skyscrapers nearby. The buildings are just a few metres taller than Chicago’s Sears Tower.

Opposite: Illuminated with floodlights situated on the Skybridge which joins the two towers, the intricate shape of the external facade is highlighted perfectly.







the structure was 25 millimetres (1 inch) off from vertical, and construction had to slow to minutely adjust concrete formwork to realign the tower.

At the forty-first and forty-second floors of the twin towers is the Skybridge. This dramatic 58-metre- (190-foot-) long, 750-tonne (827-ton) structure was added to the design as the towers were developed. Some people think it is a stabilizing element, but in fact not only does it not add stability but its design had to take into account the differential movement of each tower and be able to flex between them.

The Skybridge was built on the ground and hoisted up to its 170-metre- (558-foot-) high location using cranes. After it was lifted into position, the legs which had been installed on the towers were swung down into place, and connected under the bridge. The Skybridge was not a requirement of the building programme, but as the project developed it became an essential part of the overall function of the towers due to its integration into the fire escape evacuation plans. Its structural design is an inverted V-shaped three-pinned arch that supports the bridge in the centre; this arch accommodates all movement in the towers, while remaining equidistant from both of them.

Although completed in 1996, the towers were not officially opened until August 1999. They are now home to many multinational companies, the Petronas Corporation being the main tenant. The public are allowed inside to visit the Skybridge, with a limit of 800 free tickets available each day.

ORIENTAL TOWERS

Building taller than anyone else has always been a magnet for the proudest, richest and most egotistical of people and places. Still relatively young as a country, the USA stamped its mark on the built environment with a horde of super-tall skyscrapers in the first half of the twentieth century. In the 1930s New York saw the rise of the Chrysler Building (320 metres/1,050 feet), Empire State Building (381 metres/1,250 feet) [see page 46] and other tall towers. Later, in the 1960s and '70s, Chicago joined the act, with the John Hancock Tower (344 metres/1,129 feet) and Sears Tower (442 metres/1,450 feet) [see page 34].

More recently, Asia has usurped the West, building towers to rival America's dominance. The Petronas Towers in Malaysia became the world's tallest in 1996 (452 metres/1,483 feet). Hong Kong got in on the act with Two International Finance Center in 2003 (415 metres/1,362 feet), and Taiwan's Taipei 101, at 509 metres (1,670 feet) [see page 30], held the record from 2004 until 2007. Currently there are ambitious projects in China and South Korea, but the Arab world leads the field, with Saudi Arabia's Makkah Abraj Al Bait Hotel (485 metres/1,591 feet), and the United Arab Emirates' gigantic Burj Khalifa tower in Dubai (828 metres/2,717 feet) [see page 72] - which at the time of writing holds the world record by far.

The reasons behind this shift from West to East are blurred. Has the West tired of skyscrapers or does it fear another 9/11? Or are Eastern economies now booming sufficiently to allow such displays of wealth and power? Whatever the reasoning there will always be someone wanting to build the tallest tower in the world.

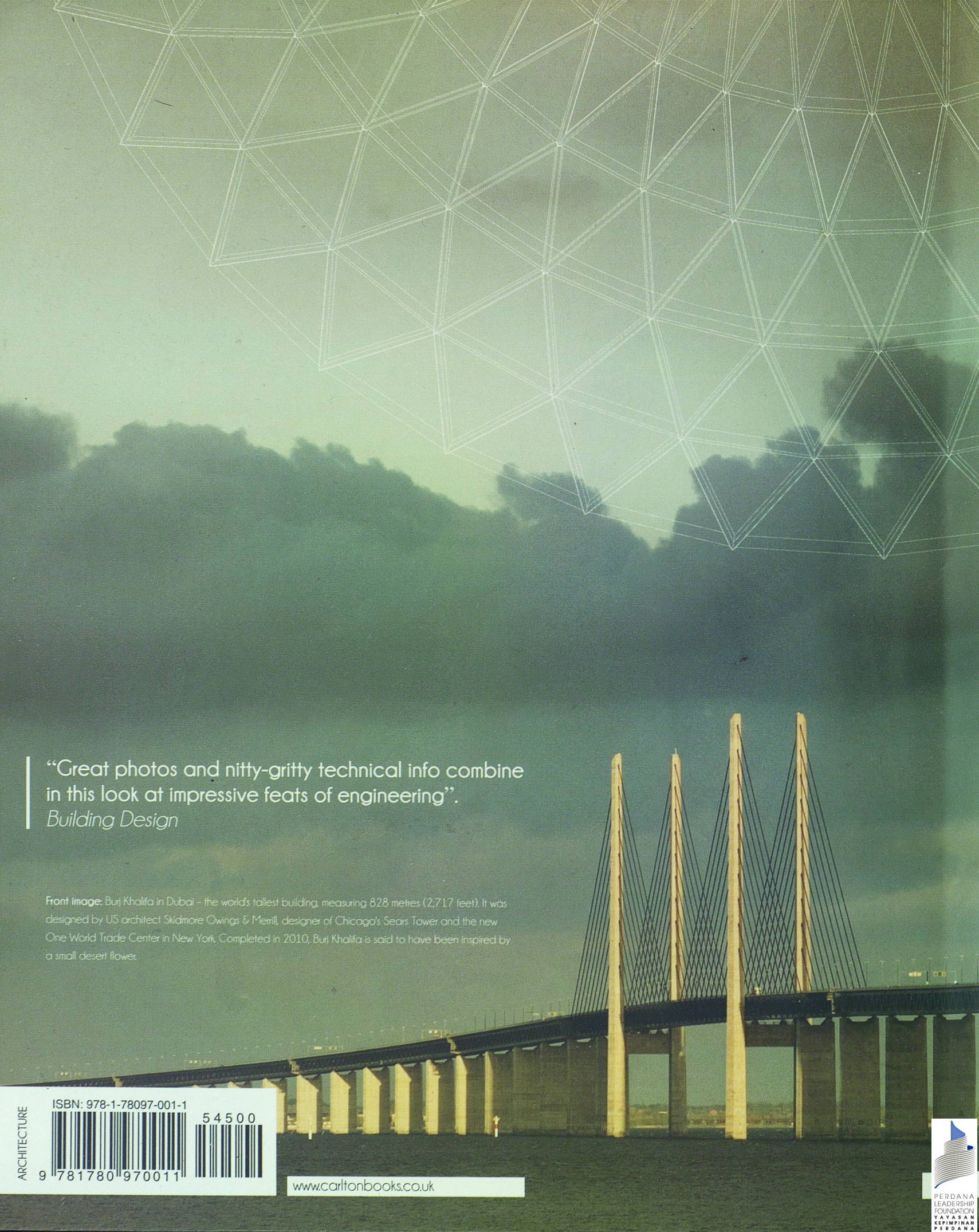
Left: Kuala Lumpur spreads out around the Petronas Towers. Once the tallest building in the world, its towers are built amidst the city blocks on relatively slim but very deep concrete pile foundations.

Opposite: From beneath the entrance canopy, the true majesty of the Petronas Towers can be appreciated against the night sky.



project data

- At 452 metres (1,483 feet) tall measured to the highest point, the Petronas Towers were the tallest buildings in the world at the date of their completion. However, the Sears Tower in Chicago (page 34) still has the highest occupied building floor, and other buildings in the Middle and Far East are steadily outpacing them.
- The Petronas Towers have 32,000 windows.
- The Skybridge weighs 750 tonnes (827 tons) and is 58 metres (190 feet) long. It spans the towers at 170 metres (558 feet) above ground level.
- The construction of the towers cost 1.8 billion Malaysian ringgit (US\$1.2 billion).
- At the peak of construction, there were 7,000 operatives working on the site.
- The 120-metre (394-foot) deep pile foundations are said to be the deepest of their kind in the world.
- Each tower contains 80,000 cubic metres (2.83 million cubic feet) of concrete, 11,000 tonnes (12,125 tons) of steel reinforcing and 7,500 tonnes (8,267 tons) of structural steel beams and trusses.



“Great photos and nitty-gritty technical info combine
in this look at impressive feats of engineering”.

Building Design

Front image: Burj Khalifa in Dubai – the world’s tallest building, measuring 828 metres (2,717 feet). It was designed by US architect Skidmore Owings & Merrill, designer of Chicago’s Sears Tower and the new One World Trade Center in New York. Completed in 2010, Burj Khalifa is said to have been inspired by a small desert flower.

ARCHITECTURE

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