INTRODUCTION

Humans have been building for tens of thousands of years – in fact we spend most of our time inside the structures we've created, from the places we live, study and work, to the bridges and tunnels we use to get around.

Our ancestors started off seeking shelter in caves, then created tents and mud huts. Since then, our structures have evolved into skyscrapers of steel that soar towards the sky and bridges that cross the widest and deepest of rivers.

From a young age, I have been fascinated by how our human-made world came to be. When I first saw the incredibly tall skyscrapers in New York that towered above me, my head filled with questions. What were these ENORMOUS things? How could I climb them? What did they look like from above? When I got home, I used my own miniature cranes, stacking building blocks to recreate what I had seen.

Now, I'm a structural engineer and it's my job to make sure these structures stand up and keep us safe.

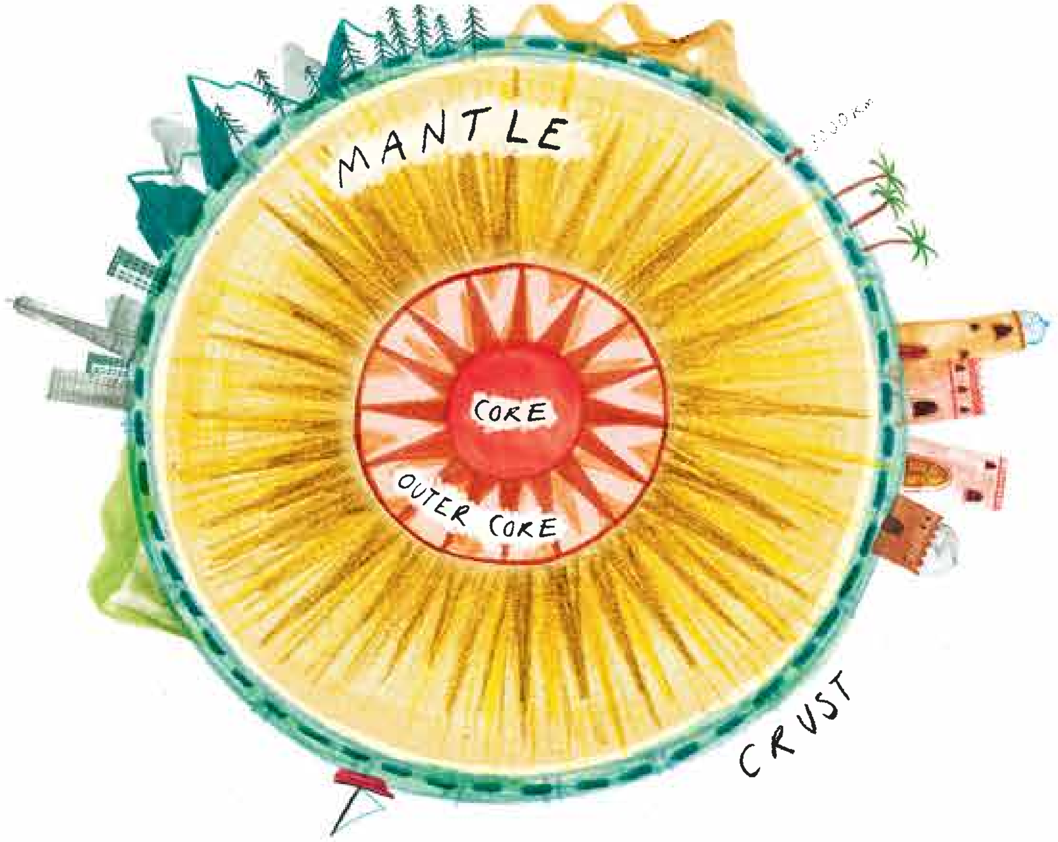
In this book, we'll explore amazing structures across all seven continents. We'll learn about the forces that act on our structures and how we resist them, what materials keep our structures strong and how to make them tall and stable. We'll find out how to build underwater and even on the Moon, and hear stories about some of the amazing engineers who created our world.

Once you read this book, you'll see the world through different eyes – the eyes of an engineer.

HOW TO BUILD FLAT

THE METROPOLITAN CATHEDRAL

Before we build structures, we need to study the ground we're building on. If we don't have strong foundations, buildings can sink or tilt. The Leaning Tower of Pisa in Italy is a famous example of things going wrong because the ground was soft and the structure moved in unexpected ways. So imagine what happens when the city you're building is in a lake.



Digging deep

The Earth is made up of different layers. The top layer, the crust, is about 40 kilometres thick. This is what our continents and the bottom of our oceans are made from. The layer below is called the mantle, which is much thicker – nearly 3,000 kilometres thick. Next comes the outer core, which is so hot that it has melted into a liquid, and finally, in the centre is the solid inner core. If you dug a hole from the surface to the centre of the Earth, it would almost cover the same distance as flying from London, UK, to New Delhi, India.

Different types of soil

Our buildings have foundations that are built in the Earth's crust. Some of the deepest foundations go 150 metres down into the ground, which is only a tiny portion of this layer.

The crust below us is made of different types of soils all around the world. In places like deserts, there is a thick layer of sand on top of rock. Near rivers, the soil is wet and soft because of the water. Some places have gravel, which is a mix of different-sized stones, on top of clay, on top of sand. This makes the construction of every structure different, as each type of soil needs a specific foundation and approach.

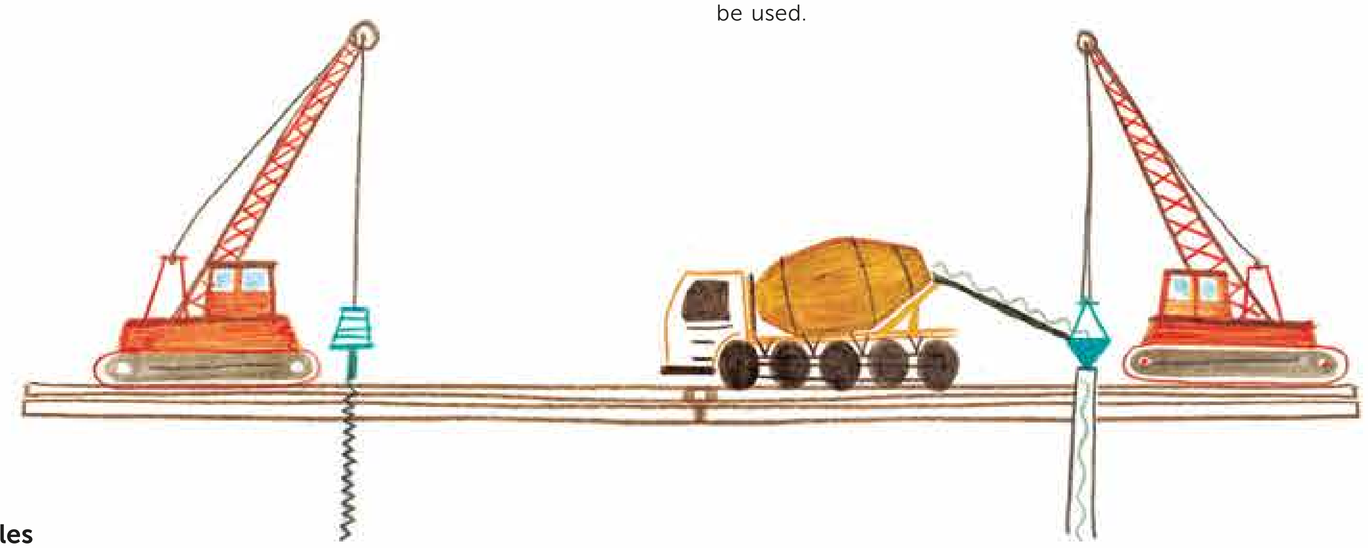
Before we design foundations, we need to know what type of soil we're building on. One way to find out is to use special maps that tell you the history of the ground. Shallow holes are dug to check the soil just below the surface. And to look really far down, we use a borehole, or deep well, where we dig out about a 30-metre-deep section of earth and examine the layers in the ground it reveals.

FOUNDATIONS AND FORCES

Rafts

Rafts are used to build on softer soils. These are thick slabs of concrete or other strong material that float on top of the ground. Like a boat – which spreads our weight across water and stops us sinking – rafts distribute the weight of a structure across the ground.

But if a structure is too heavy or the soil is too soft, rafts can sink. Then, we use piles. These are long columns we put in the ground. One way of constructing piles is to use a piling rig, a machine with a giant corkscrew that can scoop out a long thin hole in the ground. Then this hole is filled with concrete. Piles used to be made from tree trunks, and these days, as an alternative to concrete, steel or timber may be used.

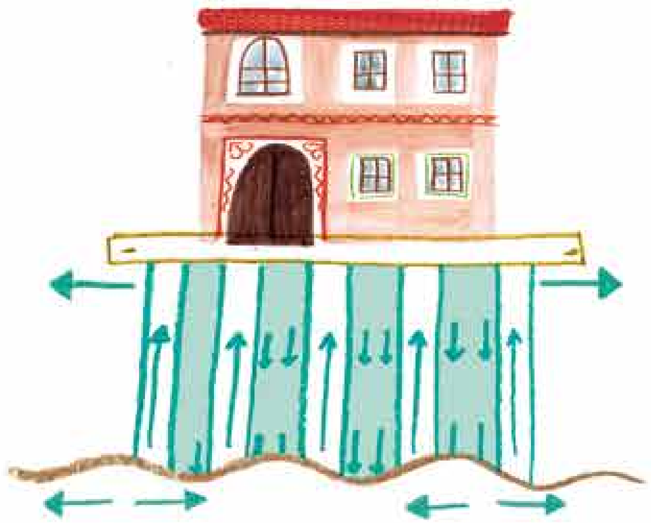


Piles

Piles are clever because they can work in two ways, using friction and bearing. If you try sliding your foot on a wooden floor when you're wearing socks, it's really easy to move around. But if you wear shoes, your foot sticks to the floor and it's tricky to slide. That's because shoes increase the stickiness, or friction, between your foot and the floor. Piles create a friction force between themselves and the soil, which stops the building sinking.

The trick is to make sure there is enough friction!

If the friction force isn't strong enough to hold the building up, then we can dig our piles deep down until we find a very strong layer of sand or rock to support it. Here, the piles push down on this material directly without sinking any deeper. This is called a bearing pile.



A city on a lake

In 1325, the Aztecs, a Central American people, founded their new city, Tenochtitlan, in the middle of Lake Texcoco. They had a vision: their god Huitzilopochtli (God of War and the Sun) said that their new capital city must be built where they found an eagle with a snake in its beak sitting on top of a nopal cactus. The Aztecs roamed Central America for over 250 years until they saw the sign, but the cactus with the eagle and snake was on a small island in the middle of a lake! They built a beautiful city in part of the lake by filling it in with earth and building platforms on timber piles. It was a scenic place with canals and large pyramid temples. Its rulers commanded vast lands.

Mexico City

Spanish invaders captured Tenochtitlan in 1521. They destroyed it and started to build a new city there. They filled in the rest of the lake and built many structures, including a cathedral.

Mexico City in Mexico, built over the ruins of Tenochtitlan, has grown quite a lot since that time, but its centre is still on top of the filled-in lake. The soil here is very wet and weak, so the buildings are sinking, fast. It is like a bowl full of jelly with buildings on top. Over the past 150 years, this area has sunk by more than the height of a three-storey building!

A sinking cathedral

The Metropolitan Cathedral, at the centre of Mexico City, also sank and tilted because of the ground. It was leaning over and parts of it were in danger of collapse. In the 1990s, engineers had to save this structure.

The cathedral sits on top of an old Aztec pyramid and also the filled-in lake. Spanish engineers built a raft foundation to spread the structure's weight over the soil, but the soil was too soft and it started to sink unevenly.

Imagine you have a bowl of sand with a coaster sitting on top. If you push down on one corner of the coaster, you'll see the sand below get squashed and the coaster sit crookedly. To make the coaster flat again, you could do one of two things. You could push down on the opposite corner of the coaster or you could remove some of the sand below the higher corner of the coaster until it straightens out.

Saving the cathedral

If your coaster is a massive cathedral, you can't push down with enough weight to straighten the cathedral! So, ingenious engineers dug 32 huge shafts, like wells, below the foundation. Then they pumped water out, drilled long, thin holes spreading out horizontally from each shaft and removed soil. Where the cathedral had tilted upwards the most, they removed the most soil. This way the cathedral tilted in the opposite direction and became flatter than before.

What next?

There are measurements being taken all the time to check how much it is sinking. The good news is that it is going down very slowly, and not tilting any more. The cathedral has been saved! Everything the engineers learned from saving the Metropolitan Cathedral can be used by future engineers, especially for building in harsh conditions as populations expand and the climate changes.

THE METROPOLITAN CATHEDRAL

A giant, missile-shaped pendulum directly under the central dome shows how far the cathedral has shifted.

Sensors in glass boxes are positioned throughout the cathedral. These send data wirelessly to a lab in Italy where engineers monitor how the structure is behaving.

Temporary steel beams and props supported the cathedral's arches and columns to prevent damage from sudden movements to the structure while the engineers worked on the soil.

32 large, long holes were dug by hand underneath the cathedral, through the foundation and into the ground, so that engineers could access the soil below the cathedral.

Pressure pads monitor how much weight each column is holding. If the weight changes, the structure might be tilting again.

Since the 1990s, the cathedral has been sinking about 60–80 millimetres per year.

1,500 smaller holes were drilled horizontally from these larger shafts so they could remove soil from the ground to level out the cathedral.

Archaeologists discovered an original Aztec pyramid in a tunnel underneath the cathedral.

HOW TO BUILD TALL

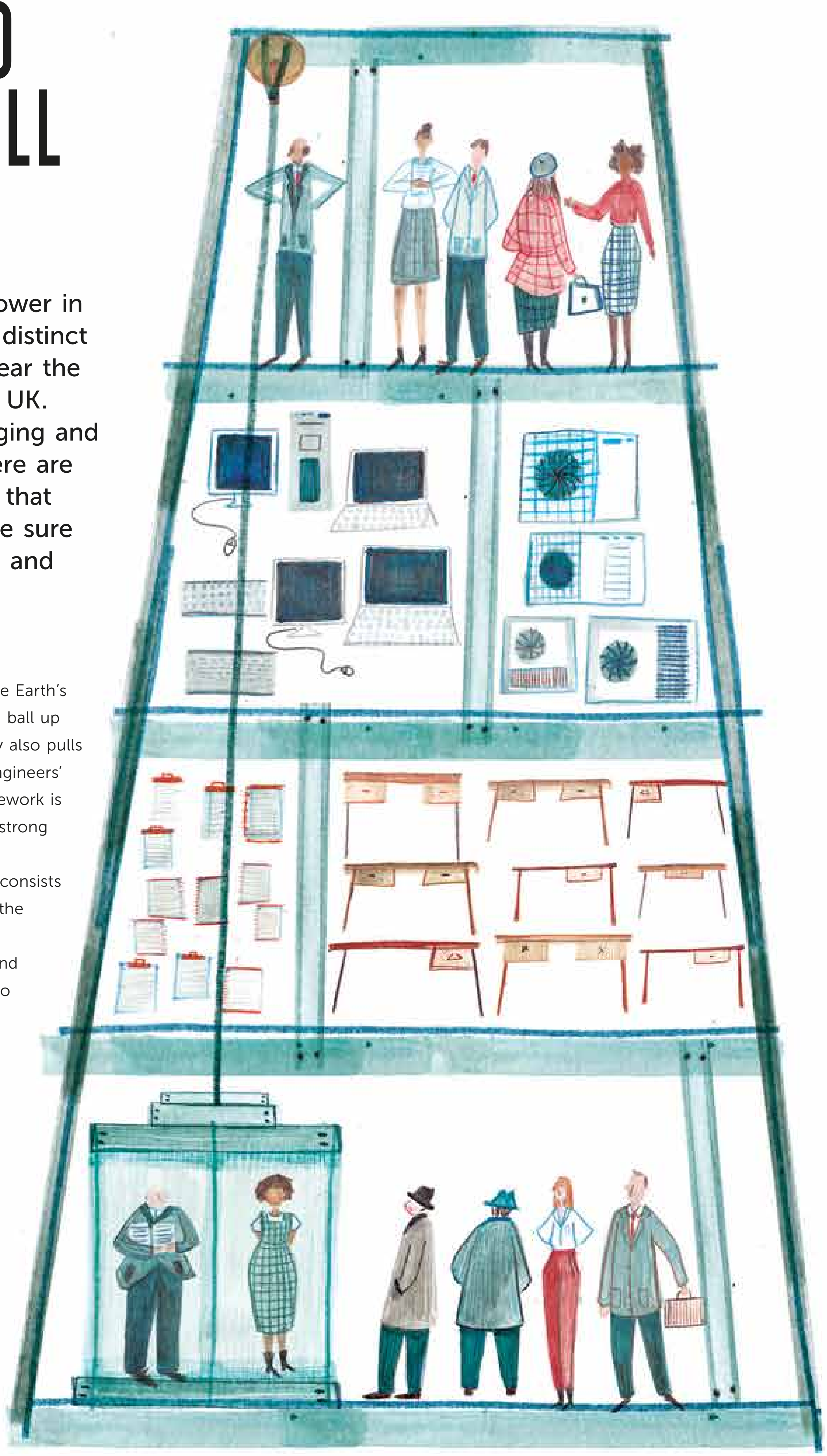
THE SHARD

The Shard is the tallest tower in Western Europe. It has a distinct triangular shape and is near the River Thames in London, UK. Tall buildings are challenging and interesting to design. There are different forces in nature that we need to resist to make sure skyscrapers stay standing and don't collapse.

What makes a building stand?

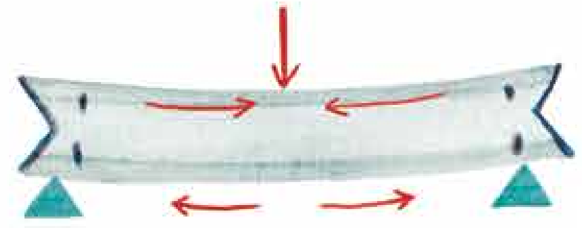
Gravity attracts everything towards the Earth's centre – that's why when we throw a ball up into the air, it falls back down. Gravity also pulls down on all our structures. It's the engineers' job to make sure the structure's framework is made from the right materials and is strong enough to fight this force.

The main framework for buildings consists of horizontal beams, which make up the floors, ceilings and roofs, and vertical columns, which hold up the beams and form walls. In a skyscraper, we have to calculate how much the materials it's made from will weigh, and also how much the stuff inside it will weigh, from lifts and air-conditioning units, books, computers and desks to all the people! We can then do the maths to check that the steel or concrete beams and columns won't get crushed by this weight and that our skyscrapers will reach brilliant heights.



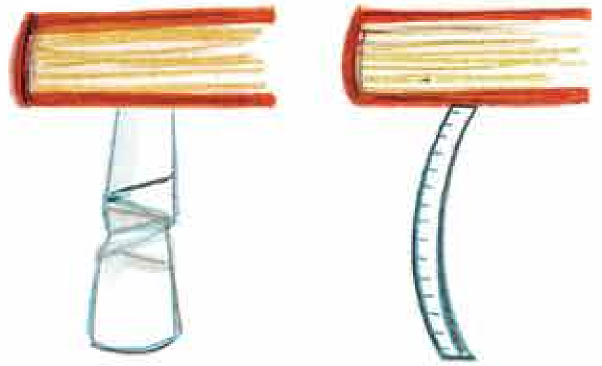
Beams

Imagine holding a carrot lengthwise between your hands and bending the ends up to form a U-shape. The top side gets squashed and the bottom gets pulled apart. Engineers call the squashing force compression and the pulling force tension. When the tension is large enough, the carrot snaps. When the compression is large enough, the top crushes. This is how beams work. Engineers check the forces acting on beams to make sure they won't move too much or break.



Columns

Try these two simple experiments to see how columns can fail. Roll up a piece of paper into a tube and tape it together. Stand it up on a table and put a small, light book on it. You'll see the tube is strong enough to hold the book up: that's what a good column does. But if you put a really heavy book on top, the tube will crush and the book will fall down. That's a bad column, which has failed by crushing. To hold up the heavy book, you would need a much stronger tube. Columns can also fail by bending. If you hold a ruler vertically on a table and push down on it, you will see it bowing. Don't push too hard or your ruler will snap!



Steel for strength

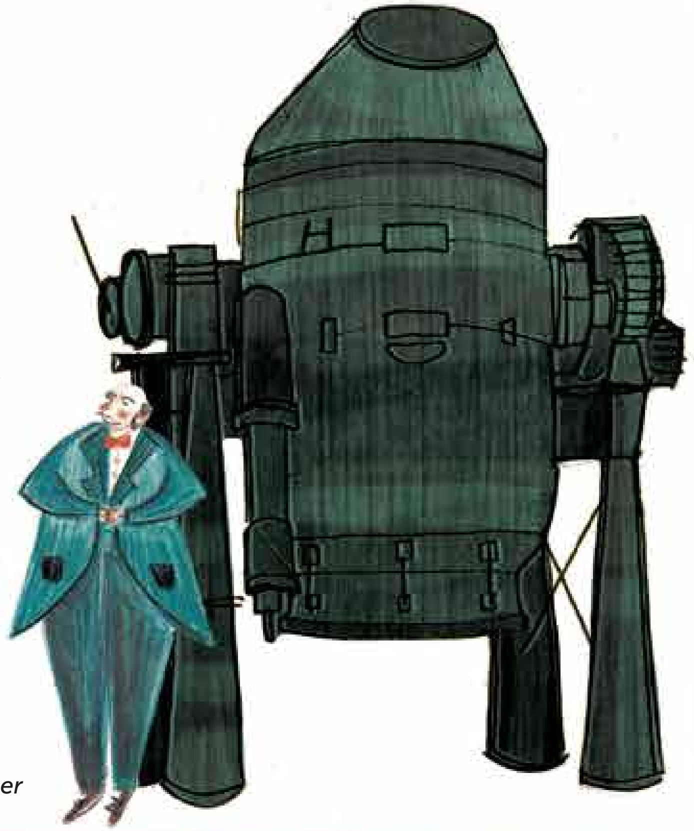
Millions of tiny atoms, arranged in patterns to form crystals, make up metals such as iron and steel. The earliest metal used in big buildings was wrought iron. But this is a relatively soft metal because its crystals slide around a little when pushed and pulled. To make iron stronger, engineers added carbon. The atoms of carbon sat within the iron crystals and stopped them moving as much, and made a metal called steel. When you try to pull steel apart, the crystals don't move as easily, and so it's a stronger material for building. But you need the perfect amount of carbon: too much makes metals brittle, which means they can crack easily.

TRY IT AT HOME: STEEL

Take a large plate and pour some Maltesers chocolates on to it. Roll your palm over them. You'll see that the chocolates move around easily – this is like the crystals of pure iron. Now sprinkle some raisins between the Maltesers and try again. The raisins block the Maltesers from rolling around as easily, which is how carbon atoms make steel stronger.

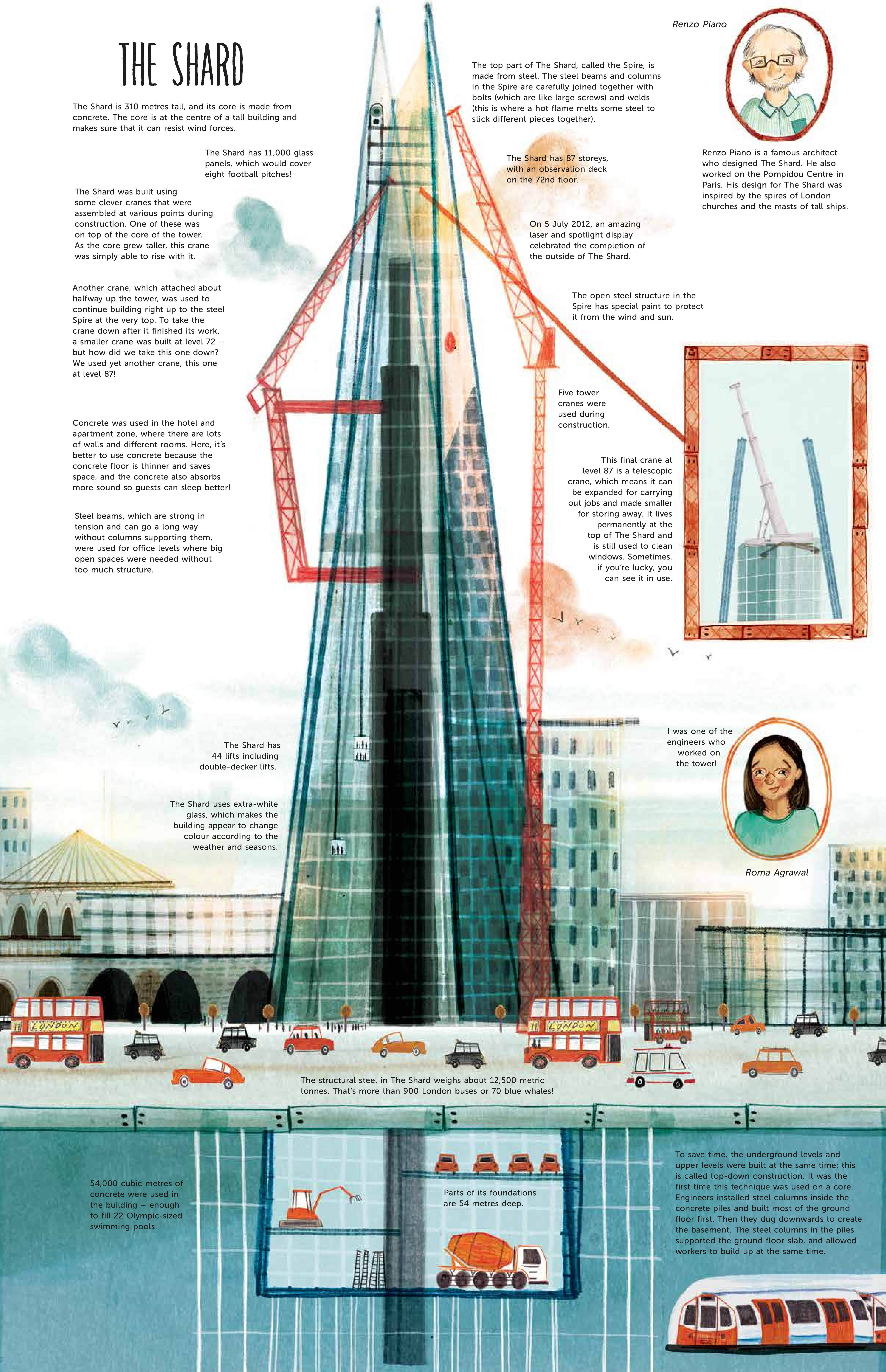
How do we make steel?

To build upward, first we have to gather materials deep inside the earth. Iron mined from the ground has a mix of different impurities, such as carbon, silicon and phosphorus. A British engineer called Henry Bessemer invented a process for making steel cheaply in the 19th century. He put iron pieces into a covered furnace and blew hot air into it. A chemical reaction happened. The oxygen in the air reacted with the carbon in the iron and released huge amounts of heat. This heat took away the impurities and left behind pure iron. Then Bessemer could add in the exact quantity of carbon needed to make the best steel. Since then, steel has been used all over the world to build our most exciting buildings, bridges, stadiums and railways.



Henry Bessemer

THE SHARD



The Shard is 310 metres tall, and its core is made from concrete. The core is at the centre of a tall building and makes sure that it can resist wind forces.

The Shard has 11,000 glass panels, which would cover eight football pitches!

The Shard was built using some clever cranes that were assembled at various points during construction. One of these was on top of the core of the tower. As the core grew taller, this crane was simply able to rise with it.

Another crane, which attached about halfway up the tower, was used to continue building right up to the steel Spire at the very top. To take the crane down after it finished its work, a smaller crane was built at level 72 – but how did we take this one down? We used yet another crane, this one at level 87!

Concrete was used in the hotel and apartment zone, where there are lots of walls and different rooms. Here, it's better to use concrete because the concrete floor is thinner and saves space, and the concrete also absorbs more sound so guests can sleep better!

Steel beams, which are strong in tension and can go a long way without columns supporting them, were used for office levels where big open spaces were needed without too much structure.

The top part of The Shard, called the Spire, is made from steel. The steel beams and columns in the Spire are carefully joined together with bolts (which are like large screws) and welds (this is where a hot flame melts some steel to stick different pieces together).

The Shard has 87 storeys, with an observation deck on the 72nd floor.

On 5 July 2012, an amazing laser and spotlight display celebrated the completion of the outside of The Shard.

The open steel structure in the Spire has special paint to protect it from the wind and sun.

Five tower cranes were used during construction.

This final crane at level 87 is a telescopic crane, which means it can be expanded for carrying out jobs and made smaller for storing away. It lives permanently at the top of The Shard and is still used to clean windows. Sometimes, if you're lucky, you can see it in use.

Renzo Piano

Renzo Piano is a famous architect who designed The Shard. He also worked on the Pompidou Centre in Paris. His design for The Shard was inspired by the spires of London churches and the masts of tall ships.

I was one of the engineers who worked on the tower!

Roma Agrawal

The Shard has 44 lifts including double-decker lifts.

The Shard uses extra-white glass, which makes the building appear to change colour according to the weather and seasons.

The structural steel in The Shard weighs about 12,500 metric tonnes. That's more than 900 London buses or 70 blue whales!

54,000 cubic metres of concrete were used in the building – enough to fill 22 Olympic-sized swimming pools.

Parts of its foundations are 54 metres deep.

To save time, the underground levels and upper levels were built at the same time: this is called top-down construction. It was the first time this technique was used on a core. Engineers installed steel columns inside the concrete piles and built most of the ground floor first. Then they dug downwards to create the basement. The steel columns in the piles supported the ground floor slab, and allowed workers to build up at the same time.