The Institution of StructuralEngineers

Essential Knowledge Series

Essential Knowledge Text 1

Introduction: Part 1 – Structure is everywhere!

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Contents

Synopsis

This text introduces the universal role of structures in our world. It explains the complex thought processes that are at play in the act of 'structural design'. It highlights the challenges and rewards of design synthesis.

1.

Structure in the universe of things

Here, the universal role of structures in our world is identifed.

Those with the good fortune to be familiar with particle physics and cosmology will already know that the universe contains natural structures which demonstrate a magnificent range of scale and complexity — from the Higgs Boson at one end, to giant galaxy clusters held in the grip of dark matter and dark energy fields at the other. At hyper-scales we are in the realm of astrophysicists; at super-small, it is genetics and nanotechnology — where there is great overlap between natural and man-made structures, and between engineering technology and the life sciences.

The working fabric of most structural engineers sits smack in the middle of this range, woven from delicately balanced pieces the size of an earring, up to towers and bridges spanning a few kilometres. This story includes many innovative structures and structural devices (buildings) needed to moderate the external environment; mankind has perfected the art and science of structural engineering in constructing a habitat throughout history. Happily, this offers plenty of scope for any one lifetime, and with a training in logic and creativity, a good structural engineer has a set of tools which may be freely adapted to work right across the profession or to specialize in one field.

The structures of the universe and the natural environment are not simply our backcloth. Rather they offer us a frame of experience, often setting an example, providing the physical parameters within which engineers practice their art. Although the benefits we seek may be great, Nature's relationship to us is not benign. It sets us a challenging context and is a demanding collaborator. In this collaboration structural engineers are vital intermediaries between Man and the natural world, interpreting it and responding to the underlying principles which govern it — a role originally and elegantly described by Thomas Tredgold as "*the art of directing the great sources of power in Nature for the use and convenience of Man*". Indeed, Tredgold's sentiments formed the basis for The Institution of Civil Engineers' 1828 charter[1.1].

References

1.1 The Institution of Civil Engineers (2016) *Royal Charter, By-laws, Regulations and Rules* [online] Available at: www.ice.org.uk/about-us/who-runs-ice/royal-charter (Accessed: 22 February 2016)

What triggers a structural project?

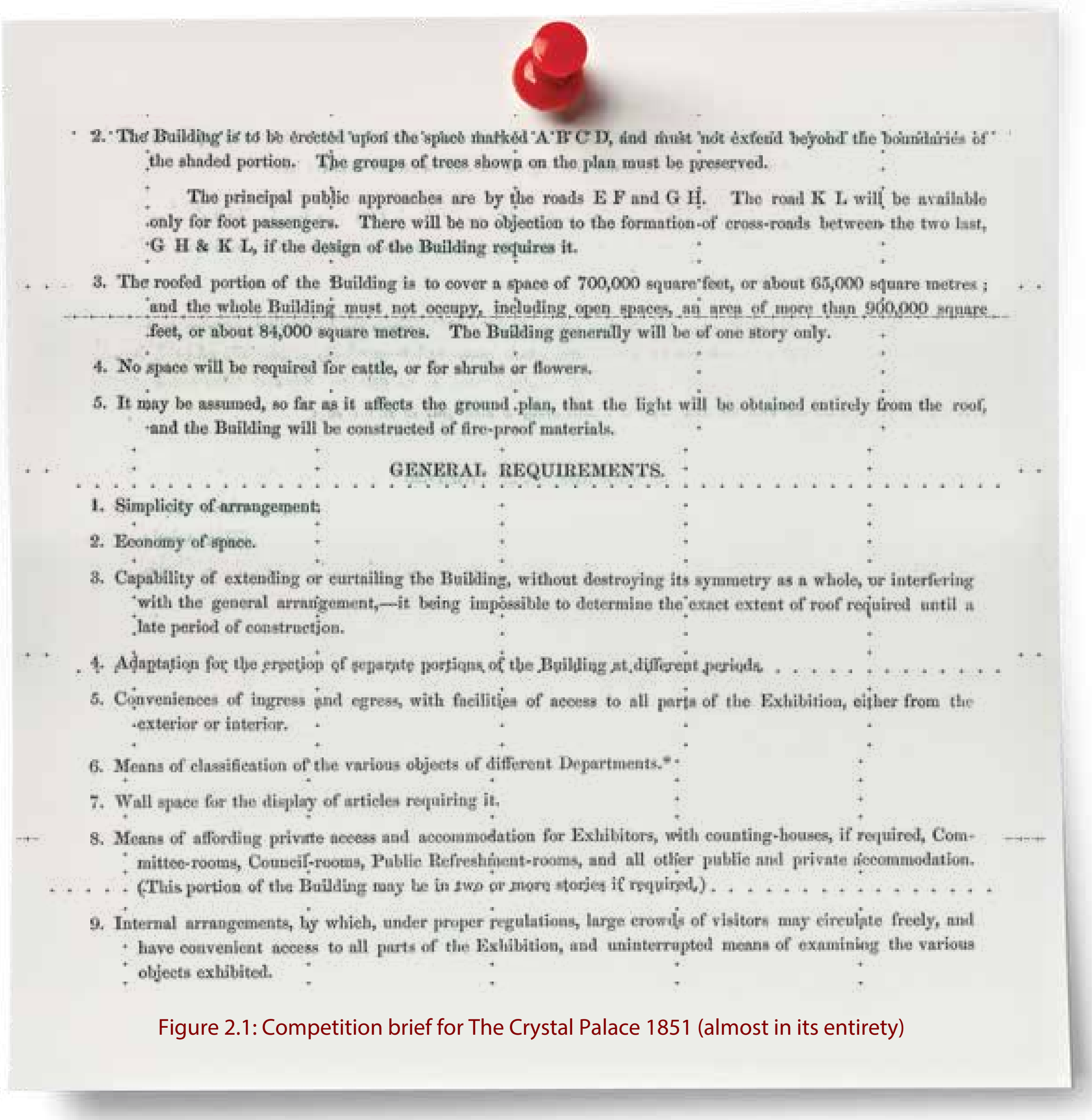
By the end of this section, the reader will have understood the complex thought processes that are at play in ‘structural design’.

2.

2.1 Introduction

In good structural engineering, it is rare to see people wandering around the streets with an armful of I-beams, saying “I wonder what I can use these for?”. Forcing a problem to fit a solution is surprisingly daft and surprisingly common. It is far better for the intelligent engineer to work out if and when they should call for a beam (or any other engineering technique, artefact or tool) once there is a purpose for which (paraphrasing Tredgold) such a beam can usefully and conveniently be directed. Better to realise that a decent engineer is a responsive person, a deductive mind, someone who initially considers the wider context and core purpose of a project by taking an interest in the underlying need; the ‘Why’ of a project, usually captured in the brief. Not only does this echo the driving forces behind successful evolution, fitting the structure to its environment rather than the other way around, but it’s much more targeted in the use of resources.

A project brief isn’t sacrosanct, and it’s worth remembering it has been prepared not by gods but by human beings. Nonetheless the brief is a good starting point and can lead to fabulous results. For example, the revolutionary structure of The Crystal Palace (1851) came out of an initial, beautiful brief (Figure 2.1) of only a few sentences, trusting the engineer to respond. Paxton did respond and the rest is history.



2. The Building is to be erected upon the space marked A B C D, and must not extend beyond the boundaries of the shaded portion. The groups of trees shown on the plan must be preserved.

The principal public approaches are by the roads E F and G H. The road K L will be available only for foot passengers. There will be no objection to the formation of cross-roads between the two last, G H & K L, if the design of the Building requires it.

3. The roofed portion of the Building is to cover a space of 700,000 square feet, or about 65,000 square metres; and the whole Building must not occupy, including open spaces, an area of more than 900,000 square feet, or about 84,000 square metres. The Building generally will be of one story only.

4. No space will be required for cattle, or for shrubs or flowers.

5. It may be assumed, so far as it affects the ground plan, that the light will be obtained entirely from the roof, and the Building will be constructed of fire-proof materials.

GENERAL REQUIREMENTS.

1. Simplicity of arrangement.

2. Economy of space.

3. Capability of extending or curtailing the Building, without destroying its symmetry as a whole, or interfering with the general arrangement,—it being impossible to determine the exact extent of roof required until a late period of construction.

4. Adaptation for the erection of separate portions of the Building at different periods.

5. Conveniences of ingress and egress, with facilities of access to all parts of the Exhibition, either from the exterior or interior.

6. Means of classification of the various objects of different Departments.*

7. Wall space for the display of articles requiring it.

8. Means of affording private access and accommodation for Exhibitors, with counting-houses, if required, Committee-rooms, Council-rooms, Public Refreshment-rooms, and all other public and private accommodation. (This portion of the Building may be in two or more stories if required.)

9. Internal arrangements, by which, under proper regulations, large crowds of visitors may circulate freely, and have convenient access to all parts of the Exhibition, and uninterrupted means of examining the various objects exhibited.

Figure 2.1: Competition brief for The Crystal Palace 1851 (almost in its entirety)

Nowadays it is more common to have a page or two of aspirational waffle married to several hundred pages specifying generic requirements for the project in rather pitiless detail. Such a heavy brief often provokes a head-scratching search for the key which unlocks everything, but it usually does nothing of the kind, saying more about a client's last project than the present one. And of course, no brief can actually tell an engineer what structure to design. Briefs are by their nature living documents that evolve with the projects and which can be influenced by the engineer. Yet any brief is a worthwhile stimulant, something to cut against, something to bash into shape as the project itself springs into life. A creative engineer is right in the thick of the action, bringing context and insight to a project, turning the dry brief into a physical reality. And creative insight only comes slowly as the design emerges out of its interaction with its environment.

The physiology of a structure

Not to run before we can walk, perhaps it would be better to recognise that what we call a 'structure' is really shorthand for the complex interrelationship between assemblies and systems of many smaller structures and nonstructural subsystems. Many of these are of great interest and beauty in their own right, and the art of revealing and playing among the interwoven layers is a great engineering pleasure. It is in this territory — in the designing and making of complex macrostructures made up of many integrated individual structures or structural elements — that structural engineers practice their art and science for the benefit of humankind. It is probably much more physiology than anatomy.

A (not-so) simple example

Let's try a structure at the smaller end of the scale; a single bookshelf fixed to the wall in your home. If it is to work beautifully, even this familiar artifact needs to be engineered as a working structure. Mentally taking it apart, we see that it turns out to be a small structural system, needing a whole range of skills. The fact that we may have seen other shelves before is of course, useful, and we'll discuss precedent as a source of ideas later. The engineer of this shelf designs and manufactures it for the purpose of storing books weighing a few kilos, and has balanced a knowledge of that purpose with an assessment of the loads applied to it. The shelf has been made from a material that, with the appliance of the right sort of engineering theory, may be shown by the structural engineer to be able to carry the internal compression, tension, bending and shear stresses from the books and the shelf itself, back to the wall. And like most structures we design, it has a relationship with the rest of planet Earth. In this case, it's fixed to planet Earth via a wall. And so the fixings to the wall have to be designed, because they are rather important to the success of the whole endeavour, and they too have forces acting on them. Thus the nature of the wall becomes rather significant:

- Is it made from a structure that can carry the load from the shelf?
- Will the fixings be strong enough?
- What are the dimensions of each part?
- Who is going to build the shelf?
- Are they competent, properly skilled and do they have the right tools for the job?

The simple shelf reveals more and more engineering layers as we peel away at it.

Another example

Now let's take a classic structure in the middle of the scale for a structural engineer: the great Gothic cathedral in Salisbury, UK. In those days, cathedrals were designed and built by 'master masons' who worked closely with their materials and their craftsmen, using construction rules developed largely by trial and error on a geometrical basis. Not all of these rules worked first time, and many cathedrals fell down; perhaps the most famous example being the collapse of the nave of Beauvais Cathedral in France. Why did Beauvais collapse, while Salisbury survived?

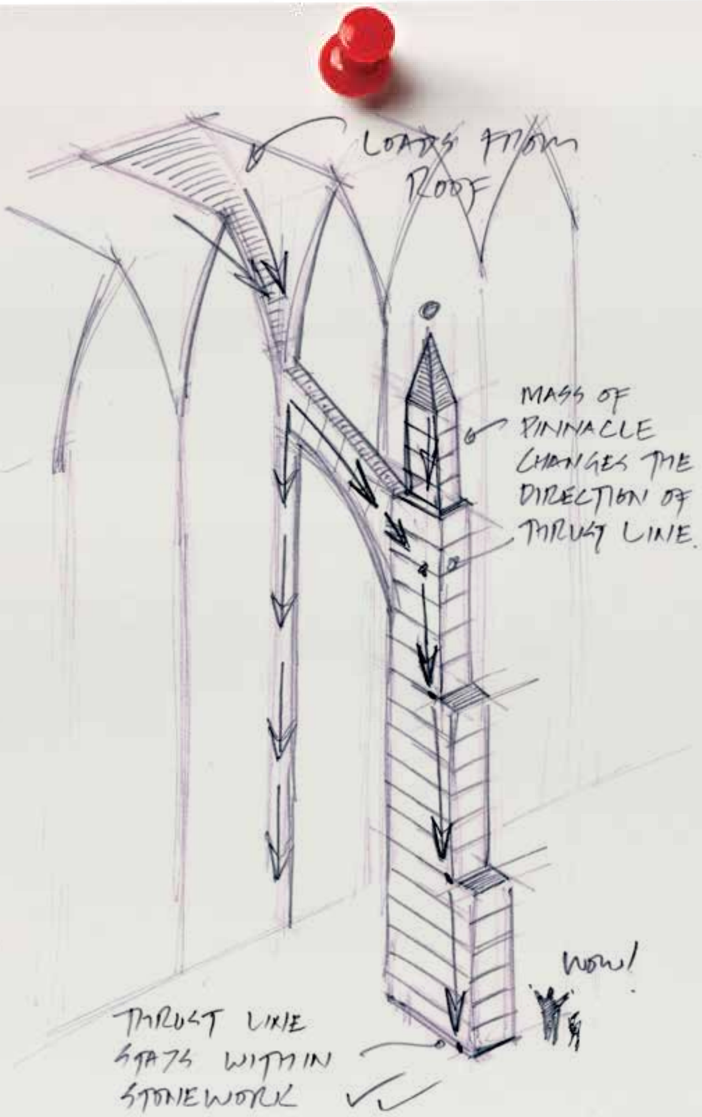


Figure 2.2: A flying buttress from Salisbury Cathedral

Nowadays, having been conscientious students of engineering theory, we'd say that if the forces stay in compression under control within the physical geometry of the stonework, the cathedral will stand (Figure 2.2). If the line of force (the thrust-line) leaves the geometry, the structure will fail. This is because to survive, the stonework would need to take bending tensile stresses which that particular material cannot do. So at its heart a cathedral takes the boundaries of its physical expression from the intimate relationship between the choice of structural form and material. In the hands of a gifted structural engineer — where it becomes possible to "read" the behaviour of the structure through a form that follows the laws of physics — rather wonderfully it is much more than that, and our built language touches the human spirit.

2.2 The structural design process

The shape of projects and the people who work on them

Engineering is, at heart, a design and construction activity, built on many generations of experience. Its projects contain more or less clearly recognisable stages, which are sketched out in Figure 2.3 in what we call the anchor diagram for a project process. So, does an engineer need to be an expert in all of that stuff? 'No' is the simple answer. There are some patterns of behaviour and aptitude which fit some of us better to some bits than others. By studying the way that many different sorts of designers at the Royal Designers for Industry Summer School approach their projects[2.1], it turns out that there are three generic approaches to project work, which we've characterised as the 'artist', the 'artisan' and the 'philosopher'. An engineer may be just one of these, or a combination. What drives people to enjoy a particular way of working is strongly linked to their intrinsic motivation, and leads to pleasure in some parts of a project and pain in others, so is worth reflecting on for a moment.

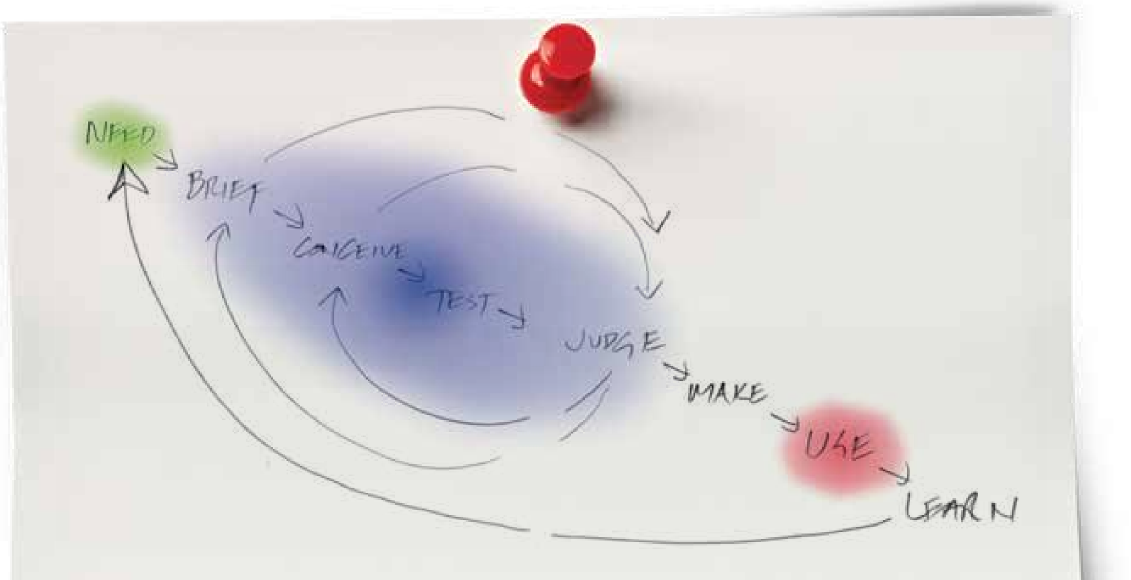


Figure 2.3: The anchor diagram for the overall design process

The strategy of the 'artist' is motivated by interest. Broadly, in a project, the artist engineer is strong in conception and subjective judgment. An artist will start out in one direction and end up somewhere else, driven by environmental interest, more often than not (Figure 2.4).

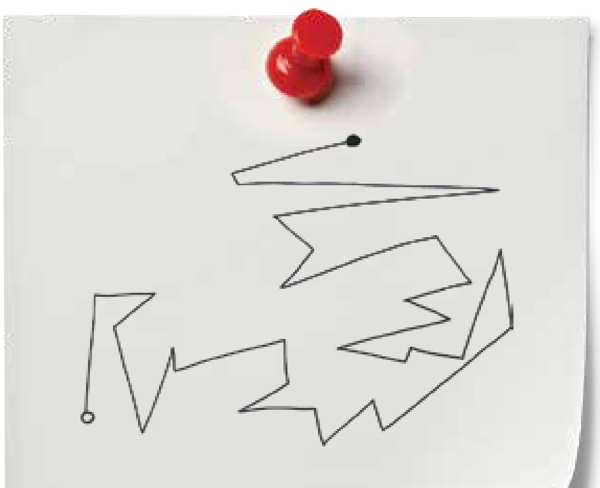


Figure 2.4: The project process for an artist engineer

The strategy of the ‘artisan’ (Figure 2.5) is motivated by perfection of form or means. The artisan engineer is very strong in testing, and in precedent analysis as part of the means of conception. An artisan seeks to absorb everything relevant to the task in hand and, from there, move the state of knowledge forward incrementally.

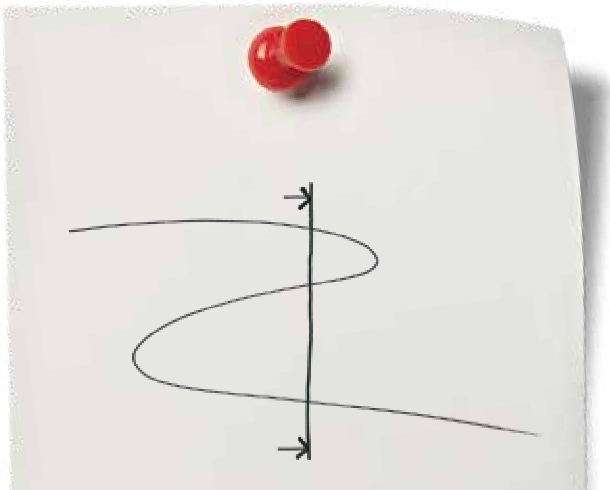


Figure 2.5: The project process for an artisan

The strategy of the ‘philosopher’ is motivated by the search for meaning (Figure 2.6). The philosopher engineer is strong in challenging and interpreting the brief, and in judging a concept against the intentions in the brief. A philosopher tries to build a world view of the project, with all of the influences and relationships clearly mapped out.

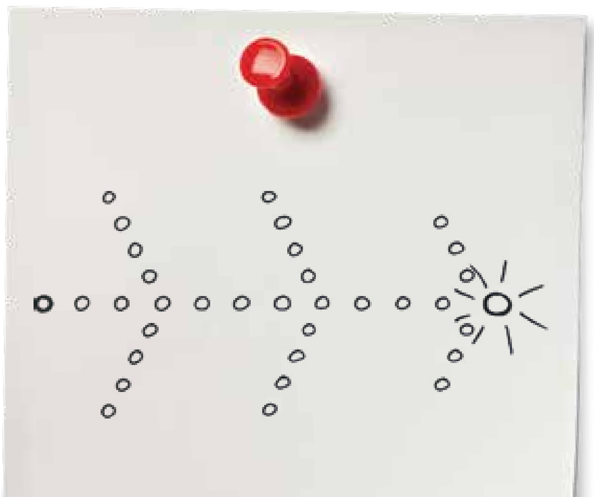


Figure 2.6: The project process for a philosopher

It is arguably good for an engineer to know of these ways of working, and to develop some self-awareness about their own preferred approach (a simple test for engineers wishing to do this can be found in the *ICE manual of structural design: buildings*[2.2]). Not only does it help to know which bits of a project you are likely to be most happy with, but you will also be able to form complementary teams which balance your own way of working with others, whose motivations and interests complement your own.

So let's take on a typical project, beginning with the brief, which is written to express the project need:

The philosophically-motivated engineer likes this stage, will often challenge the stated brief and will definitely labour to derive the meaning and core purpose of the project from it. The developed brief is the springboard which gives the engineer licence to be creative, to have ideas, to conceive a concept that might actually meet the project needs. For this reason the most telling page of a brief could be said to be the apocryphal blank sheet of paper (Figure 2.7) just beyond the brief's end; a daunting prospect for some.

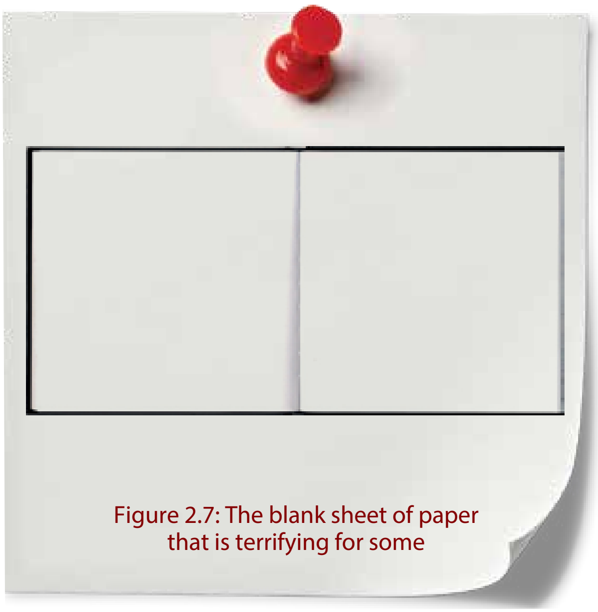


Figure 2.7: The blank sheet of paper that is terrifying for some

The design loop: a marriage of creativity, applied science and philosophy — Conceive, Test, Judge

The next task for the engineer is to develop a concept which responds to the brief, and this is the first part of the many iterations of the design loop as shown in Figure 2.3. Of course, one day the chosen concept may become a physical structural reality, actually be built, and be used. Poorly conceived, poorly tested, poorly judged, it might fall down. Luckily we have a rich heritage of case studies and examples of what has been done before to help an engineer get started with a concept, as well as archetypal forms that respond well to given situations. If a precedent exists, someone with a more 'artisanal' approach may choose one. If there is no pre-existing concept, an artistic approach may conceive one. This is not just something for junior engineers — experienced professionals also call upon every tool at their disposal, including good practical examples from all over the place. For example I.K. Brunel's father, Marc Brunel, invented the world's first tunnelling machine by imitating the way the naval shipworm (*teredo navalis*) bored through timber — arguably an artistic application of an artisan's knowledge (Figure 2.8).

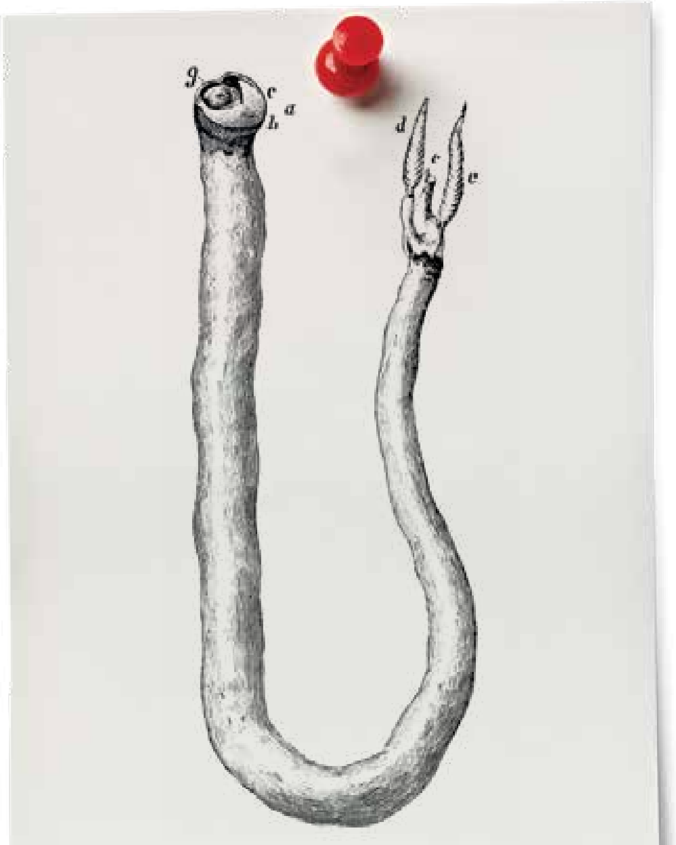


Figure 2.8: Naval shipworm showing rotating cutting shell at top left

The task of the engineer is to build from this sort of start, whatever it is, to synthesise a concept particular to their project. Usually this involves the skill of balancing many variables or drivers, many of which are apparently conflicting each other. There is also a considerable degree of artisanal analysis in the concept stage, which comes from scrutinising the brief and the site to look for appropriate precedents.

The test: does it 'work'?

Unlike conceptual artists, engineers pride themselves in knowing that something will 'work' and can be executed before it is built, and they do this by testing their concept. The suite of potential tests is large, and includes both objective tests and subjective ones. Objective tests will have the same result no matter who carries them out. The artisan engineer majors in objective testing, which can be pretty black and white, often calling on a piece of engineering science or theoretical knowledge, or may involve using a code of practice or a regulation. Objective testing (i.e. the application of engineering science) is a major part of what is taught to undergraduates at university, in part because it is important, and in part because it can be reliably assessed. And such tests are vital, but you cannot design anything purely on the basis of objective tests. Apple's Steve Jobs said: "*You don't know what you want until you know what you can have*." This is the engineer's 'design paradox', for the concept also has to stand scrutiny under subjective testing, and for those, everyone may have a different answer, and many of those answers will change the brief. The artist and philosopher major in subjective testing. Is it beautiful? Can we afford it? Is it safe enough? What is the best way to build it? It is clearly not possible to satisfy all of these tests equally on most projects, and part of a good engineer's learning is to develop insight into which tests are fundamental to each project, and which are incidental or at least non-critical. As Norman (Lord) Foster once said: "*Spend 90% of your time on the 10% of your ideas that work*".

Judgment Day:

Judgment is the stage that carries the most responsibility to society at large, as the project will be built as designed if the engineer's judgment is 'Yes, go ahead'. Put simply, the engineer has to decide whether or not the structural concept — assessed by an overall balance of the results of an appropriate series of tests — will actually play its part as a fitting response to the brief. Unless the artisan engineer can find a direct precedent, engineering projects cannot usually be designed with a single pass of the 'Conceive, Test, Judge' process. The philosopher engineer leads in judgment, clarifying the reasoning for the eventual choice of 'Yes' or 'No'.

If 'Yes', proceed to construction. If 'No', look again at the brief and come up with another concept. It is no embarrassment to recognise that it would be good to have another go. Sometimes people feel it is a sign of weakness to say "we haven't got it right yet", and an admission of personal failure. But this is where engineering takes on its own shape. It isn't personal — because engineered things don't care if someone has made a good or a bad decision, or any decision at all — they simply respond to the forces placed upon them once built. And Nature is an unforgiving adversary. So, let's go round the design loop once more shall we? A capable engineer will step through the loop many many times on a single project, until they are confident in their judgment to build. Design like this is nondeterministic and will eventually converge. The process becomes increasingly intuitive as experience builds. It is common for many potential concepts to be dreamed up, tested, and discarded in the first hour or so of design. As the project becomes clearer, the fundamental concept is tested ever more rigorously, until it stands up to pretty much any test that's thrown at it. Sometimes it's helpful to think of this as trying to balance a seesaw (Figure 2.9). Start with the heaviest things, and gradually refine the balance as more and more is added to the seesaw.

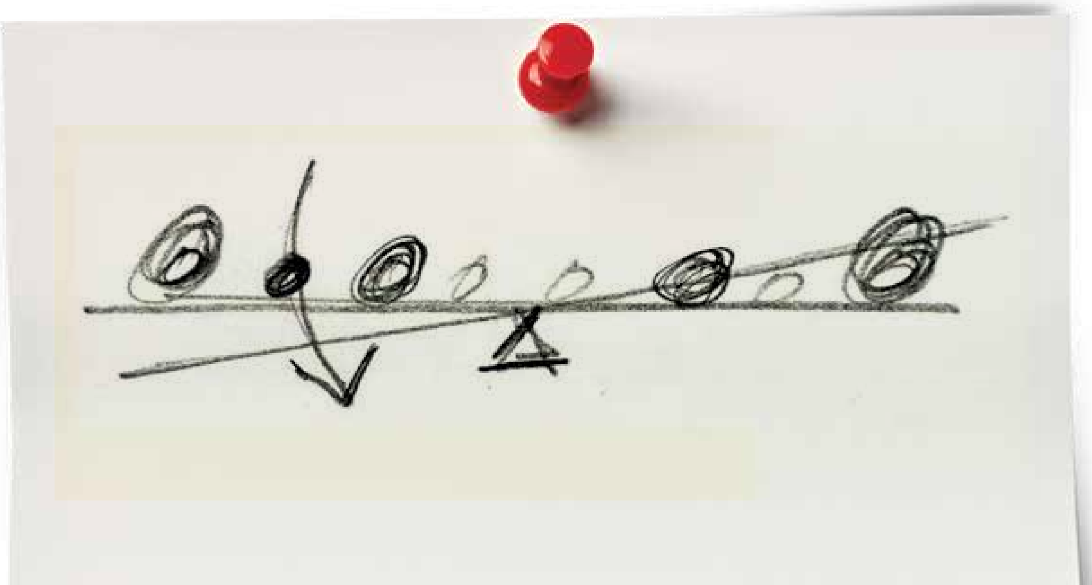


Figure 2.9: The balancing act

Engineering design is effectively encapsulated in this — the balancing of ever more interacting phenomena in repeated iterations of the 'Conceive, Test, Judge' loop, always checking its relationship to the brief. The design loop allows the engineer to gradually develop a good direction of travel and mop up the inconsistencies and incompatibilities inherent in any brief, while incorporating the evolving opinions and influences of other players in the team.

You may feel this is a matter of innate skill or some subconscious instinct, but good design is really a developed awareness of the subtleties in every project and a whole life of similar situations elsewhere, beginning with play in childhood. And like play, one of the beautiful things about structural engineering is that, once built, you can experience a structure personally, may even walk around it, learn from it good and bad, and move on.

Engineers do not learn purely by deduction i.e. by working from specific principles towards applications. They also need to develop the skill of induction, in which appropriate knowledge is drawn in by the specific needs of a project[2.3]. Engineering skill like this is not something that is imparted at university and then simply deployed as necessary, forever after. Rather, it is the continuation of a process of understanding the physical world and our relationship with it that begins when we are children. "There is no substitute for experience" and that's true for engineering, and even better if that experience is consciously sought out with engineering skill in mind.

That's not a structure, it's just a theory!

Does a structure exist in splendid isolation? Some text books would have you believe so. Those who have been victim to the classic method of teaching engineering beam theory will have sympathy. "Here is a beam", says the lecturer, and puts up a picture of some geometrical forms, within which are derived mysterious 'stresses' and 'strains' (Figure 2.10).

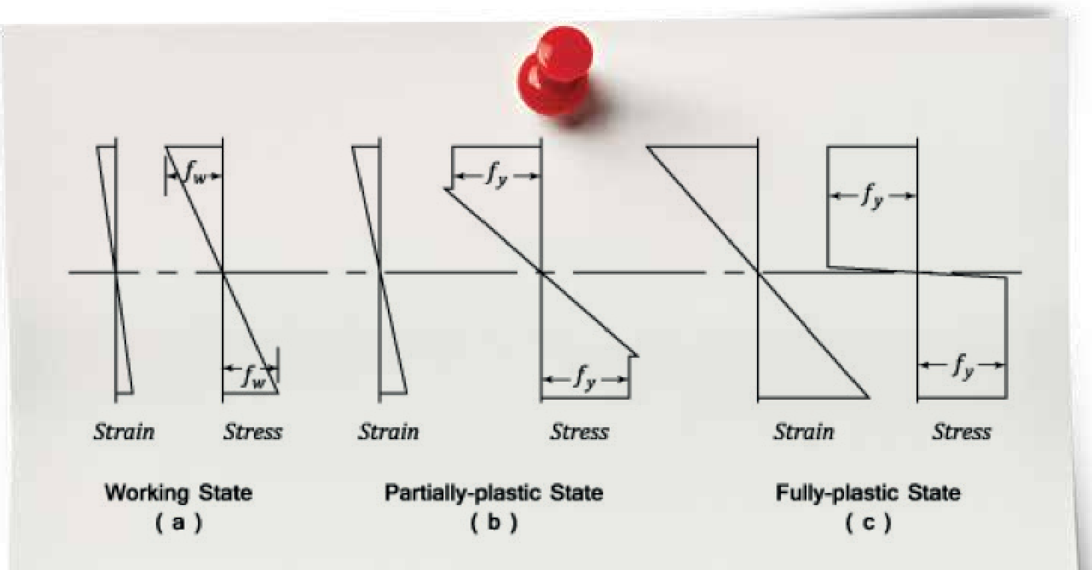


Figure 2.10: Stresses in beams

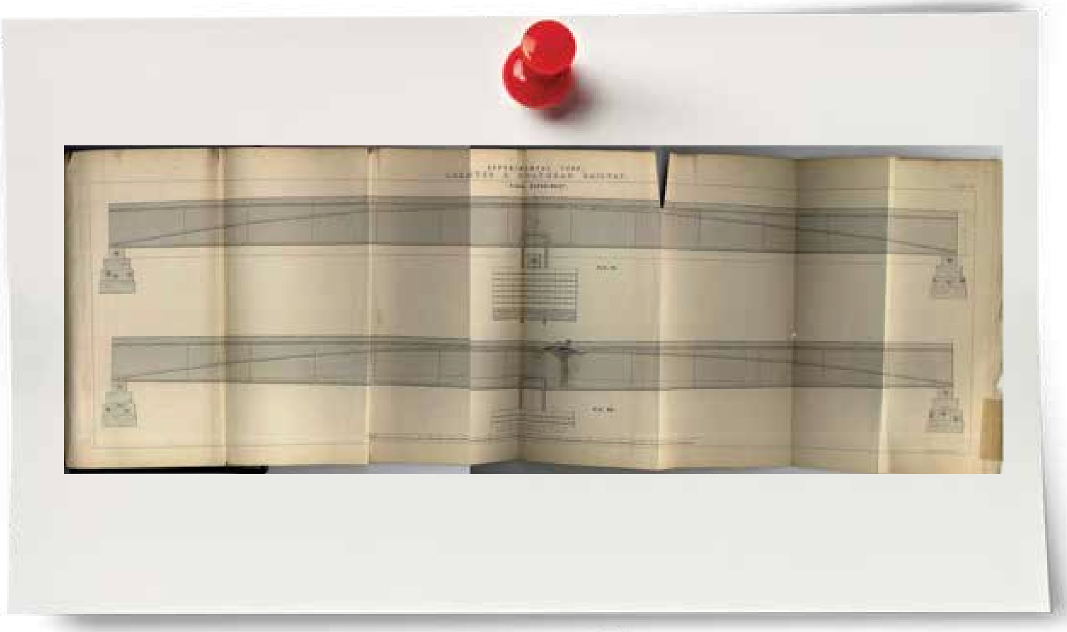
"That looks like no beam I've ever seen", you may mutter.

Of course, its not actually a beam — it's just a theory …

But might it not be a better idea to derive the notion of a beam first, as our forebears must have done, as a fine conceptual response to the need to carry load across a gap? Then you can move on to conceiving a form, exploring possible materials, understanding the loads, analysing and predicting their consequences — eventually making the beam and loading it up to see if it actually works as you, the engineer, predicted. And if it does, to a first approximation, it's either a fluke or you have shown some approximate ability to work with nature and flourish, which is profoundly satisfying. Although there is no substitute for the terror you feel as they strike the falsework on the first beam you ever design, when it stands up — that is rather a special feeling!

2.3 The importance of R&D

Of course there was a time when there had never been a 'beam'. Then someone threw a log over a stream and walked across it. The rest is history. And that history is the point, for we latter-day structural engineers can learn from it and improve our 'beams', try out different materials or combination of materials, build them, test them, derive scientific theories to explain their behavior, and improve them. There was a classic series of experiments of this type carried out by engineer Robert Stephenson, iron-worker William Fairbairn, and University College London mathematician Professor Eaton Hodgkinson, which led to the development of the engineering design (and an understanding of the science underlying it) of the box girder bridge that we still use today (Figure 2.11).



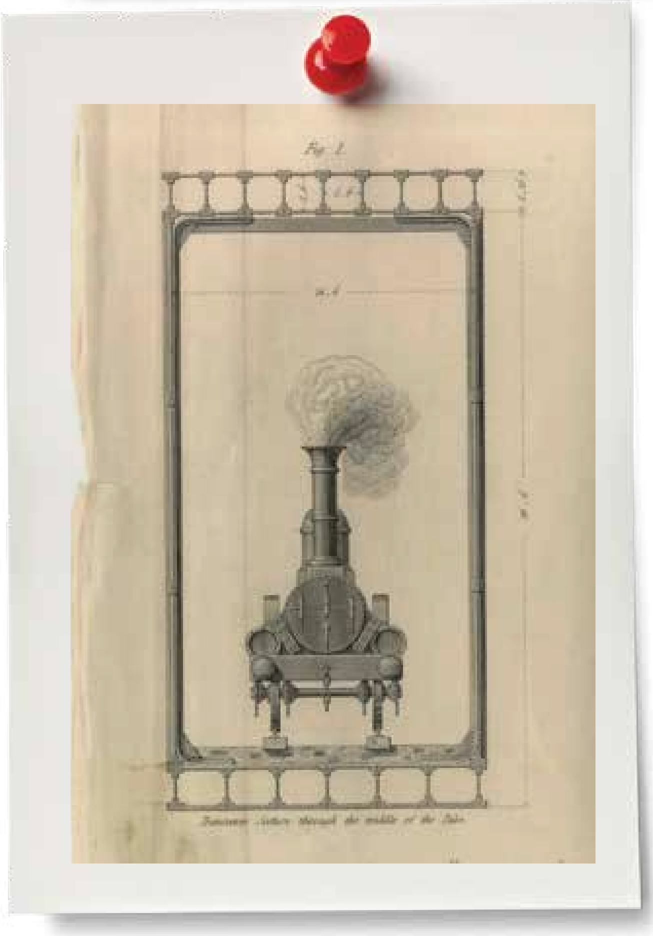


Figure 2.11: Extracts from *An account of the construction of the Britannia and Conway tubular bridges* (1849)

Expedition Engineering's Infinity Bridge over the River Tees (Figure 2.12) is a very thin box girder which used some of Fairbairn's thinking. When you see these things standing there, it's easy to forget how much ground-breaking thought and experimentation needs to go into technological advances. It repays the diligent engineer to learn about those key advances, go and see them, and harness their potential for their own projects.

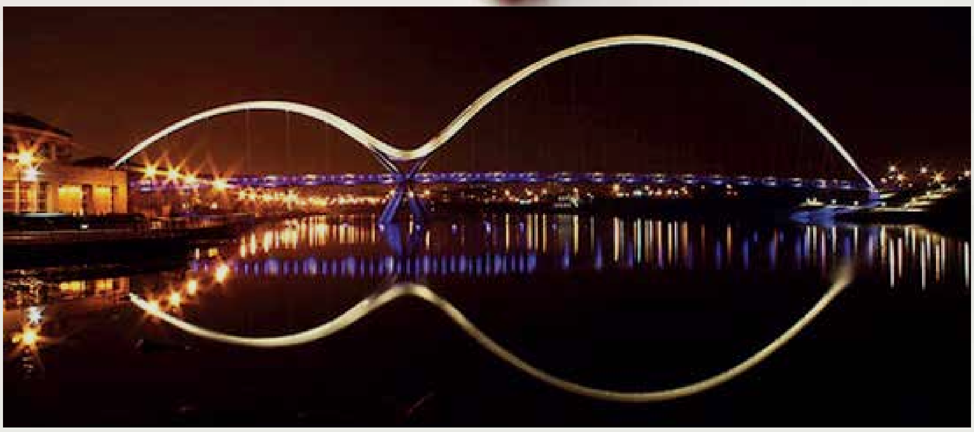


Figure 2.12: Infinity Bridge, Stockton on Tees

When you're at university, copying someone else's work is frowned upon as plagiarism. But when you are in practice as a structural engineer, it's called research, or precedent study, and is actively praised. To put it another way, one of the great pleasures of structural engineering is to be able to dip in and out of the incredible creations of those who have trodden this path before us. Their R&D survives for our benefit, and we are free to learn from them and reinterpret their best ideas for our own purposes.

2.4 How to scare a particle physicist through synthesis

We are taught that for every action there is an equal and opposite reaction, which is another way of saying in structures, that for our designs to flourish they need to find some state of balance or harmony. In mathematics for example, we learn about equations with absolutely perfect balance:

$$F = ma$$

or the beam analyser's all-time favourite:

$$M_{midspan} = wl^2/8$$

Luckily, we structural engineers have the great good fortune that life is not so predictable. Our work is so interesting precisely because we cannot readily stack up both sides of an 'equation' with predictable information. And usually the equation tips one way and then the other under the influence of lots of different effects and then changes into another form. At a given moment, something in particular may assume great importance as the 'dominant uncertainty', but given a change in context or value judgment it may be replaced by another. The engineer's response has to be more synthesis than analysis, solving all of these conflicts in one harmonious design.

By way of example, we (Expedition Engineering) found that the ground underneath a foundation excavation couldn't carry all of the resulting pressure from the existing tower next door (already occupied by the Board of Directors of our client). This happened to us at the Commerzbank, Frankfurt (Figure 2.13) and we eventually designed around the problem using very many design loops. Only when we had finally made the judgment that the nth iteration of our concept had passed all the tests we needed to throw at it (irate Directors, Jenga-like towers etc.), did we move into construction.

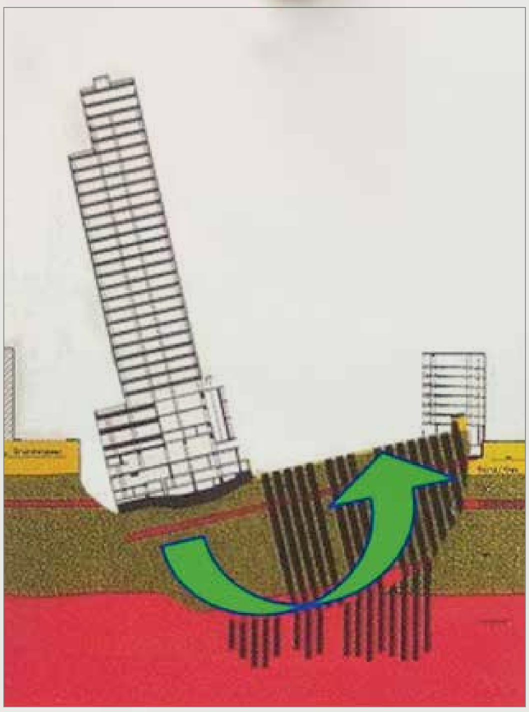


Figure 2.13: Commerzbank excavation — the undesirable consequence

References

2.1 The Royal Society for the Encouragement of Arts, Manufacturers and Commerce (2016) *RDI Summer School* [online] Available at: www.thersa.org (Accessed: 22 February 2016)

2.2 Bull, J.W. *ICE manual of structural design: buildings*. London: ICE Publishing, 2012

2.3 Felder, R.M. *Engineering Education: A Tale of Two Paradigms* [online] Available at: www4.ncsu.edu/unity/lockers/users/f/felder/public/Papers/TwoParadigms.pdf (Accessed: 22 February 2016)

Conclusion

When I was at school the BBC ran a series called the Ascent of Man, by Jacob Bronowski. Standing in a Gothic cathedral, and in his masterful English, he describes what we engineers do far better than I can, as follows:

What did the people do who made this building?

They took a dead heap of stones which is not a cathedral, and they turned it into a cathedral by exploiting the natural forces of gravity, the way the stone had lain, the brilliant invention of flying buttress and arch and so on.

They created a structure out of the analysis of Nature into this superb synthesis.

This is structural engineering practiced as a great art — the distilling of simplicity out of multi-variable complexity. It is worth mentioning that even the aforementioned particle physicists regard such acts of synthesis, even on everyday projects, as something akin to magic. It is one of the engineer's core skills, and its clear-minded application is something we can be justifiably proud of.

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