

# The Structural Engineer

The flagship publication of The Institution of Structural Engineers

## ACHIEVING THE INEVITABLE

**2017 Milne Medallist  
Roger Ridsdill Smith  
outlines his Manifesto  
for Structural Design**

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**DESIGN OF BORED PILES**

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**PERFORMANCE-BASED  
SEISMIC DESIGN**

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**TIME MANAGEMENT**

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# A Manifesto for Structural Design



Figure 1  
Foster + Partners structural engineering team



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## Synopsis

Roger Ridsdill Smith leads the Structural Group at Foster + Partners. In this paper, he proposes a Manifesto for Structural Design, in which he sets out the four points that he considers to be essential to the design process of the group. These four points are illustrated through projects that the group has designed and delivered over the seven years since its inception.

The paper is based on Roger's 2017 Milne Medal lecture and a presentation on creativity and collaboration that he delivered at the Bath IABSE Conference in April 2017.

## Introduction

The Structural Group at Foster + Partners (Figure 1) numbers around 25 and is completely international, with around 90% of the staff from outside the UK. We work on projects solely within the practice; with the architects, the environmental engineers

and the other specialists within Foster + Partners, and then with collaborators from all over the world.

**"OUR DESIGN GOAL IS TO ACHIEVE A DESIGN THAT SEEMS INEVITABLE, THAT HAS INTEGRITY, THAT LOOKS LIKE NOTHING CAN BE REMOVED"**

Having started seven years ago, we now have projects that are complete, under construction or being designed around the world. Through this period, we have developed a particular approach to the way we work.

## Inevitable design

Our design goal is to achieve a design that seems inevitable, that has integrity, that looks like nothing can be removed. Figure 2 shows two paths in Kensington Gardens in London. The path on the left is muddy and uneven, and a fence has been installed to discourage its use. Nevertheless, it has become a route, simply because it is the most direct connection between two nodes across the park. It is the inevitable route.

Figure 2  
'Inevitable route', Kensington Gardens, London





Figure 3  
Marseille  
Old Port, France  
– new canopy

### Four points to make a manifesto

The following points are the fundamental drivers of our approach to engineering. Each point is supported with projects that we have delivered at Foster + Partners over the last seven years.

#### 1) Commitment

In addition to being the basis upon which all the further points are built, I consider that commitment is essential to creativity. The more attention devoted to a design, the more potential there is for it to improve.

Commitment is not necessarily the same as time – it is not enough simply to work long hours and expect a good solution to emerge. The distinction is in the intensity of the process, the appraisal of different options, and the genuine questioning of a solution.

I have become interested in recent literature that reappraised the notion of creativity. There is a school of thought that considers creativity as a mystical process, a gift, that is bestowed on some and not others. In 1815, Germany's *General Music Journal* published a letter purporting to be from Mozart in which he describes his creative process. Here is an extract:

*'Provided I am not disturbed, my subject enlarges itself, and the whole stands almost finished and complete in my mind, so that I can survey it, like a fine picture or a beautiful statue, at a glance. When I proceed to write down my ideas, I take out of the bag of my memory. For this reason, the committing to paper is done quickly enough, for everything is already finished; and it rarely differs on paper from what it was in my imagination.'*

This is a description of the classic notion of creativity in which a piece of music comes to Mozart as a whole, and all that he needs

**"I CONSIDER THAT COMMITMENT IS ESSENTIAL TO CREATIVITY. THE MORE ATTENTION DEVOTED TO A DESIGN, THE MORE POTENTIAL THERE IS FOR IT TO IMPROVE"**

to do is to write it down. It has been cited by many writers in subsequent literature!

However, there is a problem with this piece of accepted wisdom about the creative process – the letter has been shown to be a forgery. Mozart did not write by magic. He worked at his compositions, revising them and adjusting them until he was satisfied. There was no single uninterrupted stream of imagination that resulted in a fully formed opera.

#### Canopy at Marseille

The new canopy at Marseille, France (Figure 3), is an example of a project that went through many different manifestations until the final solution was reached. The structure forms part of the masterplan for the regeneration of the quayside of the Old Port, a competition that was won by landscape architect Michel Desvigne with Foster + Partners. During the project's conception, options were studied in a range of different materials, with geometries that suited the structural and environmental implications of each design. It was only as the final concept evolved that the material and structure were settled on.

The canopy measures 46m × 22m and is supported on eight columns, with 12m spans between columns and 5m cantilevers around the perimeter. The project is a single, simple idea, designed and detailed uncompromisingly. It consists of a blade of polished, mirrored steel, intended to reflect the surrounding port activities while

becoming almost invisible from a distance.

To achieve this, the steel roof structure tapers from a maximum of 600mm across the mid-span to a point around the perimeter. There is no gutter – water drains into the columns – and no edge beam – all structure is orthogonal to the perimeter.

The wind loads are significant in Marseille, but the structure presents only minimal resistance to the wind flow. Lateral stability is provided through portal action of the primary beams, which node with the columns, which are rigidly connected to a grid of ground beams to provide additional stiffness to the frame.

The canopy won the Eiffage structural steel award in 2015.

#### Château Margaux

Château Margaux is a Premier Cru vineyard in the Bordeaux region of France. Foster + Partners was appointed to design the first new construction on the site for 200 years, which included a new winery adjacent to the existing buildings.

The building is a 28m × 66m single-storey structure with a partial mezzanine level (Figure 4). The functional challenge of the building was to create a flexible central area

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Figure 4  
Château Margaux,  
France – new winery

**"THE PERIMETER 'TREE' COLUMNS RESOLVE THE TRANSITION FROM THE INCLINED GEOMETRY OF THE ROOF PLANE TO THE HORIZONTAL GEOMETRY OF THE GROUND"**

for the wine-making process, to be free of spanning structure for maximum accessibility.

The historic location imposed height constraints on the roof, as well as requiring that the pitch matched the surrounding buildings.

The shallow roof structural solution that was required as a result is achieved by using the pitch of the roof with the 'tree' columns (Figure 5), which resist lateral as well as vertical loads. As a result, the axial loads generated by the roof pitch are resisted by the columns, which also provide support to the outside roof edge.

The effective span, and consequently the bending moment that each roof beam has to resist, is reduced both at the supports, as well as at the apex.

A layer of 120mm thick cross-laminated timber panels provide the roof surface, and brace the diagrid steel beams against lateral torsional buckling.

The perimeter 'tree' columns resolve the transition from the inclined geometry of the roof plane to the horizontal geometry of the ground. The evolution of these elements (Figure 6) was the result of an intense and committed process of physical and virtual modelling. The final geometry is constructed from single curved steel plates. Foster + Partners generated the three-dimensional geometry for these elements which was used directly for fabrication by the contractor.



Figure 5  
'Tree' prototype

Figure 6  
Evolution of tree column design







Figure 7  
Tocumen Airport,  
Panama – under  
construction

"THERE IS NO SUBSTITUTE IN ENGINEERING FOR TECHNICAL EXPERTISE, BASED ON AN UNDERSTANDING OF STRUCTURES FROM FIRST PRINCIPLES"

**2) Technical knowledge**

There is no substitute in engineering for technical expertise, based on an understanding of structures from first principles.

The ideas put forward by engineers resonate if the engineers have an understanding of how they will be able to deliver them. This is not the same as being immediately aware of the final design from the first moment of conception – innovation requires research and development time.

The structural team at Foster + Partners has grown with a particular focus on technical excellence, and with specialist knowledge in seismic and dynamic design, as well as the design of tall buildings. This knowledge is complemented by partnerships with firms around the world which bring other technical strengths and experience.

*Tocumen Airport terminal*

The new terminal at Tocumen Airport, Panama (Figures 7 and 8), is the result of a competition won by Foster + Partners in 2012. The roof solution would not have been possible without the development of an innovative structural solution during the fast-track construction process.



Figure 10  
Reinforced  
concrete column  
incorporating  
ductile fuse

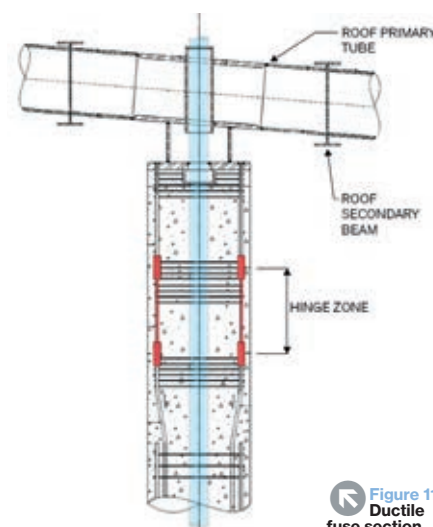


Figure 11  
Ductile  
fuse section

The structural intention was to create an exposed internal roof structure that gently varied in curvature along its length. The primary structure is located above the ceiling, and the columns do not node on the secondary beams. This creates the effect of a roofscape that appears to float above the internal buildings.

Lateral stability of the roof is achieved

in the longitudinal direction through portal action with the primary beams, which node on the columns below (Figure 9). However, since the secondary beams do not node on the columns in the transverse direction, stability is instead provided through the torsional capacity of the hollow circular steel primary beams in combination with the cantilever action of the reinforced concrete



Figure 8  
Competition visualisation



Figure 9  
Roof under  
construction

columns. This system does not fit within a prescriptive code-based design approach. As a result, we evolved a ductile fuse detail at the top of the reinforced concrete columns in order to limit the maximum seismic demand that can be transferred to the steel roof (Figures 10 and 11). This is achieved by reducing the diameter of the reinforcement in the 'hinge' zone. In this way, the steel roof structure remains essentially elastic under the seismic loading of the maximum considered seismic event.

The analysis and calculations were reviewed and approved by two independent international peer-review teams. The project was presented at the American Concrete Institute (ACI) convention in October 2017 and will be published in an ACI special publication on performance-based seismic design in 2018.

*Ocean Towers, Mumbai*

A further example of the use of technical knowledge to evolve a project design is the proposed new Ocean Towers in Mumbai, India (Figure 12). The plan arrangement of the towers arose through the client's strong preference for the living rooms



Figure 12 Ocean Towers, Mumbai – visualisation

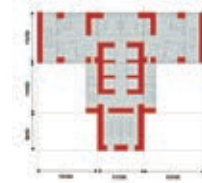


Figure 13 Original floorplan - core and moment frame

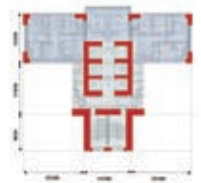


Figure 14 Revised floorplan - core with outrigger

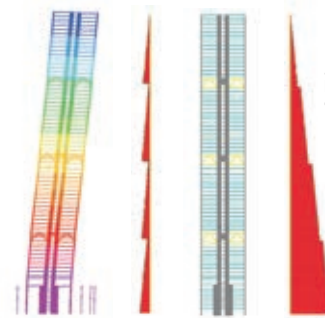


Figure 15 Deflection and axial loads in corner columns

of all apartments to have the same view – facing towards the sea. This gave a single orientation to the buildings, with the aim being to keep all service rooms and circulation to the rear. It became clear that two separate cores would better serve this arrangement, allowing for up to four apartments to be arranged along the front. These cores are deep enough to provide the lateral stability in their strong axis.

The initial stability system across the building was to be a moment frame in combination with the cores (Figure 13). In order to create a more flexible and open internal floorplate, we evolved the current system – replacement of the moment frame with three sets of outrigger trusses over the height of the building (Figures 14 and 15). In this way, all of the intermediate columns are removed, to leave 15m x 11m column-free spaces in each of the four sections of the building.

*425 Park Avenue, New York*

Another project where technical knowledge contributed to the original project concept was the 425 Park Avenue Tower competition that Foster + Partners won in 2012 (Figure 16). The tower concept arose initially through the detailed analysis of the prescriptive volumetric requirements of the New York planning laws. A single line of vertical structure on the front of the tower, coupled with the cores at the rear, provides both vertical and horizontal support. The bifurcation of these columns at the two intermediate levels transfers shear between the front and the rear. The structural philosophy is a direct manifestation of the forces that need to be resisted (Figure 17).

The project is currently under construction, and the Structural Engineer of Record for the tower is WSP Cantor Seinuk.



Figure 16 425 Park Avenue, New York – competition visualisation

Figure 17 Overturning moments due to wind load on x and y axes

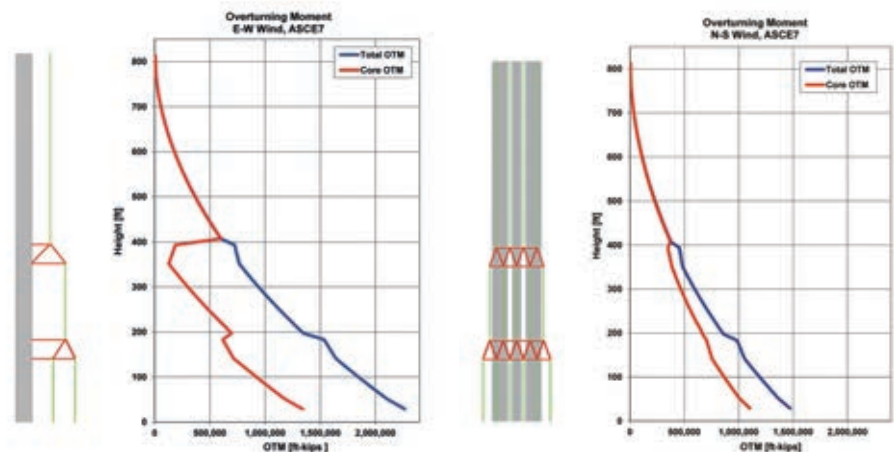






Figure 18  
Maggie's Cancer  
Centre, Manchester

### 3) Collaboration

In the first of my four points, I associated creativity with commitment. In the same way, I consider that innovation is strongly associated with collaboration. It is through collaboration that technology and knowledge can be transferred, be it inside the Structural Group, across the different disciplines within the practice, or with other partners.

What is important in collaboration is a genuine appraisal from a different view of the same question – and it is this that can lead to innovation.

#### *Maggie's Cancer Centre, Manchester*

The structure of the new Maggie's Cancer Centre in Manchester (Figure 18) is on a domestic scale – small spans for a single-storey building. The innovation is in the detailing of the timber in order to minimise the size and visual intrusion of the nodes. This arose both through internal discussions and research, and through close working with the specialist timber contractor Blumer-Lehmann.

**"I CONSIDER THAT INNOVATION IS STRONGLY ASSOCIATED WITH COLLABORATION. IT IS THROUGH COLLABORATION THAT TECHNOLOGY AND KNOWLEDGE CAN BE TRANSFERRED"**

The project evolved through consideration of the spaces that would create an inviting open atmosphere for visitors to the building. Timber was chosen as the primary building material for its aesthetic and structural properties, as well as for cost and carbon efficiency.

The intention was to minimise the use of material so that it is only present where needed, and to avoid the heavy steel detailing that is sometimes required to connect timber frames. The laminated veneer

lumber trusses provide both lateral stability across the building, and vertical support to the roof (Figure 19). The form and density of the trusses are optimised to the forces that they resist; any part of the structure that is superfluous has been removed.

A key point of the structure is the triangular node, where vertical loads from the roof are transferred to the columns below (Figure 20). This node also acts as a portal frame haunch to provide the rigidity required for the horizontal stability of the building across its width.

The project won both the Arnold Laver Gold Award and the Structural Award at the 2016 Wood Awards.

#### *Musée de la Romanité, France*

Another example of collaboration is the Musée de la Romanité, a new 20 000m<sup>2</sup> museum for the local archaeology around the Narbonne region in the south of France (Figure 21). The result of an international competition won by Foster + Partners, the



Figure 19  
Internal view



Figure 20  
Timber  
truss node details





Figure 21  
Musée de la Romanité,  
Narbonne – visualisation



Figure 22  
Roof soffit – visualisation



Figure 23  
Site progress

project is currently under construction and due for completion in 2019.

The project budget is extremely tight for this public building, and the exposed structure formed part of the original competition concept, to unify the different functions of the building into a single volume.

The entire roof is exposed along its soffit (Figures 22 and 23). The idea of the prefabricated 'double tee' concrete roof emerged as a cost-effective structure that would define the architectural spaces, while providing thermal mass to contribute to the environmental cooling strategy. These roof sections span onto prestressed concrete beams, which are in turn supported by a grid of columns and shear walls. The vertical structure is constructed in cementitious rammed layers using local aggregates, the result of research across the industry, and in particular working with experts Terra Firma.

*Apple Union Square Store, San Francisco*  
Foster + Partners have delivered Apple Stores all over the world as an integrated

team of architects, structural, environmental and specialist engineers, and working with international partners for each location. Each store carries project-specific challenges – be it the seismicity of the region, connection to an existing building, or redesign of the stability system of the tower in which the store is located. In each instance, the final store retains the same design philosophy, and the same family of details.

The recently completed Apple Union Square Store in San Francisco (Figure 24) involved major alterations to the existing building structure. In particular, the new store volume, measuring 32m x 25m in plan, is supported by a giant steel truss structure that spans over the ballroom located in the basement underneath the store. The internal space contains a 10m cantilevered

mezzanine floor (Figure 25), which tapers to less than 30cm at its tip, through which the lighting, air and sprinkler requirements of the space below are integrated, along with tuned mass dampers to control the response of the floor. Special concentrically braced frames comprise the seismic lateral force-resisting system in both directions.

This design was achieved through teamwork between the different disciplines and coordination with the other partners involved in the delivery process, notably our close partnership with the Structural Engineer of Record, Simpson Gumpertz and Heger.

The store has won the SEAONC (Structural Engineers Association of Northern California) Excellence in Structural Engineering Award of Merit in the category of Landmark Structures.



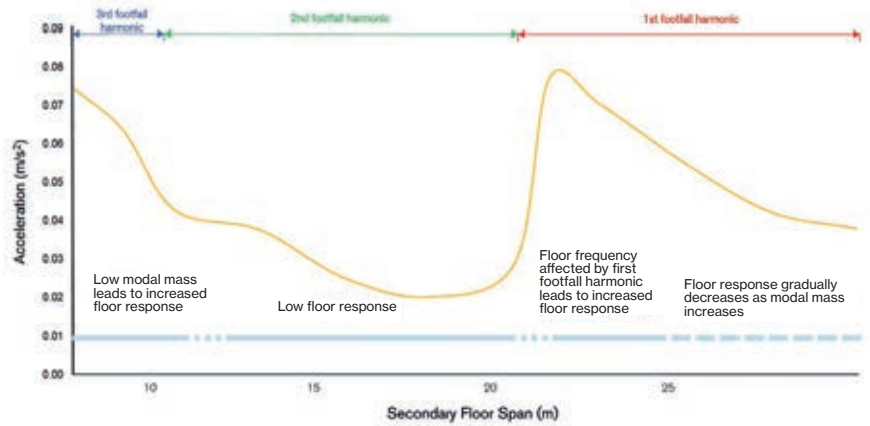
Figure 24  
Apple Store Union  
Square, San Francisco



Figure 25  
Internal view



**Figure 26**  
Plot of floor response vs floor span for composite floor designed to satisfy minimum strength criteria



**4) Curiosity**

The final point, curiosity, is one that should, in my view, permeate all aspects of the way we approach our profession. It stretches from the requirement to constantly review projects through all stages of their design and construction, to the need to look further, into other industries, or unrelated fields.

At Foster + Partners, we question our designs continuously in various formats. There are formal design reviews by the Practice Design Board, as well as pure structural reviews within the group. We hold talks where any of the team can present a subject which interests them, as well as inviting guests and holding webinars. Just as importantly, there is a constant exchange around the studio, a complete mixing of the different professions and specialisms.

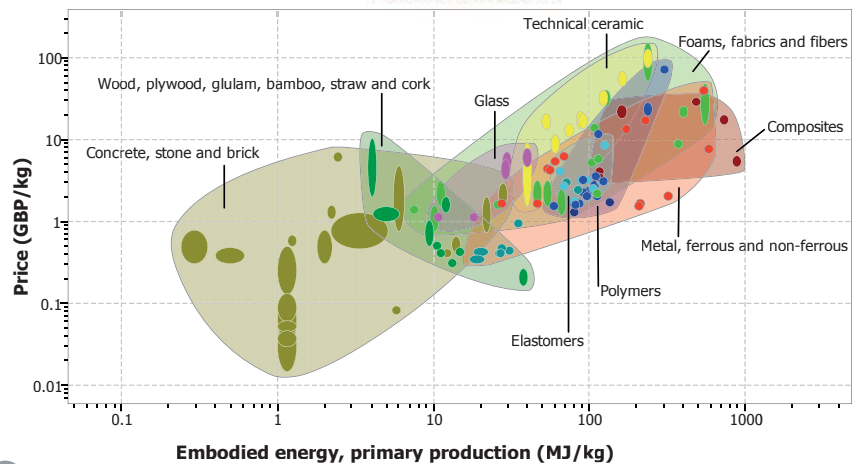
Research and development is carried out at varying scales at Foster + Partners. Two examples of research projects are set out here. As the efficiency of buildings improves and their energy in use reduces as a consequence, the relative importance of the embodied energy of the materials used in construction will increase. Both these studies consider the efficient use of materials.

*Efficient floor beam design*

Floor beams are designed for two structural criteria: strength and serviceability. Strength design represents the minimum acceptable threshold; the beam must be designed to resist the factored loads that are applied to it. However, in practice, beams are often defined by serviceability criteria: either deflection or, increasingly, vibration. Material has to be added beyond the minimum required to satisfy the strength criteria. This is an inefficiency in material use, and we were interested to investigate whether strength or serviceability governed the beam design over a range of floor spans from shorter than is usual, 7m, to longer than is generally regarded as economic, 25m.

A composite steel grid was used as a simple common floor typology and analysis carried out for an assumed 9m primary span, with secondary beams at 3m centres.

The study found that for a given set of boundary conditions, a range of floor spans could be found where the floor beam that is designed to achieve the strength criteria also fulfils the vibration criteria without any additional material or depth (Figure 26). The span in this range is long enough to provide adequate modal mass, while not so long that the first floor frequency is excited by the first footfall harmonic. Designing floors in this span range should result in an efficient use of



**Figure 27**  
Cost of materials per kg vs embodied energy of materials per kg

material. A more detailed paper on the beam design study will be published in due course.

*Comparison of embodied energy versus cost of materials*

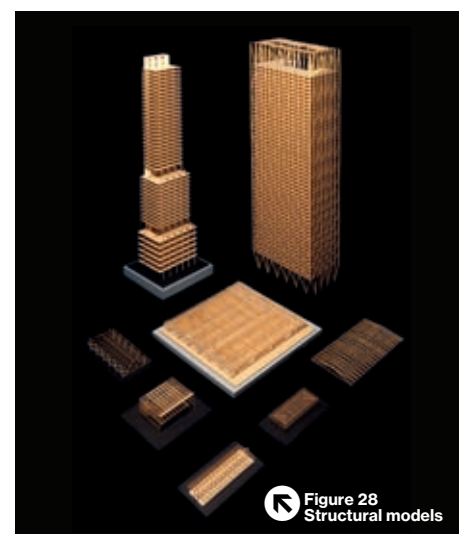
The building structure is one of the major contributors to the building's embodied energy. This study arose through a desire to examine whether there was any relationship between the cost of materials and their embodied energy of production.

Figure 27 shows a plot of the cost of materials against their embodied energy of construction, on logarithmic scales. The graph supports the theory that there is, in general, a close relationship between the two variables. In other words, the cost of bulk material is closely related to the cost of the energy required to produce it. High-temperature processes, such as the production of steel or other metals, require large amounts of energy and are costly. Materials such as aggregate or timber require lower quantities of energy and are less costly.

The conclusion that can be postulated from this is that if we can minimise the total cost of the materials in a building, then we should have a reasonable first approximation for minimising the embodied energy of its construction. In this way, material cost can be used as a proxy for embodied energy.

**"DESIGN IS NOT MAKING BEAUTY, BEAUTY EMERGES FROM SELECTION, AFFINITIES, INTEGRATION, LOVE"**

Louis Kahn



**Figure 28**  
Structural models

REFERENCE

- ▶ 1) Ashton K. (2015) *How to Fly a Horse: The Secret History of Creation, Invention, and Discovery*, London: Doubleday