Darwin Centre Phase Two, Natural History Museum, London

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“The realisation of the Darwin Centre represents one of the most important developments undertaken by the Natural History Museum, since it moved to its present site in 1881.”

Sir Neil Chalmers, Emeritus Director, The Natural History Museum

Delivering the vision

The Natural History Museum (NHM), designed by the eminent Victorian architect Alfred Waterhouse and now listed Grade I, opened on Exhibition Road, London, in 1881. Drawing originally on collections from the British Museum, its holdings now cover some 70M items within five main collections: Botany, Entomology, Mineralogy, Palaeontology, and Zoology.

The new Darwin Centre houses the preserved specimens; Phase One exhibits the Museum’s 22M specimens stored in alcohol, while Phase Two houses the 17M entomology and 3M botany specimens. Phase One has been fully operational since September 2002, and welcomed more than 320 000 enthusiastic visitors in its first year. Phase Two, the subject of this article, was opened in September 2009 by HRH Prince William, who said: “As the superb facilities of the new Darwin Centre show, the Natural History Museum is at the very forefront of research. This magnificent new wing will further enhance the museum’s peerless reputation.”

1. Viewed from the Museum’s Wildlife Garden, the completed Darwin Centre Phase Two complements the Victorian architecture of the original Waterhouse Building.
The NHM developed a unique concept for a new type of public access to the Museum’s vast collections and the scientific research. In the words of Sir Neil Chalmers, NHM Emeritus Director: “The challenge for the architect and design team is to introduce public access to a working scientific establishment in an exciting and innovative way... whilst allowing the day-to-day workload of the scientist to continue without interruption... Our goal is to enthuse, empower and educate, to enable more people than ever before to gain a genuine understanding of science and the world about them.”

The Danish practice CF Møller Architects was appointed in November 2001 to deliver this vision with the support of Arup providing structural engineering services. CF Møller distilled the Museum’s vision into three fundamental drivers:

**Preservation**

The primary function of the building is to protect, conserve, and sustain the existing dry entomology and botany collections in pest-resistant areas with stable environmental conditions, where risk from fire or any other damage is reduced to an absolute minimum.

**Public access**

In addition, the aim was to steer away from the traditional concept of the museum as an exhibition of historical artefacts, and to increase public awareness of the collections and their importance to research, through the architecture and interaction with the scientists and the collections.

**Research**

To enable world-class research facilities, it was essential to ensure the flexibility, functionality, environmental and architectural standards required for the laboratory and curatorial areas, with easy access to the collections.

**Structural overview**

The NHM is one of England’s cultural gems; its buff and blue terracotta colours create a unique architectural expression in London. Whereas Phase One of the Darwin Centre was constructed as a separate building beyond the north-west corner of Waterhouse’s masterpiece, Phase Two now forms a culmination to the original 1868 scheme, extending south-north to complete the west wing in a contemporary architectural language and linking the Victorian building with Phase One.

CF Møller’s response to the design challenge was to create a minimal nine-storey glass vitrine enveloping and displaying a vast cocoon within. It is the cocoon that both symbolically and literally provides the environmental protection to the collections. The main engineering challenge Arup faced was to deliver an efficient and affordable structural solution to the complex geometry of the 65m long, 12m wide, and eight-storey high cocoon.

The “dry” collections are stored on mobile shelving which is assumed to impart a load of 12.5kPa to the supporting structure, equating to a 1.25m depth of water. The surrounding superstructure, C-shaped on plan, comprises reinforced concrete flat slabs supported on reinforced concrete columns and walls. The basement slab and retaining walls are also of reinforced concrete construction and founded on pile-caps and ground beams supported by bored concrete piles. A single-storey basement accommodates the mechanical equipment required to maintain the environment of the cocoon. Beyond the cocoon, there is a north wing for research activities, with an additional ninth storey housing the staff common-room (Fig 4).

The primary atrium structure supporting the glazed façade and the triple-layer translucent ETFE (ethylene tetrafluoroethylene) roof pillows is of fully welded fabricated steel members. The atrium frames are free-standing and only restrained at the top along the western and eastern edges by a “structural gutter” and a fabricated beam, connected to the reinforced concrete structure (Fig 6).
The cocoon

Concept

A cocoon is the normal place for a pupa to grow before emerging as an adult insect. The architect extended this analogy to the cocoon being a good place to protect its body from harm once dead. The main cause of this harm in the previous buildings was the Museum’s living pests, dining on the botany and entomology specimens, and then reproducing their next generations.

The cocoon is the iconic centrepiece of the building and its structural sprayed concrete shell, on an unprecedented scale, forms the perfect response to the questions posed by the architectural form and the environmental requirements. Expansion joints in the polished plaster finish extend this analogy, appearing as silk threads crisscrossing the surface (Fig 7).

The need to form the curved geometry without incurring high construction costs presented one of the most complex design challenges. The cocoon’s varying curvature and non-developable shape precluded a conventional approach to efficient modularisation of structural components or formwork, prompting Arup to look at more homogeneous and innovative construction methods. Options such as steel mullions supporting cladding panels, precast concrete, and in situ concrete formed from CNC (computer numerical control) cut polystyrene moulds, were investigated but eventually rejected in favour of sprayed concrete.

The sprayed concrete could not only be formed to the required geometry, yielding a uniform thickness of insulation and polished plaster finishes, but also sprayed to a thickness whereby it could hold its own shape and resist vertical loads, thereby eliminating the need for a conventional supporting sub-frame. In this way this elegant engineering solution became by far the most expedient, as the extended programme implications of bending individual steel mullions or producing uniquely curved shuttering would have led to significant delays.

Another important factor for this choice of structural solution was the Integrated Pest Management (IPM) requirements, which ensure that living pests do not destroy the dead insects and plants in the collection. This is achieved by controlling the temperature of the environment with the thermal mass of the internal exposed concrete surfaces, and ensuring that all surfaces can be easily cleaned by avoiding nooks and crannies where pests can hide.

The cocoon structure is formed from a continuous sprayed reinforced concrete shell, typically 250mm thick, supporting internal flat slabs. This solution maximises the internal net area by avoiding the need for perimeter columns, provides thermal mass to maintain temperatures within the cocoon, ensures flexibility of services distribution, and avoids inaccessible areas for cleaning.

The building is stabilised laterally by a series of vertical cantilevering reinforced concrete cores and shear walls. Lateral loads are transferred to these stability elements by the floor slabs acting as stiff diaphragms. The cocoon shell gains lateral stability by being tied into the concrete floor slabs, which are in turn stabilised by the cores.
The idea of using sprayed concrete technology to form the structural skin of a building was conceived by Arup and had been used at this scale only once before – to support the façade substrate of the iconic Selfridges Building in Birmingham, England. The cocoon is the next generation and an evolution of this technology in that the shell forms part of the primary vertical load-bearing structure from which all movement joints have been eliminated. This was very much anticipated at that time and it was recognised that this technology would “undoubtedly lead to other buildings ‘borrowing’ the techniques and solutions”, as the desire for amorphous forms increasingly becomes an architectural norm.

Geometry
The architect’s design philosophy was captured as follows: “It’s a question of magic, you don’t want to show the cocoon all at once.” It conveys the message of its purpose, namely that though the cocoon holds 20M specimens (Fig 8), 90% of the world’s species remain to be discovered or classified – ie nature is so enormous it cannot be seen all at once. Similarly, the cocoon cannot be viewed in its entirety from any one vantage-point.

The key to successful design from the structural engineering perspective was the architect/engineer collaboration, resulting in a shape that both satisfied the ambition for the project and by observation would work as a structural shell. Once a suitable shape was derived, the shell could be set out as a thin-walled section and holes could be considered early in the design process with confidence that the structural integrity would not be compromised. Also with such a shape, initial analysis could be simple and intuitive and not rely on the use of sophisticated finite element (FE) software early in the design.

Using Rhinoceros (Rhino) software, the Arup team fine-tuned the amorphous surface geometry and created the model of the cocoon structure, including all internal and abutting structures, from which the structure was directly built by the contractor. Without knowing his preferred construction method, it would have been impossible to know where to cut and dimension the vertical and horizontal sections through the cocoon for the construction information (Fig 9).

Analysis and design
The cocoon shell was designed using a range of analysis techniques, engineering intuition, and rationalisation. Since building the doubly curved shell was a significant challenge in itself, the aim of the design was to create a generic cross-section with constant thickness, and a reinforcing strategy that would be applicable for most of the shell. The benefits of design simplicity for the construction process were seen to outweigh materials savings if a minimum material quantity strategy was adopted. In fact, the final shape chosen distributes the forces evenly around the shell, so that there wasn’t a large penalty in terms of quantity by selecting constant wall thickness and reinforcement layout.

Design of the central portion
The cocoon is doubly curved at all positions on its surface, but the elongation of the shell along the north-south axis allowed the central portion of the structure to be considered as a plane frame problem for initial analysis, with the primary curvature being vertical (Fig 10).
The shell’s cross-section in this central portion is a simple arch some 8m tall above the sixth floor (Fig 11). The east side of the arch sits on columns at the sixth floor and the resulting arch thrust is imposed on the sixth floor slab. The opposite west side does not tie directly to the same floor slab, but instead is restrained by a series of internal ramps spanning horizontally, and by the fifth floor slab. The ramps and slabs transfer the in-plane forces back to various internal structures. Since the arch tie forces are imposed on slabs at different levels, shear walls are required to resolve the arch tie forces.

The west side of the arch continues down to principal floor level, where the shell wall transfers load to perpendicular walls that continue through the basement to the foundations. The interface between shell and columns is through a floor-deep shear transfer rather than direct bearing, so as to maintain the shell’s thin wall section. This also allowed large openings at ground floor level on one side of these transfer walls for exhibition spaces. The design of these openings was by strut-and-tie hand calculations, informed and checked by the FE analysis and design.

The cocoon arch above the sixth floor is so shaped that little bending is created in the section; the largest bending moments are created by the ramps and slabs that are attached to the wall, even cantilevered directly off the wall in places. The cocoon wall is vertically curved at all positions between floor slabs, which creates bending in it, but the wall’s greatest bending moments are caused by the fixity of the 350mm thick floor slabs that it supports. The axial load in the wall helps the design of these connections.

Considering the system as a plane frame, the bending moments were readily predictable in simple analysis models and hand calculations. Reinforcement was provided according to these moments and their interaction with axial force, and this design was subsequently checked in the 3-D Sofistik analysis model. The resulting design was a simple “background” reinforcement arrangement with additional bars placed where required to meet the increased bending requirements.

**Design of the cocoon ends**

The double curvature at the ends of the cocoon made the analysis more complicated and bending moments more difficult to predict by simple methods. However, by observation the shape helps to stiffen the wall and reduce moments. In these areas, the Arup team used the 3-D model to assess the wall’s performance, with the final reinforcement selection by hand.

The most highly stressed areas of the cocoon are the end walls at the base of the shell, where the surface is most inclined and where curvature is greatest in both directions. Here the higher horizontal curvature of the wall sets up horizontal “hoop” stresses that help restrain the wall from expanding outward due to vertical curvature. Thicker wall sections and more reinforcement were used in these areas to match the required capacity.

Plots of the axial forces and moments, for both magnitude and direction, were used to rationalise the doubly-curved wall areas into groups that could then be designed to specific capacities, informing a simple general reinforcement layout. Alongside this method, the reinforcement design module in the 3-D analysis software was run to provide a second check of the solution.

The concrete’s non-linear behaviour was modelled and used to provide a second estimate of the extent of cracking in the shell – which was found by observation to be small, as much of the shell is in compression with little bending.
lines of longitude with additional bars introduced to maintain the minimum spacing required. Smaller bars at closer centres were favoured so as to be easily curved on site and minimise difficulties at laps (Figs 15, 16).

The shell was broken into similar areas, chosen by observation of the preliminary results from the 3-D models. The areas were derived by being grouped into similar levels of force, and shaped according to where changes in the reinforcement could be accommodated with the least degree of fixing difficulty. These groups were set up in the 3-D FE model and maintained through the design process as a simple reference system.

**Analysis model**

The shape of the structure required a full 3-D FE model to be able to accurately predict forces and to check hand calculations for shell forces and moments, slab diaphragm forces, and shrinkage calculations. The long-term creep effects of the sloping surface, together with the potential differential axial shortening between the stiff shell and the adjacent columns, also had to be modelled.

The shape of the cocoon was derived from and existed as a collection of NURBS* surfaces in the Rhino model. The adjoining structure was then modelled as centreline surfaces of slabs and walls and centrelines of columns within Rhino. The designers carefully aligned centrelines at connections; this meant often departing slightly from the true geometry so as to create a simple FE mesh, avoiding areas with unnecessarily high concentrations of small elements. Less detail was required in the structure away from the cocoon, so the geometry was simpler in these areas.

Each core wall was modelled as a single vertical 1-D element and given a suitable stiffness as calculated in a separate analysis. This greatly simplified the 3-D model and allowed shear and bending forces in the core walls to be simply extracted.

The cocoon centreline surface was split into a collection of quadrilateral elements, meeting the slab and column centrelines. The geometry was imported from Rhino into AutoCad and the surfaces were redefined and meshed to the desired density with Sofistik’s meshing module as a plug-in to AutoCad (Fig 14).

The text-based interface of the FE program was used extensively to manage the model, allowing the designer to specify loading, analysis routines, combination cases, design and reinforcement parameters, results extraction, and graphical representation from within spreadsheets linked to the text file, rather than from within a graphical interface that was slow and difficult to navigate due to its size. Multiple analysis and design runs could be carried out overnight without opening the large model, and the desired graphical results in the form of organised contour plots would be automatically generated.

**Reinforcement design**

Rationalising the reinforcement bars was key to the simplicity and success of the design and construction. The reinforcing mat layout was resolved early in the process, before the exact quantities of reinforcement were known. The double curvature required reinforcing bars to be laid out carefully so that multiple overlapping layers were avoided where the orientation of the bars on the surface change, with rectilinear arrangements of vertical and horizontal bars chosen for the most constant central portion of the shell.

Radial arrangements were selected for the north and south ends. Here the horizontal bars follow lines of latitude with constant spacing, while vertical bars follow

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* NURBS (Non-Uniform Rational B-Splines) are mathematical representations of 3-D geometry that can accurately describe any shape from a simple 2-D line, circle, arc, or curve to the most complex 3-D organic free-form surface or solid. Because of their flexibility and accuracy, NURBS models can be used in any process from illustration and animation to manufacturing².
Construction methodology

Concrete shell

Quasi-permanent sloping reinforced concrete columns around the cocoon perimeter, which temporarily supported the slabs in advance of shell construction, were constructed with the main frame and then demolished once the structure was complete and had achieved design strength. This approach initially seemed counter-intuitive, but actually generated significant savings over the more conventional steel temporary works originally proposed (Figs 18, 21).

The contractor’s initial proposal was to demolish the columns using small jackhammers, but this was quickly reviewed, after the scientists objected to the noise levels, and replaced by a method which involved sawing the columns into sections and removing them piecemeal. For this solution the floors had to be propped locally in order for the fork-lift truck to track across the slabs.

Due to the mathematically indefinable geometry, presenting the construction information in the form of a 2-D drawing would have been inappropriate and time-consuming. Instead, Arup issued the construction information for the cocoon as a 3-D Rhino file. This gave the contractor the opportunity to extract the geometric information that best suited his setting-out and construction methods, which involved a grid of horizontal scaffold poles penetrating the shell and supported by an independent scaffold structure. The inner and outer concrete surface co-ordinates for the grid of the scaffold poles were extracted from the Rhino model and marked on the scaffold tubes on site with sticky tape.

The shape of the cocoon was defined at each floor level by the edges of the slabs, and the reinforcement was then sized so that no pre-bending was required. This enabled the natural curvature of the rebar on site, spanning between the floor slabs, to provide the smooth vertical curvature of the shell. However, prior to placing the shell reinforcement, the slab edge starter bars had to be bent to suit the profile of the cocoon (Fig 19, 20).
Expanded metal mesh was used as permanent formwork, attached to the curving vertical reinforcement and held in position by the scaffold support system. The expanded metal mesh was fixed directly to the inside face of the reinforcement, thus avoiding the need for spacer blocks – an evolution from the method Arup developed for the Birmingham Selfridges building, in which the expanded metal mesh was left exposed internally (Fig 21).

The central through thickness concrete was placed by pumping and spraying a wet concrete mix directly onto the expanded metal mesh to a thickness of typically 200mm from the outside of the shell (Fig 22). A 25mm thick dry mix was then used for both the internal and external layers, using a pre-bagged mix with smaller aggregate to allow a final trowelled finish suitable to receive the 50mm thick polystyrene insulation and polished plaster finish. With the dry spraying operation the water is introduced at the nozzle to allow more time to achieve a smooth finish, and without the time and cost pressures of a waiting concrete truck (Fig 23).

Polished plaster finish

The surface patterning of beads to generate the “woven” appearance was generated using a bolt-on program to Rhino called Toycar. Locking the virtual steering of the Toycar and “driving” it across the surface of the cocoon generated setting-out that ensured the beads were only bent in one direction and not warped. This method also ensured that cutting the groves into the polystyrene to receive the beads was as simple as driving the car over the virtual surface.

Other than these geometric constraints imposed on the beads, the only other limitation to their setting-out was to ensure that the maximum area and maximum linear dimension of any one plaster panel bounded by the beads, doubling up as movement joints, was limited to ensure the plaster surface does not crack (Fig 24).

The sprayed concrete shell was delivered in 22 weeks, two weeks under the original programme and significantly less than the timescales associated with the alternative structural solutions. This equated to 130m² each week.

The cost of the 2800m² concrete shell was on budget and again significantly less than the alternative solutions.

Conclusion

The Darwin Centre, and specifically the cocoon, demonstrates the efficient delivery of a highly functional yet geometrically complex structure – Arup bringing innovation to the built environment, and a prime example of successfully synthesising form, function, materiality, construction methodology, and information exchange.

This project demonstrates that close collaboration coupled with innovative design and construction techniques can deliver elegant yet highly functional and environmentally sensitive buildings. The benefit of the Natural History Museum to society is immense in enriching and broadening our understanding of the natural world and raising awareness of the natural world in a very accessible way.

The NHM Project Director, Richard Toy, said: “Arup has gone beyond the requirements of their appointment to provide innovative and cost effective structural solutions for this important and complex building, allowing the Museum to match its aspirations to the funds available.”

The project continues to be submitted for awards. It won the award for “Arts or Entertainment Structures” at the Institution of Structural Engineers’ Structural Awards 2009 on 9 October, fittingly held at the Natural History Museum, and most recently was the Overall Winner of the Concrete Society Awards 2009.

Matt Clark is a senior engineer with Arup, now based in the New York office. He was responsible for the analysis and design of the cocoon structure on Phase Two of the Darwin Centre.

Ed Newman-Sanders is an Associate Director of Arup in the Buildings London 5 Group, and was Project Manager and lead structural engineer for Phase Two of the Darwin Centre.

Credits


References

(2) http://www.rhino3d.com/nurbs.htm