Proceedings of the International *fib* Symposium on the
Conceptual Design of Structures
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The conference is organised by the Swiss group of the International Federation for Structural Concrete (fib).

The fib, Fédération internationale du béton, is a not-for-profit association formed by 41 national member groups and approximately 1000 corporate and individual members. fib’s mission is to develop at an international level the study of scientific and practical matters capable of advancing the technical, economic, aesthetic and environmental performance of concrete construction.

The fib was formed in 1998 by the merger of the Euro-International Committee for Concrete (the CEB) and the International Federation for Pre-stressing (the FIP). These predecessor organizations existed independently since 1953 and 1952, respectively. Today, the fib is the main international organization dedicated to concrete construction.

The fib-CH group achieves fib’s goals in Switzerland by locally disseminating information and knowledge obtained through the association’s international activities.
The conceptual design of structures is at the heart of the design process and when the most fundamental and influential decisions are taken for a project. It merges experience, intuition, tradition, site constraints, technical solutions and, above all, the genius and sensitivity of the designers.

The aim of the International fib Symposium on Conceptual Design of Structures 2021, which continues a series of symposia opened by fib and whose first edition was held in Madrid in 2019, is to generate a fruitful exchange event for academics and practitioners from engineering, architecture and other disciplines on the topic of the conceptual design of structures. The focus is placed on experiences made particularly during the design process. The discussions reflect how a project emerges, how design decisions are taken, how responsibilities are distributed, how obstacles and constraints are handled, how fundamental design principles are applied and the way the individual members of the design team collaborate.

Taking place in September 16-18, 2021, the Symposium follows an hybrid in-person/online format. The in-person events take place at the Attisholz Areal, close to the city of Solothurn (Switzerland). This reconverted industrial venue, which was originally used as a cellulose factory, witnesses the tremendous architectural potential for reuse of existing structures. More information on the venue and its access is available at https://www.attisholz-areal.ch/.
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The International fib Symposium on Conceptual Design of Structures 2021 is jointly organized by the Laboratory for Structural Concrete Engineering at EPFL Lausanne (Professor Aurelio Muttoni) and the Chair of Structural Design at ETH Zurich (Professor Joseph Schwartz) in collaboration with the fib (International Federation for Structural Concrete):

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themes & contributions

The contributions in these proceedings are organized according to the four main topics of the Symposium, as follows:

**exposed or concealed**: the interaction between structure and architecture.
How does structural design shape the overall concept?

**challenging gravity**: contemporary structures for our built environment.
How can structures challenge gravity with new systems, materials and construction technologies?

**rediscovering the past**: forgotten structures and concepts to rethink the future.
How can projects and concepts from the past be a valuable source of inspiration and knowledge for future projects?

**behind the curtain**: the creative role of structural engineers and architects in the 21st century.
Which responsibilities do structural engineers and architects face and which skills will they require in the future with respect to society, economy, and environment?

Authors had the choice between submitting a paper or a video. Papers are provided in full in these proceedings. Videos and a digital version of the proceedings are available on the website of the Swiss Society for the Art of Engineering:

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rediscovering the past
Beyond the spherical solution: the contractor’s contribution to the roof of the Sydney Opera House

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Abstract
The history of the design decisions directly related to the construction of the Sydney Opera House remains largely anecdotal. A rich group of items recently discovered in Australia may now start filling this gap, as documents brought to light include the drawings issued by the general contractor to build the concrete formwork for the shells, drawings of the temporary structures and falsework, site images, and contractor’s notes. All in all, the drawings display sophisticated combinatory solutions for attaining the structural form required whilst introducing repetition and flexibility in the making of the discrete pieces. While suggesting a remarkable combination of manufacturing and structural shrewdness, these blueprints call into question the canonical history of the building roof’s famous ‘sails’ and the rhetoric of the ‘spherical solution’ used to arrive at them.

1 Introduction
The Sydney Opera House is the object of a prodigious hagiography of the personalities involved in its realization and their legendary querelles. Publications on the building rely on the memoirs and actions of three major actors: Jørn Utzon (the architect of Stage 1 and 2, 1958-1966), Ove Arup (the structural engineer and project manager of Stage 2, 1959-1973), and Peter Hall (the architect and project manager of Stage 3, 1966-1973) [1]–[5]. By contrast, and somewhat surprisingly for a building of such legendary renown, the history of the design decisions directly related to its construction on site remains largely anecdotal, if not utterly obscured by the so-called ‘spherical solution’, namely the breakdown (or approximation) of the original roof shells into triangular sectors, eventually labelled ‘sails’, belonging to the same sphere. By contrast, the contribution of the contracting side to the engineering of the assembly process and, by extension, the detailed design of the components involved, has thus far frustrated scholarly attention, also due to the scattering of the original documentation. This is particularly so for the work produced by the general contractor for Construction Stage 2, the Australian company Hornibrook, which played a significant role in developing the construction solutions and the casting procedures for the roof shells.

A rich group of items recently discovered by the authors in several locations across the Australian state of New South Wales may now be set to shed important documentary light on the details of such role, and the collaboration it entailed particularly with the structural engineer.

The documents include site notes, new original site images, and a massive corpus of 5,300 drawings issued by the contractor, including construction layouts of the site as well as calculations and execution instructions of the temporary structures used for the erection of the building roof's famous 'sails' (fig. 1). Though technically classifiable as shop drawings, i.e., non-contract production documents describing the manufacturing process leading to the realization of the building [6], Hornibrook's sets betray strong degrees of design integration with the drawings produced by the structural engineer ARUP, which, in several cases, contain explicit references to 'Hornibrook solutions'. If this type of notational citations suggests at least an accredited combination of efforts in the project, scope and magnitude of the shop drawing series reveal the considerable endeavour of the construction company in the conceptual ordering of the physical tasks.
Fig. 1  Hornibrook Ltd, Sydney Opera House, Stage 2. On the left: construction layout indicating the location of the casting yard for the shells’ components and, highlighted in red, the different storage areas. On the right: northern precast segment storage layout used for organizing the rib segments before their erection (NSW State Archive and Records).

2  The formwork system

Among the collection of drawings, 85 of them describe the formwork system developed to build the concrete shells. Examining this lot is interesting because it reveals not only the length of the engineering work on the contractor's side but also the integration of industrial fabrication thinking and *ad-hoc* construction concerns.

To understand the achievements, one must first introduce the problem, which in this case concerns the roof and the form of its main components, also known as the 'sails'. These have been described as a combination of 'side' and 'main' shells, with the latter taking the shape of an ogive vault formed by a series of arches labelled 'ribs'. The dominant geometry describing each half vault is a slice of a sphere with a radius of 75 meters, which gives all the ribs the same curvature and allows them to be notionally divided in concentric and repetitive segments. Each rib is formed by a variable number of segments with a Y-shaped cross section. All ribs start with three solid concrete segments, followed by a fourth one featuring a cylindrical void to reduce its weight, and the remaining ones designed as an open Y, closed at its top by means of precast cross bracings (fig. 2). Moreover, as each half vault feature a fan-like spherical shape all the ribs have a tapering section that increases from bottom (pedestal) to top (ridge). Mutual connection between segments of the same rib was assured by a stabilizing compression force obtained with prestressing cables running along the rib’s radius. As such the result post-tensioning forces were ‘nearly centroidal’ [7] with each rib being self-supporting upon its completion.

Each ogive arch or rib is completed with a special last segment acting as a connector between the rib and the ridge. Like the ribs, also the ridge of the vault is formed by a series of concentric precast elements.

Leaving instrumentally aside all the cast-in situ elements of the system (i.e., pedestal and tripods footings) and its special pieces (i.e., ridges, crowns and warped segments) allows one to focus on the formwork designed and tested by Hornibrook for the production of the rib segments.

As explained in the drawings, each formwork accommodated five contiguous segments. Each segment was separated by a precast bulkhead which, besides working as a formwork diaphragm, also acted as a matrix for the positioning of the spigots and the anchor plates that had to be embedded in each segment. Moreover, to assure the necessary geometrical continuity between segments, the segment last poured in the previous formwork was positioned as first in the following one (fig. 3).
Fig. 2  Explanatory diagrams showing the different types of shells and their components. On the left the typical cross-section of a main shell with the axonometric view of a rib-block with an open Y-shape section.

Formworks were made out of two moulds: an exterior one and an inner one (fig. 4). The form of the exterior one was shaped against the Y cross-section of the ribs. It was divided in two shells that could be closed and opened via a rail sliding system actioned by hydraulic cylinders placed at the base of the shells. The shells, built with a light frame structure in steel studs and plywood lining, were completed with a cast-in-situ curved spine, running along the centre-line of the rib that realized the base form of the Y stem. Once the formwork was stripped from the segment, the central spine acted as temporary support for the piece itself before it got lifted by the crane. For the fabrication of the steel inner forms, Hornibrook designed a special timber jig with two adjustable horizontal arms through which it was possible to set out the interior tapering geometry of each segment, necessary to follow the varying cross section resulting from the discretization of the sphere in slices (fig. 5). Once realized, the inner form needed to be adjusted and modified so as to allow the insertion of pockets and corbels for stressing anchors, bolts and other permanent connections. Original shop drawings show a series of so-called “modification to inside formwork” alternatives, which illustrate and detail the numerous construction variations required or imagined.

Fig. 3  Construction sequence showing the Hornibrook formwork system used to manufacture rib segments with Y-shape cross-section (photographer: Max Dupain and Associates. Records and negative archive: un-commissioned Sydney Opera House construction photographs, 1965-1972. Courtesy: NSW State Library).
Fig. 4 Hornibrook Ltd, Sydney Opera House, Stage 2. Rib Segment Formwork, Section, Frames, Detail, Segments from 1 to 5 (NSW Archive and Records).

Fig. 5 Hornibrook Ltd, Sydney Opera House, Stage 2. Special timber jig with two adjustable arms for moulding the interior formwork according to the tapering of the rib cross-section (NSW Archive and Records).
In synthesis, the drawings for the formwork articulate sets of sophisticated combinatory solutions for attaining the structural form required whilst introducing repetition and flexibility in the manufacturing of the discrete pieces. In order to do so, their producers had to consider the vertical layering of segment sub-pieces across the Y section of the rib as well as the tapered progression of the segments along the curve of the half arch, which was made possible by the introduction of sliding registers into the idea of the form. All this without losing sight of the limited, narrow space available to organise a casting yard around the footprint of the building, in itself demanding a high rate of reuse of the moulds, as well as stockage locations for the segments awaiting erection (fig. 6). Shape, length and functioning of the formwork, in other words, had to respond to architectural ambitions, structural engineering requirements, manufacturing precision and speed, site logistics, and economy of materials.

Fig. 6 The Sydney Opera House construction site (photographer: Max Dupain and Associates. Records and negative archive: un-commissioned Sydney Opera House construction photographs, 1965-1972. Courtesy: NSW State Library).

Such challenges acquire significance against the celebrated 'spherical solution' for the roof, which is by now part of architecture's modern history. On the one hand, the 'spherical solution' allowed for a conceptual macro-discretization of the sails into ribs, and for envisioning the production of the latter through a nearly industrial process. Yet, on the other hand, at the 'segment' scale, it could not foresee and solve all the engineering issues embedded in the very solution, which remained open for the construction of a roof constituted by over 2,400 precast segments, the majority of which required an ad hoc precast bulkhead, precast cross bracing, and specific adjustments to accommodate all the necessary post-tensioning apparatuses.

Such degree of detailing required the structural engineer ARUP to issue 30,000 dimensions to Hornibrook – dimensions that were promptly translated by the contractor into detail drawings often supplemented with data tables indicating variables dimensions and locations of single details. Those dimensions were generated by a system of coordinates based on the spherical configuration which was also at the base of the surveying criteria adopted for controlling both the casting yard (including the formworks) and the erection of the roof [8].

3 Contractor's agency in the project

Even such a short analysis of the construction of the formworks for the structural segments of the sails enables a series of considerations on the work conducted as well as the process that led to it. Firstly, it
shows the enormous amount of product engineering and operational planning that went into the definition of the catalogue of components and their casting procedures. Whilst responding to the building performance requirements set by the architect and the engineer, the general contractor made strategic decisions concerning sub-component geometries and combinations, moulding systems and fabrication sequences, element re-use patterns and bespoke requirements. Type and extent of the documentation produced, together with the photographic records of the operations on site, betrays the significant degree of autonomy enjoyed and exploited to this end. While the geometry of the precast components of the arches suggests differences with the streamlined aesthetics of the architectural surface of the sails, it does respond very well to both the production-related needs for modular yet flexible casting on a difficult site and the extreme complexity embedded in the task of recomposing all the pieces of the three-dimensional structural puzzle.

Hornibrook's successful search for manufacturing efficiency and assembly viability suggests that the elements of interest in the construction of the sails go beyond the definition of their overall form and the methods employed to extrude its surface in layers. Indeed, they include the composition of its discrete precast pieces and the process of manufacturing them. This because it was the set of decisions underpinning such a process that determined not only the layout and the organization of the site but also structured construction operations and quality assurance methods for critical parts of the project and important portions of its duration.

The casting of the formworks thus bears testimony to the existence of 'agency' functions on the general contractor's side, requiring vision and the ability to enforce it. As an inevitable aside, due to space limitations of this paper, it could be important to reflect on the fact that, if Hornibrook's experience and track record to this point of its history had produced a kind of manufacturing shrewdness capable to respond to the challenges thrown at them by the official professional design team, the company's actual ability to do so on the Sydney Opera House was determined contractually, by the provisions explicitly regulating work boundaries and expectations of the builder during Stage 2.

4 Design or translation of intent?
Irrespective of the importance of contracts in enabling critical contributions to project developments, did the work of Hornibrook as described amount to 'design', or did it embody the mere translation of design intent into instructions for production, as per the conventionally accepted nature of shop drawings?

If one looked at the image of the building and the compositional logics of its structural system as a whole, then the answer to the design question would be negative. By servicing a higher order concept - that of the form and the structure of the sails - the contractor's documentation and the work instructed within it would be subordinate to these main ends; as such, they would not constitute design per se. Yet, if one considered design almost etymologically - as "a problem-defining, problem-solving, information-structuring activity that, on the basis of understood conditions and rules, defined specific courses of action" - then the casting of the formworks would attain full design status.

In fact, when sketched in these terms, design activity would not be limited to what definable solely under architecture prescriptions or structural engineering work, but rather enter all the specific dimensions of the building procurement process - including at least site layout, building components production, building erection, and building use and maintenance. Such scenario would shape the idea of both 'building' and 'project' in scholarly useful ways, with 'building' becoming understood as the combined result of the implementation of multiple scope-specific designs; and 'project' indicating the social space where the gradual integration of these designs would occur, following a process of negotiation between objectives internal to each design dimension and objectives related to their integration - very much the case with the work carried out by Hornibrook on the Sydney Opera House [9].

5 Design as a broad construct
Opening the notion of design up in the way just outlined makes it plausible to turn established mental images of construction around and think of the building process, with all its ramifications, as a system of design production independent of corporative schemata - a cycle, that is, within which all the information necessary for the implementation of the building would have to be conceived and either produced or assembled. How this system organized to deliver its product, what logics it followed in doing it, what it would be constrained by, and how many units of production it would consist of would then
become the object of the discussion. Such a conceptual framework would add critical dimensions to the analysis of the design process and its dynamics, certainly by positing the importance of socio-technical diversity within the project team, and with it the relevance of sophisticated actor-networks descriptions across the history of the project [10].

Analytically, the design system of sorts determined through this exercise would be helpful for two reasons. Firstly, because it would provide a proper index of the design challenges that exist within the building process, and a measure of the substantive breadth the design task must gain to respond to them. Secondly, because it would help form a view of the building project not tied a priori to specific actors but rather open to the recording of direct or indirect design contributions, to qualify in relation to the areas of impact. By creating the conditions for isolating and then bringing together the work conducted on disparate design domains by clusters of contributors, such a multi-dimensional view of design could be used as a tool to interrogate project challenges and results, eventually to intervene on the dynamics that led to them.

The authors have a research funding application pending almost exactly on this topic in Sydney. Hopefully, it will be possible to make more than informed guesses on the efficacy of such analytical methods before too long.

Yet, the importance of the difference just articulated, essentially between 'design as product' and 'design as process', can be gauged effectively by returning to the sails of the building and the rhetoric surrounding their creation. While their canonical history celebrates the so-called 'spherical solution' as a stroke of genius on the side of the architect and the engineer, the story of the works put together by the contractor for their fabrication on-site tells a tale of work planning and ingenuity that counterbalances the myth of the 'eureka' moment by highlighting the amount of labour – intellectual as well as physical – required to make Utzon’s great idea materialize (fig. 7).

Without taking anything away from the leap of imagination that led to the solution eventually employed, the actual construction of the sails owes a huge debt to the preparatory design and engineering work by the general contractor. Indeed, the spherical solution generated a series of significant construction chain challenges, from task identification to site planning, system engineering to visualization of decisions, work monitoring to quality control, which were all tackled by the main party 'on the ground'. Hornibrook did overcome the technical issues posed by the fabrication of all the parts required through the production of copious, detailed documentation based on and refined via a long period of prototyping work, which would be difficult to liquidate as mere, although remarkable, construction management. If such documentation will necessarily remain a critical object of analysis and reflection in future studies on the building and the meanders of the technical design process, a provisional conclusion can be attempted on fairly safe grounds: for a building justly considered unique and out of time – and as such worthy of world heritage status [11] – the mundane aspects of its realization and the design challenges

Fig. 7 On the right: The rib formwork system located on the eastern side of the casting yard (photographer: Max Dupain and Associates. Records and negative archive: un-commissioned Sydney Opera House construction photographs, 1965-1972. Courtesy: NSW State Library). On the left: Hornibrook Ltd, loading diagrams for the member of the erection arch (NSW State Archive and Records).
these raised for the industry at the time may well constitute the true gauge of its ‘concrete’ achievements.

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References
The conceptual design of structures is at the heart of the design process and when the most fundamental and influential decisions are taken for a project. It merges experience, intuition, tradition, site constraints, technical solutions and, above all, the genius and sensitivity of the designers.

The International fib Symposium on the Conceptual Design of Structures 2021 generates a fruitful exchange event for academics and practitioners from engineering, architecture and other disciplines on the topic of the conceptual design of structures. The focus is placed on experiences made particularly during the design process. The discussions reflect how a project emerges, how design decisions are taken, how responsibilities are distributed, how obstacles and constraints are handled, how fundamental design principles are applied and the way the individual members of the design team collaborate.

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