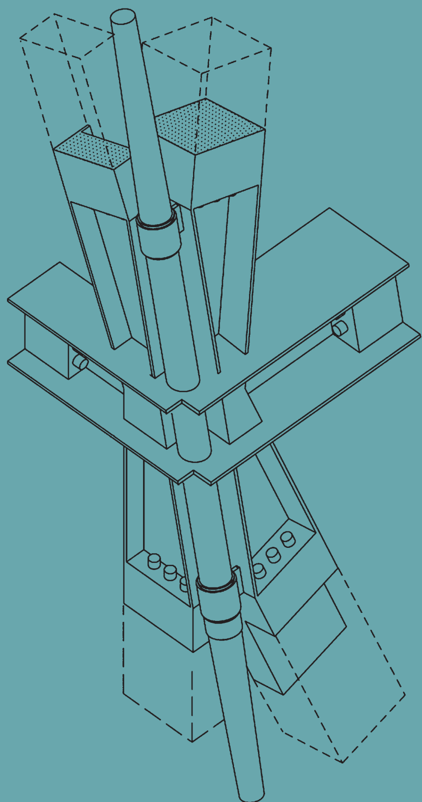
Bartlett Design Research Folios

Megaframe

External Structural Steelwork System of the Leadenhall Building



by Dirk Krolikowski
(Rogers Stirk Harbour + Partners)

Project Details

Practice:	Rogers Stirk Harbour + Partners
Designer:	Dirk Krolikowski Krolikowski has been in charge of design, development and delivery of the Megaframe structural steelwork stability system.
Title:	Megaframe: External Structural Steelwork System of the Leadenhall Building
Output type:	Building
Building:	Leadenhall Building
Function:	Office development
Location:	London, UK
Client:	British Land
Practical completion:	Topping-out, April 2013; practical completion, mid 2014
Budget:	approx. 310 million GBP overall; structural steelwork approx. 65 million GBP
Tonnage steelwork:	18,500 metric tons
Area:	55,740m^2 NL
Structural engineers:	ARUP London, UK
Service engineers:	ARUP Services London, UK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The Leadenhall Building in the City of London (CGI)

Statement about the Research Content and Process

Description

The Leadenhall Building (2005–2014) is an office development in the City of London by Rogers Stirk Harbour + Partners. The external structural system of the 51-storey tower is unique and pioneering with a view to the integration of architecture and engineering. Since 2005, Dirk Krolikowski has led the design, development and delivery of the Leadenhall Building's structural stability system, the Megaframe.

Questions

The building aims to innovate three areas of architectural design:

1. How to integrate architectural and structural requirements to achieve the desired tectonic expression and incorporate architectural interface requirements.
2. How to develop a digital workflow that integrates a scattered software ecology in a multi-model environment.
3. How to develop a design approach that enables separation of service core system and structural stability system while maintaining the desired architectural language.

Methods

The structural system of the Leadenhall Building develops its research propositions through:

1. Practice-led, interdisciplinary research to develop strategies for the stability system as a main architectural component of the building's expression.
2. The development of an integrated digital design team workflow to facilitate the development of a comprehensive digital prototype.
3. The development of a diagram that separates the service core from the main structural stability system.

Dissemination

The Leadenhall Building has already been exhibited and published in numerous international locations and magazines. Due to its prominent location and its architectural significance, it is expected to attract major attention in the form of publications and critiques upon completion.

Statement of Significance

Awarded first prize in the 122 Leadenhall Street Competition, a major international architectural competition, against competitors including Grimshaw Architects and Wilkinson Eyre. The team won the Bentley Excellence Award (2007) for the exemplary implementation of digital tools. Major awards are expected after building completion in 2014.

2 *(overleaf)*
Node 5 and 6
assembled on site


25

Introduction

The Leadenhall Building is a 51-storey office building in the City of London, designed by Rogers Stirk Harbour + Partners with ARUP as structural engineers. The author is lead for the Megaframe, the exposed structural system, a highly customised external main stability system, unprecedented at this scale for an occupied building and a major subject of research and innovation throughout the process. The implementation of digital tools throughout the advanced design workflow and the digital fabrication of the structure were essential to the successful integration of architecture and engineering. [fig. 1 & 2]

Aims and Objectives

1. The design of the external, structural steelwork system not only required interrogating existing codes and innovating methods of analysis for its engineering, but also demanded pioneering an architectural approach with an interdisciplinary emphasis. The objective was to integrate engineering principles with the demand for a highly architectural design solution. This led to extensive research for the development of a clear tectonic language, which displays the intrinsic logic of the system.
2. High levels of interdisciplinary integration made it necessary to develop a digital prototype, capturing design team knowledge and serving as a means to test and develop the system to the highest comprehensive level achievable. This was facilitated by an effective digital workflow from inception to fabrication.
3. A key to the efficiency, flexibility and architectural expression of the design was the separation of service core system and structural stability system. Extensive research into the structural diagrams, which supports the programmatic approach, was required to understand how issues of stability and fire protection can be overcome, while maintaining the desired architectural expression.

Questions

4. The key research question was how to integrate architectural and structural requirements to achieve the desired tectonic expression and incorporate architectural interface requirements. There are no known precedents for this kind of structural system, consequently base research into structural engineering and fabrication aspects, while achieving the highest degree of architectural articulation of the kit-of-parts philosophy, was required. The main focus of research was to find global structural system principles, which can manifest their intrinsic logic in the architecture.

5. Due to the size of the project team, the number of employed software tools is vast and eclectic. The underlying research question was how to develop a digital workflow that integrates a scattered software ecology in a multi-model environment.

6. A further fundamental research question was how to develop a design approach that enables separation of service core system and structural stability system while maintaining the desired architectural language.

3 *(previous page)*
Site photo taken from Leadenhall Street (September 2012). Lifting operations take place 24/7. Most large elements are assembled during the night shifts as day traffic does not allow for delivery of the 27m-long columns. Due to the high degree of prefabrication, the superstructure is expected to be erected in 16 months.

Context

The concept of structural expression is not new and its principles refer to gothic architecture and Victorian engineering, among others. However, the Megaframe moves beyond known precedents owing to its scale, level of interdisciplinary integration of practices and implementation of digital tools. The John Hancock Tower, Chicago, by SOM, expresses its structural system similarly, but is effectively a clad structure, where the actual structural system and its components are not expressed. This leads to the display of merely a diagram and not the structure and its relationship to the building itself. In this context the Leadenhall Building can be compared to the Eiffel Tower, which, however, is not an occupied building. Furthermore, the Leadenhall is recognised as a prime example in the industry for its implementation of digital tools from inception through development down to fabrication and assembly. Digital prototyping led to an unprecedented high degree of prefabrication for a high-rise building with no wet trades for the superstructure on site. [fig. 3]

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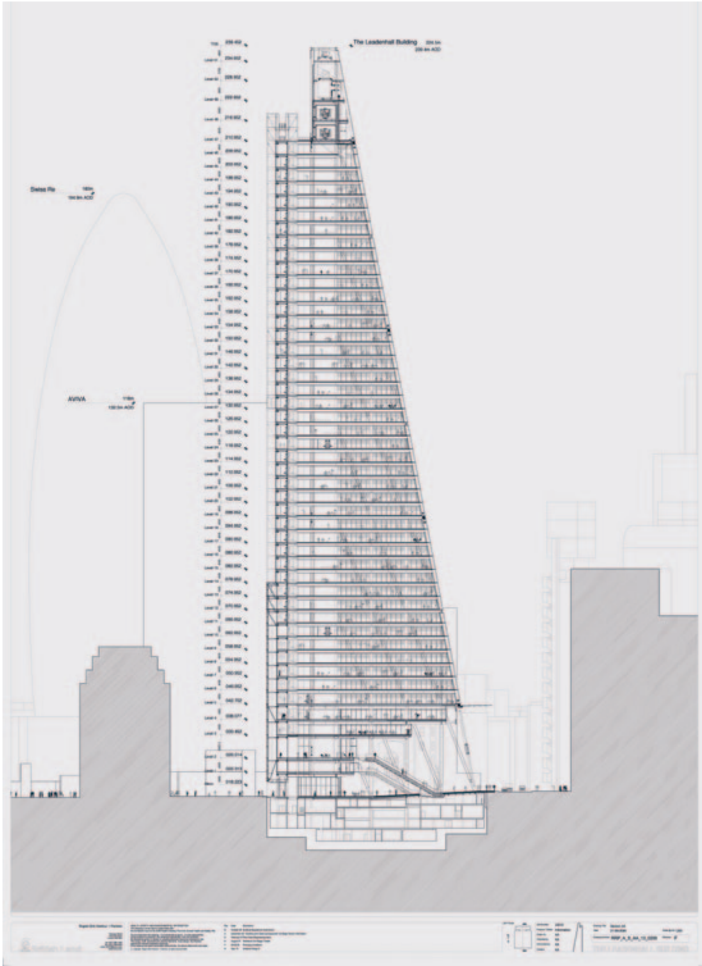
Photo of assembly site taken from West London (January 2013) — the Megaframe is a key component of the architecture itself.



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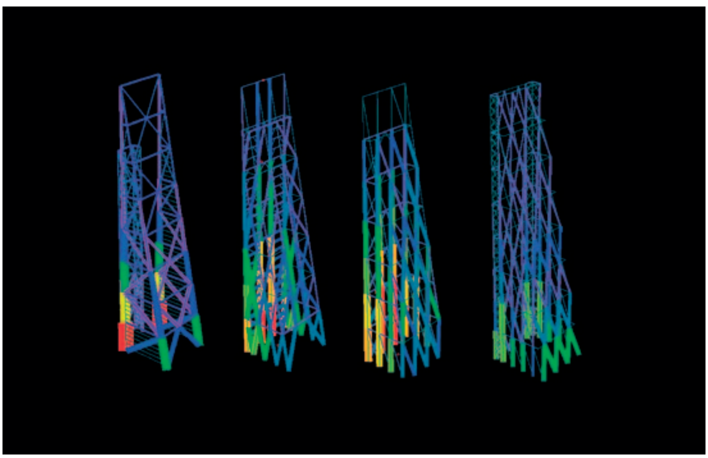
Cross-section north–south. The external system is subdivided into eight 28m-high Megalevels, accumulating to an overall height of 224m.



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Megaframe diagrams by ARUP describing the development of the geometric layout – they illustrate that an introduction of columns to the flank and north elevations of the building reduced the eccentricity effects of the asymmetric geometry significantly, spreading the loads more equally.

Methods

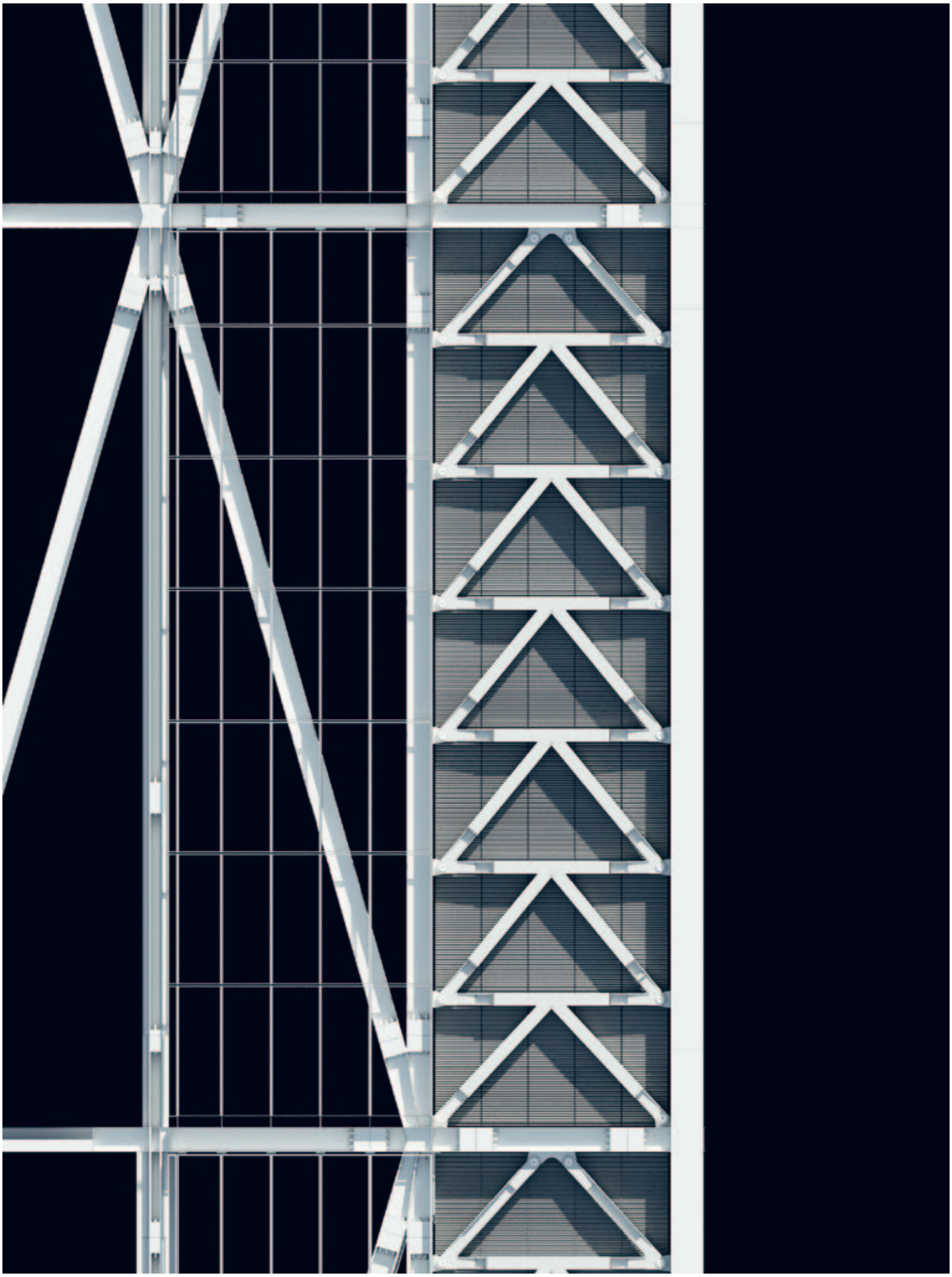
The Leadenhall Building develops its research propositions through specifically architectural practice-led processes.

The development of the Megaframe

The main structural stability system of the Leadenhall Building is a tapered braced tube with internal columns, referred to as the Megaframe. The external system is subdivided into eight 28m-high Megalevels with seven storeys of office space each, accumulating to an overall height of 224m. The overall steel tonnage of the building is 18,500 metric tons which, as a comparison, approximately equates to the gross tonnage of Brunel's SS *Great Eastern.* The design research was driven by the aim of integrating structural and architectural performance to the highest possible – and, at this scale, an unprecedented – degree. The fact that the structural system is not clad but external, forming an important part of the external architectural language, informed the 'architectural steelwork is structural steelwork and vice versa' approach.

Base geometry

The Megaframe base geometry has undergone an extensive variant study. Architecturally it is driven by floor heights, footprint, cladding grid and planning requirements. The distinctive taper of the frame geometry derives from a view corridor restriction towards Sir Christopher Wren's St Paul's Cathedral. Tapering the building back assured compliance with view corridor requirements, while allowing sufficient floor space at upper levels with higher lease returns. During analysis of the actual geometry configuration it was determined that an introduction of columns to the flank and north elevations of the building reduced the eccentricity effects of the asymmetric shape significantly, spreading the loads more equally. However, the south elevation, as least loaded elevation, remained without vertical columns, requiring the diagonals to act as vertical loadbearing elements and diagonal bracing members at the same time. In order to standardise cladding interfaces, as well as a strategy for structural response to vertical load accumulation, structural member envelope sizes remain constant throughout the height of the building. [fig. 5–7]



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7
North elevation drawing with secondary bracing

8
Node type 7 in fabrication. Node 7 incorporates the thickest plate sizes of the whole Megaframe (180mm).

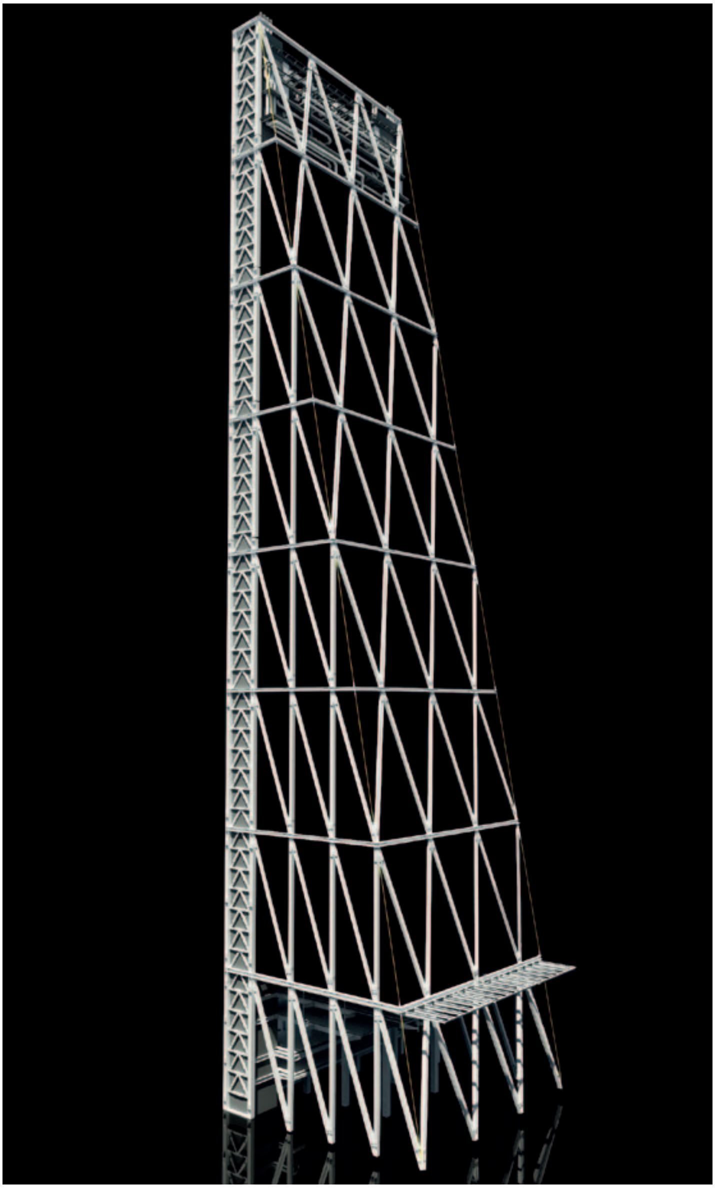
Development of the Meganodes

A key driver for the geometry has been the kit-of-parts approach to the Megaframe system where every element shares a developed overarching tectonic logic derived from an intensive dialogue among all participants, mainly architect, engineer and fabricator. In order to understand downstream parameters such as fabrication limitations and constraints governed by actual assembly, fabricators have been engaged into PCSA (Pre-Construction Service Agreements) from early concept stage. Overall, the perimeter Megaframe consists of approx. 475 individual parts (secondary K-Bracing system) encompassing varying plate thicknesses, incoming member angles, and connection and façade interface requirements. [fig. 7]

These elements vary in tonnage from 60 metric tons to 12 tons and incorporate plates thicknesses from 180mm to 25mm. In particular, the so-called Meganode connections have been the subject of many years' intense research and development. There is no precedent for the design of this kind of external node. In order to achieve a consistent systemised approach to the highly differentiated external frame, typological node connections have been driving and informing the individual instances of a node. These node connections have been geometrically defined as a family of components, sharing the same tectonic logic. The component family has about 12 node types with individual sub-types [fig. 2–4]. These types do not vary in terms of member envelope sizes but respond to varying structural requirements, due to vertical load accumulation, by variation of individual flange and web dimensions and their steel grade. [fig. 8–10]

8

Node 6 entails the most onerous geometry. This node occurs (six times overall in three different variations due to different plate sizes) at the meeting of the inclined south and triangular flank faces and deals with complex member relationships, converting loads from the diagonal members on the south façade into vertical flank columns. Its resolution ensures an optimised load path while satisfying the architectural geometric requirements. While incorporating the facade supporting Megahanger in a birds-mouth detail, node 6 has set the basic rules for the design of the other node types. [fig. 12–18]



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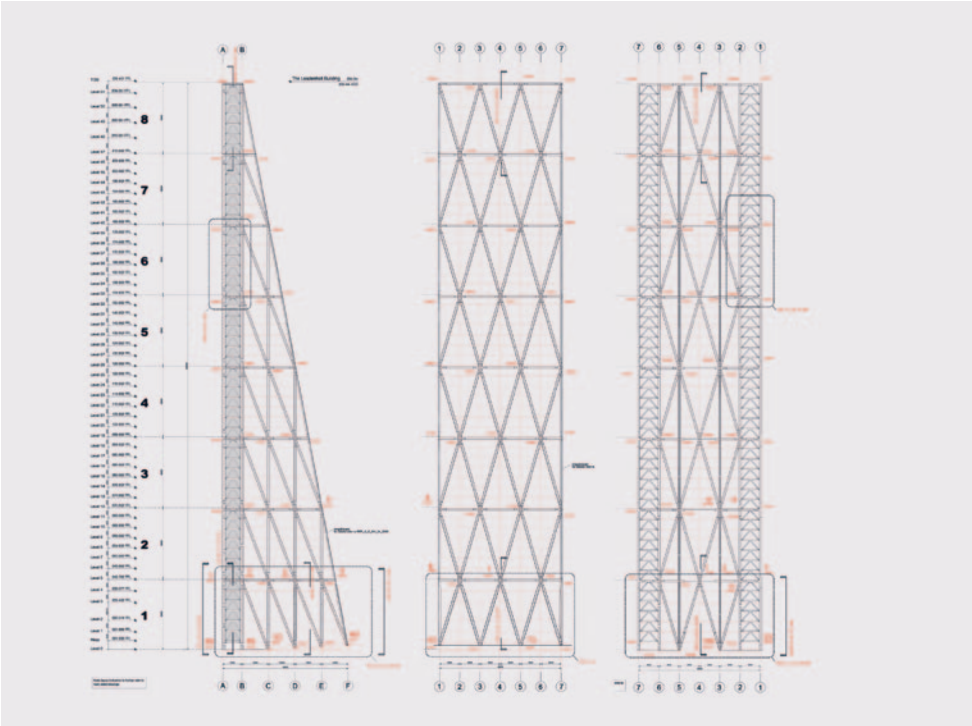
Megaframe geometry model. The structure is subdivided into eight 28m-high Megalevels with seven storeys of office space each, accumulating to an overall height of 224m.

10
Megaframe elevations with node naming convention. In order to introduce a shared tectonic language the nodes have been developed as a family of components with sub-types.

11
Node type 7 which occurs on the inclined south façade.
A complex façade interface had to be considered as part of the architectural requirements.



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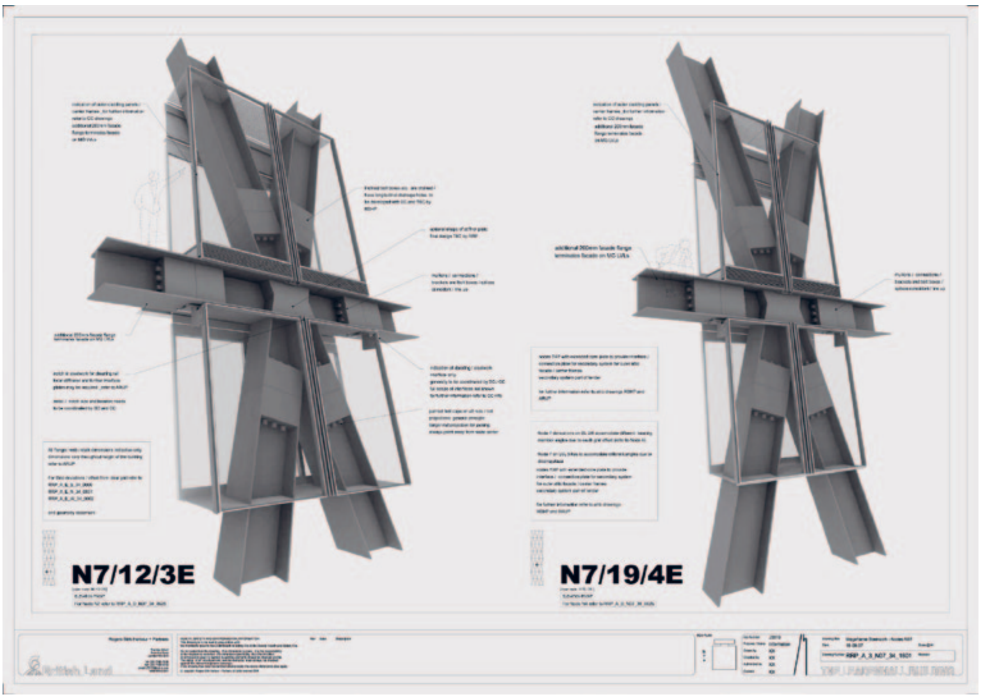

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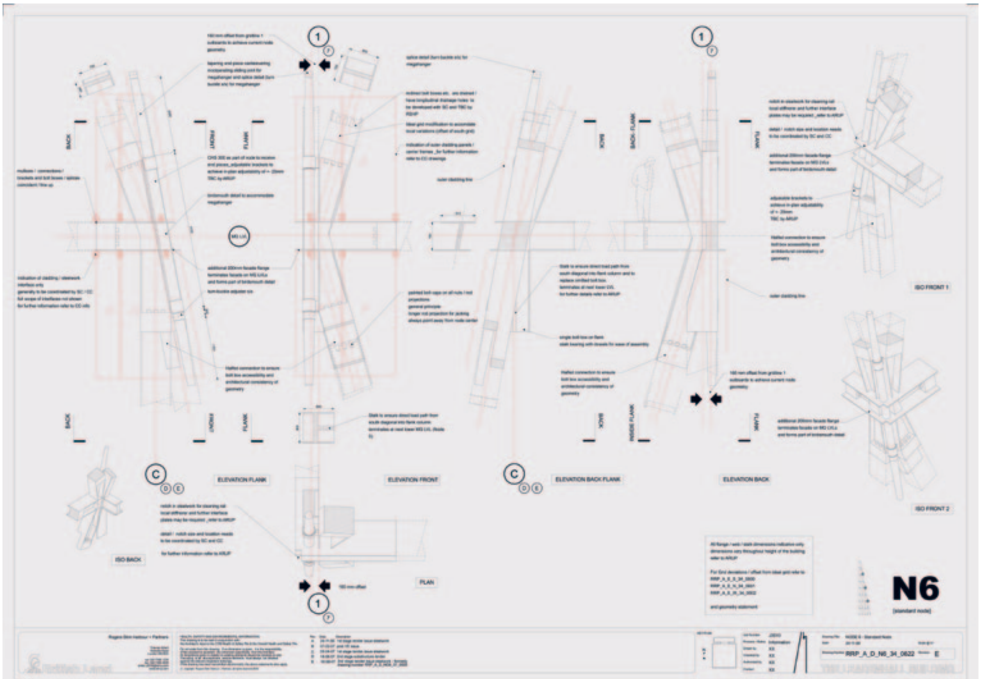

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Architect's drawing of Node 6. Node 6 has set basic rules which inform the geometry of all other nodes.

On the east and west elevations, the outer half of the Megaframe diagonals act in shear as bracing and are required to be half the depth of the columns. This has led to the development of a node connection (node 5) with thick core plates to transfer loads. This principle improves the buildability and allows ease of assembly while it reduces the complexity of the node design. Due to the building geometry, the vertical load distribution is concentrated toward the north. The loads on the south are relatively small and consequently do not require columns in addition to the diagonal members. [fig. 18]

North façade nodes are treated as derivations of those on the south but with the integration of columns. While using the principle of the split column developed on the flank façades, a special column type has been developed here to minimise the impact on the node design. The column is a channel section with two projecting 'stalks' which interfaces with the diagonal-bracing, north-core connections and terminates the cladding system. These have become known as the 'Space Invader' columns. Node 10 (also known as 'Union Jack') has nine incoming members (including Northcore connection) and as such entails characteristics of all other node types. [fig. 19–23]

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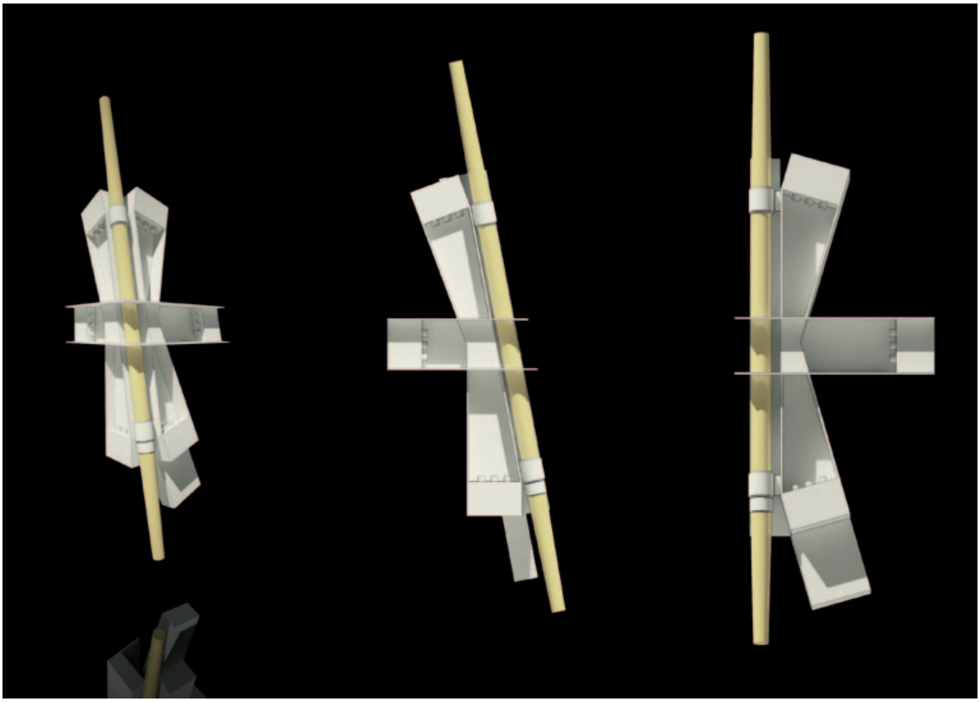
Node 6 in fabrication

14
Node 6 ground with intumescent film applied

15
Node 6 after the application of finishes, ready for component sign-off by RSHP

16
Node 6 at level 19 installed with framing interface



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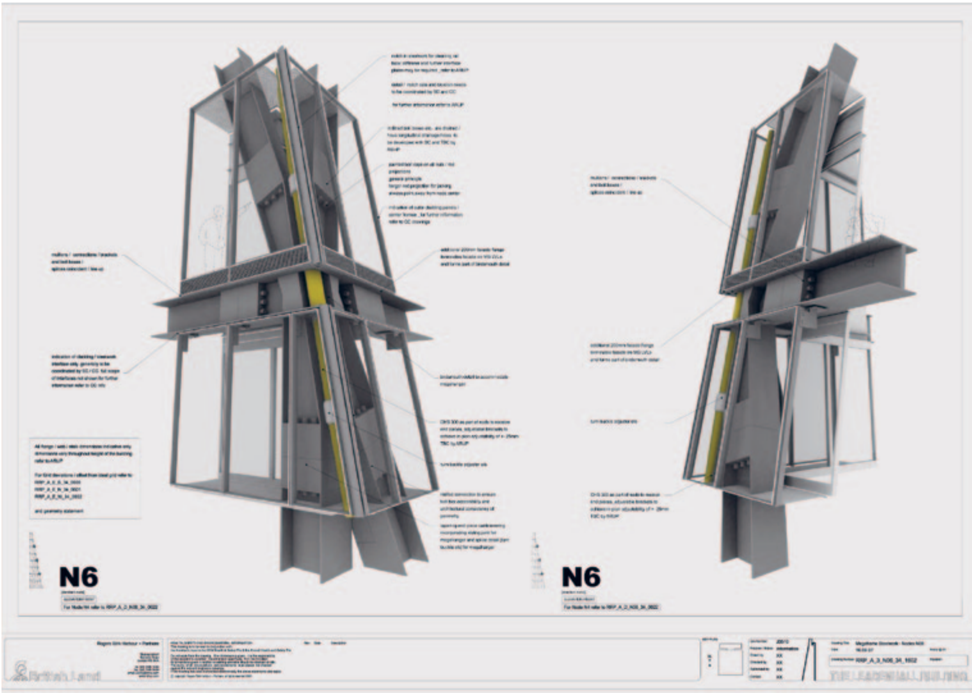
Node type 6 is the most complex type. It incorporates the façade- supporting Megahanger in a birds-mouth detail.



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Node 6 with façade interface

19 *(overleaf)*
Node 6 in fabrication


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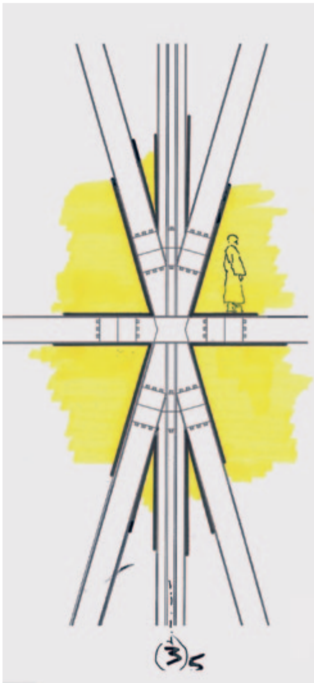

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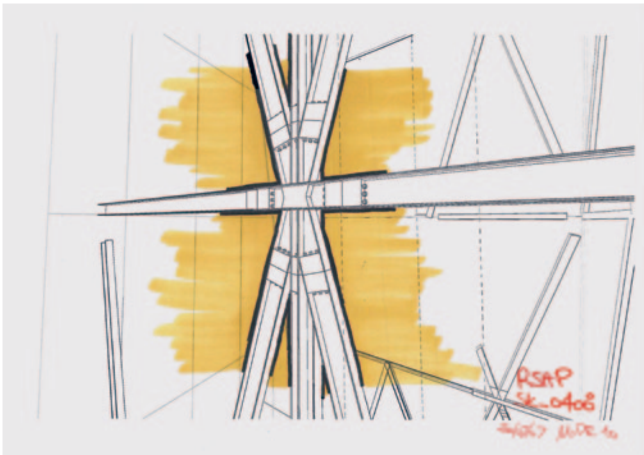

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Node 10 sketch. Due to its geometry node 10 is also known as 'Union Jack'.

21
Sketch of node 10 in perspective

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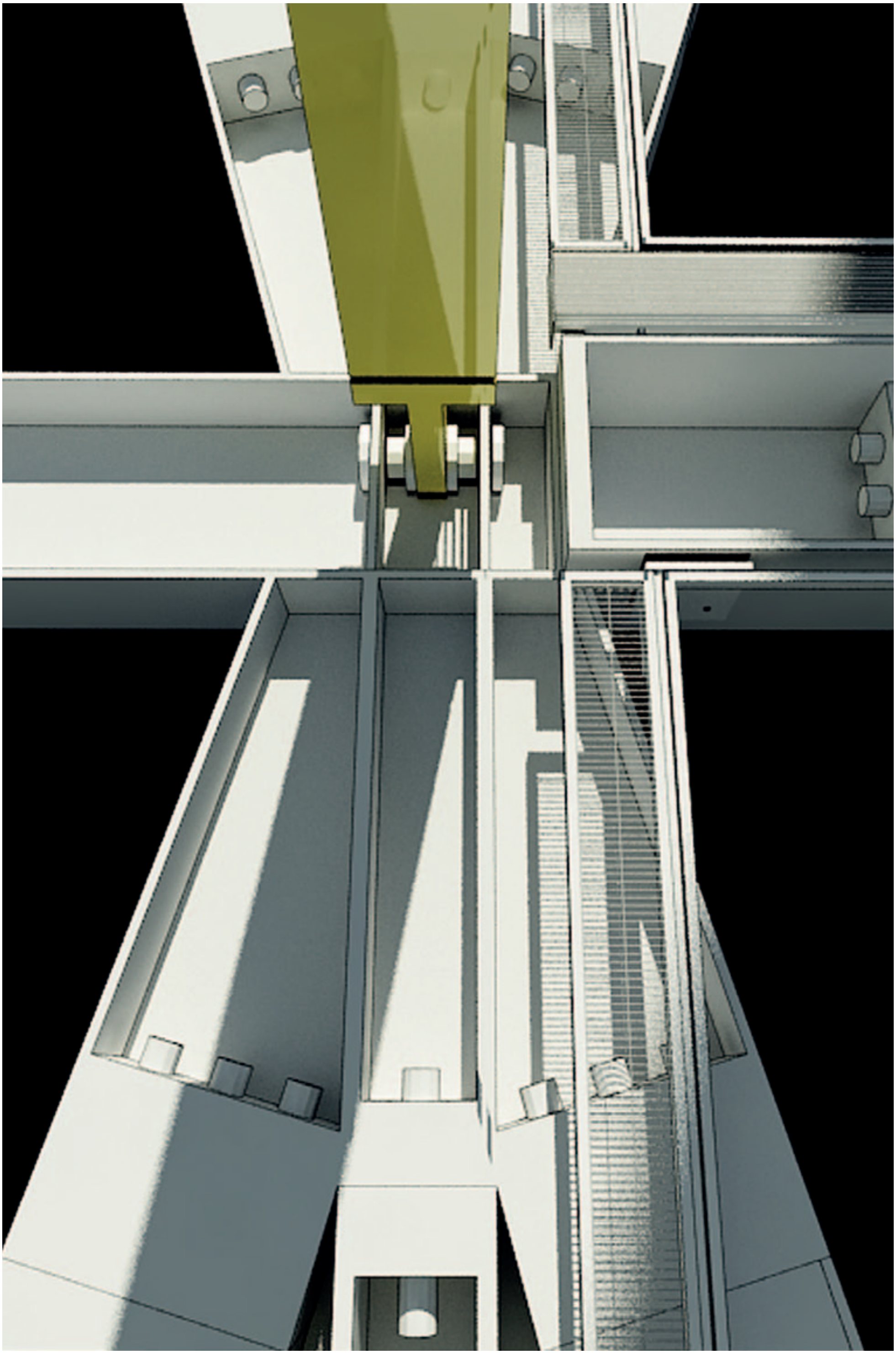
Node 10 model with double-stalk 'Space Invader' column to receive Northcore connection



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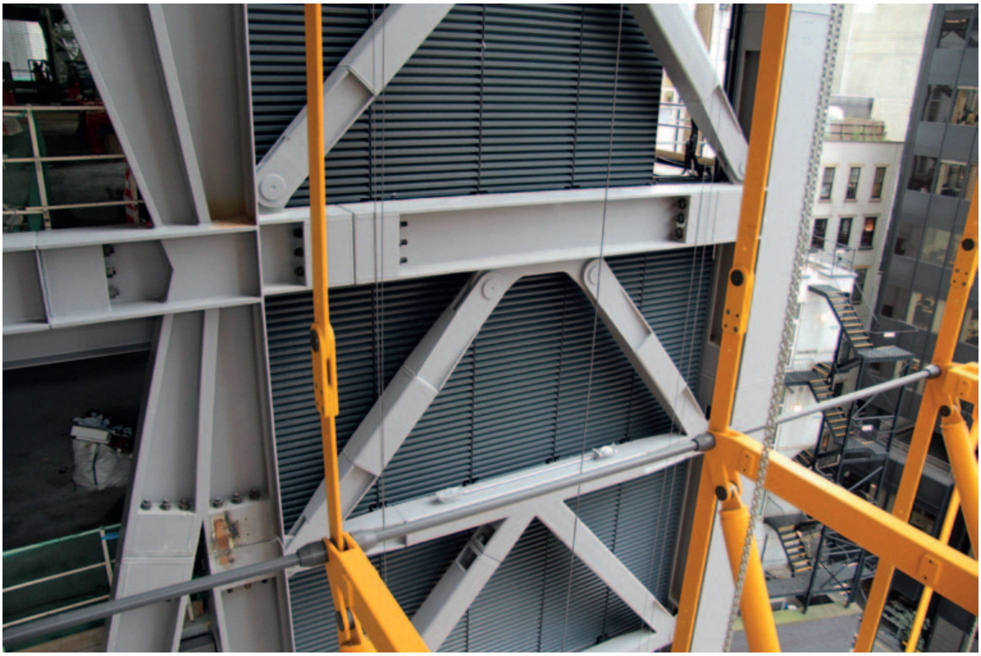
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Node 11. Node 10
sub-type installed

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24
South wall nodes 7 and 6 at level 40 with lifting gear still attached, the so-called ‘Lollypops’. Picture taken from inside of building

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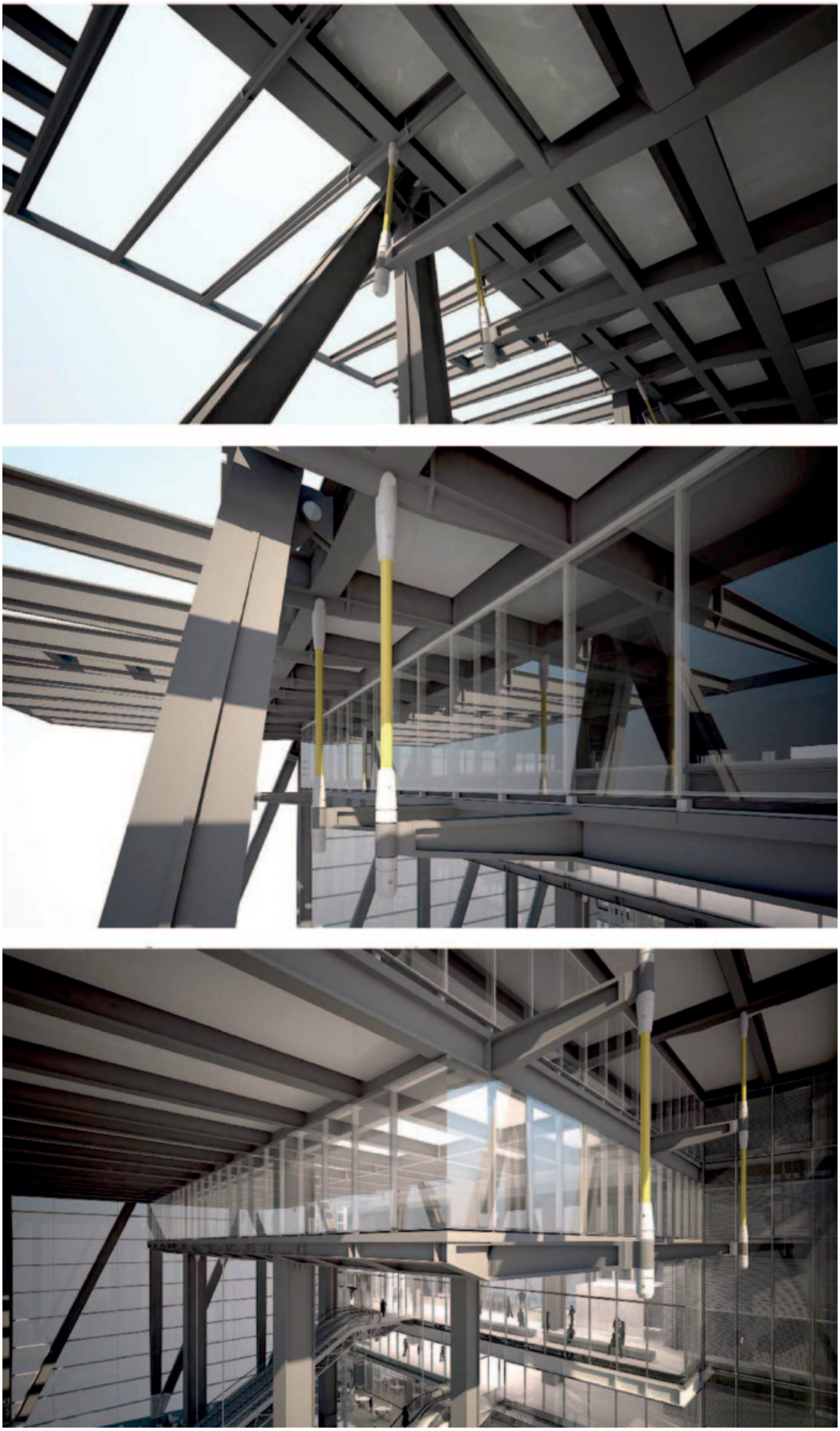
25
Sub-assembly of node 11 with Bolt-Box stiffener arrangement. Endplates are not yet installed.

26
Galleria framing model. The tectonic language of the frame has been maintained by rigorous application of developed design principles.



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The bolt-box connection

While early schemes favoured a flange-dominant scheme, the eventual refinement of the connection strategy led to a web-dominant system to ensure optimised load paths throughout the system while meeting the architectural requirements of the connection strategy.

The developed unconventional Bolt Box solution incorporates three to six highly pre-stressed bolts in a stiffener assembly mitigating a potential opening-up under certain load cases. It was an architectural requirement to establish the connections in the actual envelope of the member sections to maintain the tectonic language and limit space take of the external frame. [fig. 25]

Secondary steel design

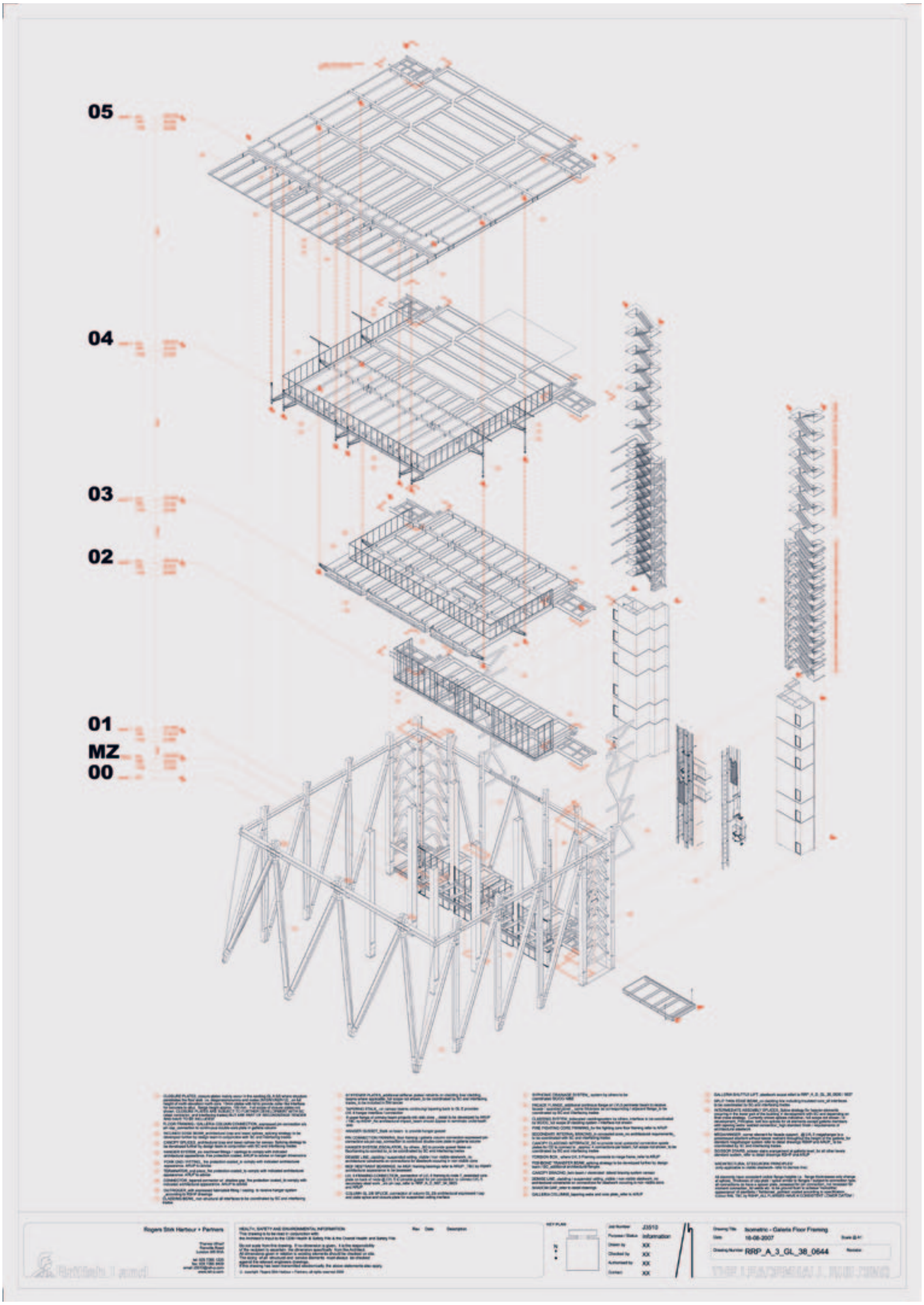
The design of the secondary steelwork framing has undergone the same level of tectonic interrogation and development that the external frame has been subject to. The framing structure in the Galleria (lowest Megalevel at GF level) expresses its hierarchy of components legibly. [fig. 26 & 27]

Further research developments

The intumescent paint system – The architectural expression of the structural system was heavily reliant on the availability of an intumescent paint system which could achieve the required 90 minutes fire rating and withstand the external environment conditions at great height. The only paint system that fulfilled the given requirements was an epoxy composite system which has not been applied yet at this scale. The chosen system has so far been used for non-architectural industrial applications such as offshore platforms. Research and development into the application of the system in an architectural context was necessary to prove feasibility.

Active alignment – For several structural reasons the building deforms during erection. In order to mitigate those movements (e.g. settlement) and tolerances it has been decided to active align the building during erection. The flank diagonals are temporarily fitted with 6 × 600 kN jacks on six locations which equals about 22,000 metric tons capacity. This force is used to pull or push the building straight, based on survey information. The fact that active alignment was crucial to the erection of the structure also proves its conceptual similarity to the Eiffel Tower, which, albeit less sophisticated, required similar methods during erection.

27
Isometric model extract. All framing systems in the Galleria are exposed and in a clear and legible relationship.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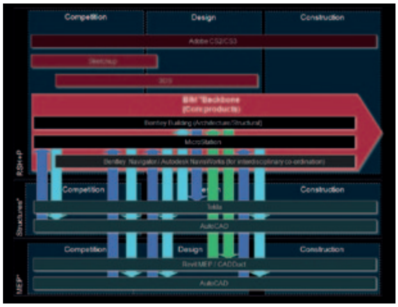

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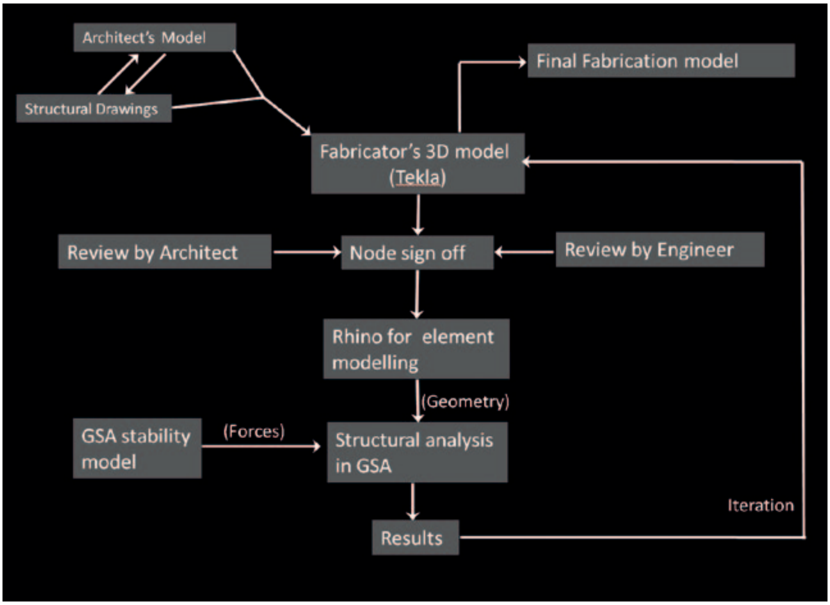

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A complete digital prototype has been developed aiding design, fabrication and assembly processes.

29
An accurate map of involved software technologies and their compatibility helps to forecast workflow issues. This map is dynamic and changes throughout the design process.

30
Diagram of workflow for model sign-off

Digital prototyping

Digital tools and the actual implementation thereof have been a key area of investigation throughout the whole design process down to fabrication. Early system design has been carried out through the evaluation of prototype variants of the Megaframe, which have been tested globally with engineering analysis tools. These were in turn architecturally verified with an early-stage information model which finally, over many model generations, became a comprehensive digital prototype, required to develop the complex system. [fig. 28]

Best of Breed

Component design required pioneering a more refined approach for model verification. Sophisticated system analysis suggests a 'Best of Breed' approach to employed modelling tools in order to address the various data analysis needs of design team members. The 'Best of Breed' approach to digital tool choice has so far succeeded over integrated systems, as individual systems offer broader functionality. As a consequence big project teams produce an ecology of software tools with individual outputs. In order to establish a consistent digital workflow a comprehensive strategy to carry out system-verification in a multi-model environment had to be developed. Software tools involved have been analysed and mapped to understand their compatibility in order to forecast workflow issues. [fig. 29]

Digital workflow

A rich digital tool ecology requires a distilled and refined digital workflow among design team members to achieve a format-independent approach. Figure 30 captures a conceptual example of design and digital workflow developed, allowing for re-evaluation and calibration of design team data in a multi-model environment. Basic parameters are a shared model space and data structure conventions. Throughout model evolution, downstream aspects of fabrication and assembly could be considered during concurrent design activities. These aspects included design space considerations of available robotic milling equipment, availability of thick plate material and weldability of overall node assemblies. This downstream knowledge was harvested and introduced into the workflow via PCSA, which were in place to facilitate an accurate understanding of production system performance and involved technologies. It was clearly identified that, due to the nature of the Megaframe, allowing interdisciplinary non-linear design exploration throughout the process, was paramount. Parametric modelling of geometric as well as non-geometric data models allowed feedback loops. It further increased flexibility in testing, prototyping and evaluation of variants while capturing developed design logic. Several model generations enabled the data and analysis methods to be refined, proving to be key to the accomplished result. [fig. 30]

Final fabrication-model generation and fabrication

The final generations of information models were fabricator-led and underwent a two-stage sign-off procedure. The first stage entailed material take-off models with determined geometry and the second stage a phased final fabrication model, including all secondary design connections. During approval, full geometry and interface checks were carried out. Exact assumptions of fabrication system performance in upstream design processes resulted in a minimal degree of model re-calibration. The notion of a file-to-fabrication process has transformed from an ideological aim into an implementable strategy. The developed design team information-handling methods enabled a holistically informed, interdisciplinary design process leading to a comprehensive virtual prototype. The importance of upstream design activities, taking fabrication parameters into account, significantly reduced 'through-put' time, realising value through reducing tolerances, and minimising and even eliminating error. Among others, these parameters were weldability of plate assemblies, robotic milling design space and crane capacities for assembly. The implementation of robotic milling into the fabrication process decreased system complexity significantly by reducing fabrication tolerances. [fig. 31]

Separation of service core system and structural stability system

A key to the efficiency, flexibility and architectural expression of the design was the separation of the service core system (the Northcore) and the structural stability system. Extensive research into the structural diagrams, which support the programmatic approach, was required to understand how issues of stability and fire protection can be overcome, while maintaining the desired architectural expression. The core gains its lateral stability from being attached to the Megaframe via a pin joint connection [fig. 20]. There is no known precedent for the separation of stability system and service core for a building of this height. [fig. 32]

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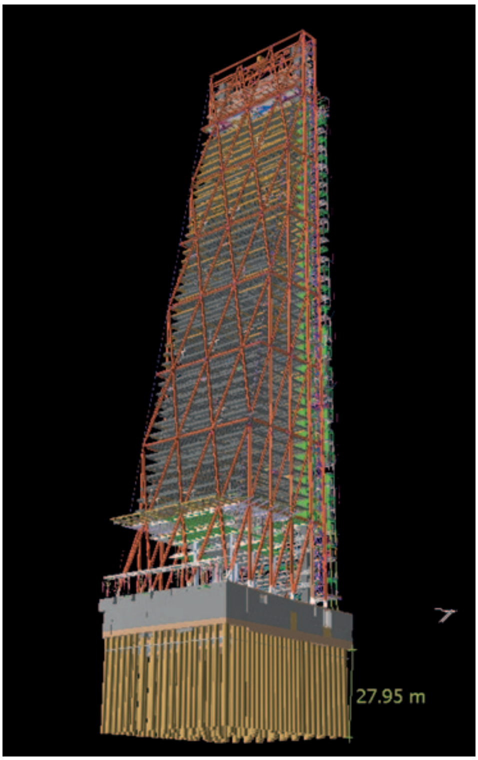

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31
3d scanner surveying the fabricated node carcass. The 3D model of the Megaframe is used during assembly to calibrate the final node component and machine endplates to sub-millimetre accuracy.

32
Screenshot of the complete digital prototype

Dissemination

Even before completion, the project has been the subject of several invited talks and international conference contributions, as well as reviews.

Exhibition

Richard Rogers + Architects: From the House to the City
(curated by Richard Rogers and Olivier Cinqualbre).
Touring exhibition: Centre Pompidou, Paris (Nov 2007–Mar 2008)
Design Museum, London (Apr–Aug 2008)
CaixaForum, Barcelona (Mar–Jun 2009)
CaixaForum, Madrid (Jul–Oct 2009)
Taipei Fine Arts Museum, Taiwan (Mar–May 2010)
Urban Redevelopment Authority, Singapore (May–Aug 2011)
International Finance Centre Mall, Hong Kong (Jun 2012)
Capital Museum, Beijing (Sep–Nov 2012)

Lectures

Dirk Krolikowski, 'The Leadenhall Building', Council on Tall Buildings and Urban Habitat Conference, London, 2013.
Dirk Krolikowski, 'Digital Prototyping – The Leadenhall Building', Construction Industry Research and Information Association, London, 2013.
Dirk Krolikowski, 'Digital Prototyping – The Leadenhall Building', Royal Institution of Chartered Surveyors, BIM National Conference, London, 2013.
Dirk Krolikowski and Damian Eley, 'The Leadenhall Building', ARUP, London, 2012.
Dirk Krolikowski, 'Digital Practice', Royal Institution of Chartered Surveyors, I.E. Business School, Madrid, 2012.
Dirk Krolikowski, 'Parametric design of structural steelwork', Smart Geometry, Munich, 2008.
Dirk Krolikowski, 'Bentley Excellence Award – The Leadenhall Building', Bentley Conference, London, 2007.
Dirk Krolikowski, 'Building Information Modelling in Large Project Teams', BIM Forum, London, 2007.

Talks at universities

RWTH Aachen, Germany
University of Koblenz, Germany
University of Greenwich, UK
Cardiff University, UK
Nottingham University, UK
The Bartlett, UCL, London, UK
TU Munich, Germany
I.E. Business School, Madrid, Spain
University of Regensburg, Germany
Manchester University, UK

Publications

Dirk Krolikowski, 'Design for Fabrication – Digital workflow and downstream fabrication system performance – Case study: The Leadenhall Building' in *Proceedings of the Annual International Conference on Architecture and Civil Engineering* (Singapore, 2013).

Dirk Krolikowski, 'Node 7' in *Sketch/Artefact* (catalogue for exhibition and auction), Fondation Architectes de l'urgence, Paris, 2011. [Other contributors include Tadao Ando, Mario Botta, Massimiliano Fucsas, Richard Meier, Claude Parent, Renzo Piano and Robert Venturi.]

Richard Rogers and Dirk Krolikowski, 'The mind informs the matter' in *Wendepunkt(e) im Bauen – Von der seriellen zur digitalen Architektur* (ed. Rainer Barthel, Roland Krippner, Frank Petzold), Munich: Edition DETAIL, 2010 (pp. 209–10).

Dirk Krolikowski, 'Developments in high-rise building' in *High Rise Towers and Tall Buildings 2010: Design and Construction of Safe and Sustainable High Rise Structures: Conference Proceedings* (ed. Konrad Zilch and Daniel Dunkelberg), TU Munich, 2010 (pp. 72–73).

Dirk Krolikowski, 'The comprehensive designer' in *Konstruktion* (ed. Mirko Baum), RWTH Aachen, 2009 (pp. 6–7).

Related publications by the researcher

pp. 38–42
Dirk Krolikowski, 'Design for Fabrication – Digital workflow and downstream fabrication system performance – Case study: The Leadenhall Building', in *Proceedings of the Annual International Conference on Architecture and Civil Engineering* (Singapore, 2013).

p. 43
Architectes de l'urgence

p. 44
Dirk Krolikowski, 'Node 7', in *Sketch/Artefact* (catalogue for exhibition and auction), Fondation Architectes de l'urgence, Paris, 2011. (Other contributors include Tadao Ando, Mario Botta, Massimiliano Fucsas, Richard Meier, Claude Parent, Renzo Piano and Robert Venturi.)

pp. 45–47
Richard Rogers and Dirk Krolikowski, 'The mind informs the matter', in *Wendepunkt(e) im Bauen – Von der seriellen zur digitalen Architektur* (ed. Rainer Barthel, Roland Krippner, Frank Petzold), Munich: Edition DETAIL, 2010: 209–10.

pp. 48–49
Dirk Krolikowski, 'Developments in high-rise building', in *High Rise Towers and Tall Buildings 2010: Design and Construction of Safe and Sustainable High Rise Structures: Conference Proceedings* (ed. Konrad Zilch and Daniel Dunkelberg). TU Munich, 2010: 72–73.

pp. 50–51
Dirk Krolikowski, 'The comprehensive designer', in *Konstruktion* (ed. Mirko Baum), RWTH Aachen, 2009: 6–7.

Related writings by others

pp. 53–65
Volker Mueller and Makai Smith, 'Generative Components and Smartgeometry: Situated Software Development' in *Inside Smartgeometry: Expanding the Architectural Possibilities of Computational Design* (ed. Brady Peters and Terri Peters), Chichester: Wiley, 2013: 142–153.

pp. 67–75
Herbert Wright, 'Motioning a table', *Blueprint* No. 325 (Apr 2013): 44–51.

pp. 76–77
Pamela Buxton, 'Greater London', *Building Design* (Issue 02/11/2012): 14–15.

pp. 79–83
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