MIDDLE EAST TECHNICAL UNIVERSITY
DEPARTMENT OF ARCHITECTURE / BUILDING SCIENCE PROGRAM

BS 536
STUDIES ON TALL BUILDINGS: DESIGN CONSIDERATIONS
Spring 2014-2015

Case Study: **The Leadenhall Building**
by
Ozan Taşlı

Submitted to: Assoc.Prof.Dr. Mehmet Halis Günel
Assist.Prof.Dr. Bekir Özer Ay

LEADENHALL BUILDING – PROJECT FACTS


Fig. 2: Aerial view of Leadenhall Building, retrieved from https://www.pinterest.com/pin/500884789779834437

Official Name : **The Leadenhall Building** [1]
Other Names : **The Cheesegrater Building** [1]
Construction Period : **2011 - 2014** [1]
Location : **London | England** [1]
Architect : **Rogers Stirk Harbour + Partners** [1]
Building Function : **Office** [1]
Developers & Owners : **British Land and Oxford Properties** [1]
Architectural Height : **224 m / 735 ft** [1]
Floors Above Ground : **50** [1]
Floors Bellow Ground : **4** [1]
Lettable Area : **56,670 m²** [1]
Number of Elevators : **24** [1]
Gross Floor Area : **86,414 m² / 930,153 ft²** [1]
Construction Cost : **£286 million** [2]
Style : **Structural Expressionist** [2]
Regional | National | City Ranking : **21 | 4 | 4** (by year 2015) [1]
Structural Engineers : **Arup** [1]
Aspect Ratio (h/d) : 4.68

1: The Leadenhall Building Facts | Retrieved from http://skyscrapercenter.com/building/the-leadenhall-building/1194
2: The Leadenhall Building Facts | Retrieved from http://www.skyscrapernews.com/buildings.php?id=49

LEADENHALL BUILDING – PROJECT FACTS


Fig. 3: West facade of Leadenhall Building, retrieved from http://www.rsbpg.com/wp-content/uploads/2015/01/View-of-Leadenhall-building.jpg

Construction Material : **Steel** [1]
Structural System :

- According to Gunel;
  Trussed – Tube System [3]
- According to Taranath;
  Trussed Tube System [4]
- According to Smith;
  Braced Tube Structure [5]
- According to Buyukozturk;
  Trussed Tube [6]

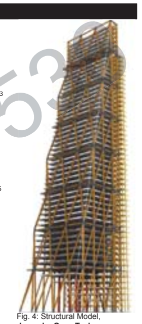
Fig. 4: Structural Model, **drawn by Ozan Taşlı**

1: The Leadenhall Building Facts | The Skyscraper Center, Retrieved from http://skyscrapercenter.com/building/the-leadenhall-building/1194
3: Gunel, H. & Ilgın, E. (2014). Tall Buildings: Structural Systems and Aerodynamic Form. Routledge – Taylor and Francis Book Company
4: Taranath, B. (1998). Steel, Concrete & Composite Design of Tall Buildings, New York: McGraw – Hill Book Company
5: Smith, B.S. & Coull, A. (1991). Tall Building Structures: Analysis and Design. New York: Wiley
6: Buyukozturk. O. (2004). High Rise Buildings - Evolution and Innovations. Cambridge: MIT

LEADENHALL BUILDING – TIMELINE & DECONSTRUCTION

Planning Consent	Start Demolition	Project Suspension	Joint Venture	Restart	Contract Placement	Pre-let	Completion	Opening
2005	2007	2009	2010	2010	2011	2011	2013	2014

Timeline, **prepared by Ozan Taşlı** (Source :http://www.theleadenhallbuilding.com/wp-content/uploads/2014/08/Exhibition_Totem_1.pdf)


Fig. 5: Deconstruction of P&O Building, retrieved from http://forum.skyscraperpage.com/showthread.php?t=129755

- Between 2007 and 2009 the demolition and earthworks took place.[7]
- Due to the recession, the project was put "on hold" for two years, but re-commenced in 2011 and the remaining earthworks were completed.[7]
- The demolition took 15 months, and it is done in 32 stages. When they reach the 12th stage, they started piling and foundation work, even though most of the current building is still standing.[7]

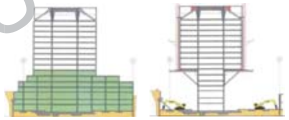
Fig. 6: First and twelfth stages of deconstruction, retrieved from http://www.skyscrapercity.com/showthread.php?t=415718&page=2

7: The Methodology for Deconstruction, retrieved from http://www.mcgee.co.uk/projects/122-leadenhall-street/ on 20th May 2015

LEADENHALL BUILDING – LAYOUT & NEARBY BUILDINGS

- The 225m tall office tower is located on Leadenhall Street in the City of London, directly opposite the Richard Rogers/Arup 1980s masterpiece the Lloyd's building, and within a "cluster" of other tall buildings that also includes 30 St Mary Axe , Heron Tower, Tower 42, and the Pinnacle.[8]


Fig. 8: Leadenhall Building with nearby towers, retrieved from http://forum.skyscraperpage.com/showthread.php?t=129755&page=4


Fig. 7: Layout Plan, retrieved from The Arup Journal 2012 Issue 2


Fig. 9: Leadenhall Building with nearby towers, retrieved from http://www.makearchitects.com/media/news-and-events/140225-leadenhall-planning/

8: Annereau, N., Thonger, j. & Eley, D. (2012) *The Arup Journal.* Issue 2, pp. 67-77

LEADENHALL BUILDING – DESIGN PHILOSOPHY

- The distinctive triangular form was developed in response to concerns about the position of the tower behind St Paul's Cathedral when viewed from Fleet Street. Leaning away from St Paul's, the building's silhouette can be much taller than would otherwise have been possible in such in a sensitive location.[9]
- Leaning away from St. Paul's, the building's tapering silhouette means less of the mass emerges above surrounding buildings, the key view of St. Paul's remains unaffected, and the tower can be much taller than would otherwise have been possible in such in a sensitive location.[9]


Fig.10: Relation between St Paul's Cathedral and the Leadenhall Building, retrieved from http://www.theleadenhallbuilding.com/galleries/leadenhall-building/


Fig. 11: Schematic drawings of design process, retrieved from http://www.theleadenhallbuilding.com/wp-content/uploads/2014/07/TheLeadenhallBuilding_Broadsheet01.pdf


Fig.12: View from Leaden hall Street retrieved from http://www.theleadenhallbuilding.com/galleries/leadenhall-building/

9: The Leadenhall Broadsheet, retrieved from http://www.theleadenhallbuilding.com/whats-on/broadsheets/ on 27th May 2015

LEADENHALL BUILDING – BUILDING FORM

- Floors range from 1,950 m² to 557 m², enabling a wide range of occupiers' requirements to be met.[10]

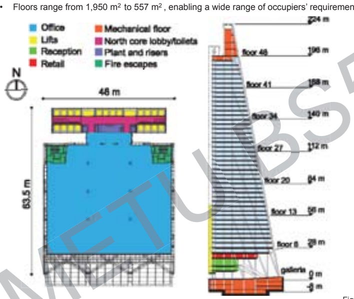

Fig. 13: Functional Plan and Section, **redrawn by Ozan Taşlı**


Fig. 14: East Elevation retrieved from https://www.flickr.com/photos/125871357@N02/15102540675

10: Young, A., Smith, B., Annereau, N. Butler, A. (2013) *CTBUH Journal* Issue 2 pp. 12-17
Fig. 13 : Leadenhall Tower Functional Section , **redrawn by Ozan Taşlı** based on drawings provided by *The Arup Journal 2012 Issue 2*

LEADENHALL BUILDING – BUILDING FORM

- The lack of obstruction and heavy structural elements in the center of the building has permitted the creation of another unique element – the galleria.[10]
- At ground level, almost the entire footprint of the building is a 28-meter-high open public space. This provides pedestrian routes across the site and a sheltered urban environment, within which two sets of escalators connect to the building's two reception spaces.[10]
- We try to balance flexibility with more customized, intimate spaces. The enclosed atrium gardens at the foot of the Leadenhall Tower are driven by an idea of intimate public space. (Stirk G., 2013)


Fig. 15: Galleria, retrieved from http://www.theleadenhallbuilding.com/galleries/public-space/


Fig. 16: Galleria, retrieved from http://www.theleadenhallbuilding.com/galleries/public-space/

10: Young, A., Smith, B., Annereau, N. Butler, A. (2013) *CTBUH Journal* Issue 2 pp. 12-17

LEADENHALL BUILDING – BUILDING FORM

- With a building of this height maximizing its entire site, the plot ratio at 29:1 is exceptional for central London, where most office buildings are lower-rise and have a ratio of 20:1 or lower.[10]
- The upper floors of the building consist of two distinct zones, the primary office floors and the north core, connected by a relatively narrow linking section floor.[10]


Fig. 17: Two story high reception floor, retrieved from : http://www.broadgateestates.co.uk/the-leadenhall-building

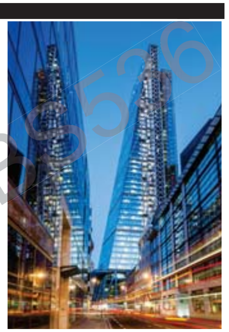
Fig. 18: View from Leadenhall Street, retrieved from https://www.flickr.com/photos/astigmatik/10114807595/

10: Young, A., Smith, B., Annereau, N. Butler, A. (2013) *CTBUH Journal* Issue 2 pp. 12-17

LEADENHALL BUILDING – BUILDING FORM

- The Leadenhall Building comprises a tapering, perimeter-braced diagrid structure containing the office floors and adjoins a northern support core, which houses all passenger and goods lifts, service risers, on-floor plant, and lavatories. Office floors are connected to the structural tube, termed the "mega-frame," at every floor, without the need for further perimeter columns.[10]
- The building's triangular geometry in profile and the layout of its perimeter braced structure (the "mega frame") enable seven floors to fit 28m height, with each floor 750mm less wide than one below.[10]


Fig. 19: View of South facade from ground level, retrieved from http://www.theleadenhallbuilding.com/galleries/leadenhall-building/


Fig. 20: West Elevation, retrieved from https://www.flickr.com/photos/125871357@N02/15102540675

10: Young, A., Smith, B., Annereau, N. Butler, A. (2013) *CTBUH Journal* Issue 2 pp. 12-17

LEADENHALL BUILDING – BUILDING FORM


Fig. 21: Perspective section, retrieved from http://blog.krigh.co.uk/2evolve/

- In the lower portion of the tower, the office floors are rectangular in plan, 48m wide and up to 43m deep, and virtually column-free. At 16m x 10.5m, the large column grid means that only six internal columns are required on the largest floors.[10]
- The typical floor build-up within each 4m story consists of a 15cm deep concrete slab over 70cm deep fabricated steel beams.[10]
- A zone of 15cm is provided for raised floors, and the services pass through holes in the steel beams. This ensures that a 2.75m floor-to-ceiling height is maintained throughout.[10]

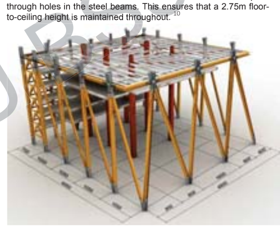
Fig. 22: South-West view of first mega level (galleria), **drawn by Ozan Taşlı**

10: Young, A., Smith, B., Annereau, N. Butler, A. (2013) *CTBUH Journal* Issue 2 pp. 12-17

LEADENHALL BUILDING – LOW-RISE FLOOR PLAN

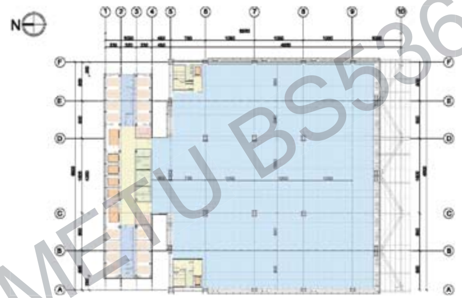
Fig. 23: 6th Floor Plan, **drawn by Ozan Taşlı**

Fig. 23: Leadenhall Tower 6th Floor Slab Plan, **drawn by Ozan Taşlı** based on drawings provided by Damian Eley's presentation at CTBUH conference center on 12th June 2013

LEADENHALL BUILDING – MID-RISE FLOOR PLAN

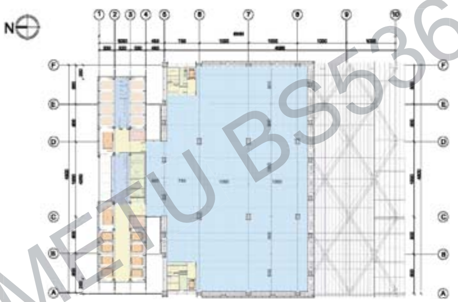
Fig. 24: 15th Floor Plan, **drawn by Ozan Taşlı**

Fig. 24: Leadenhall Tower 6th Floor Slab Plan, **drawn by Ozan Taşlı** based on drawings provided by Damian Eley's presentation at CTBUH conference center on 12th June 2013

LEADENHALL BUILDING – HIGH-RISE FLOOR PLAN

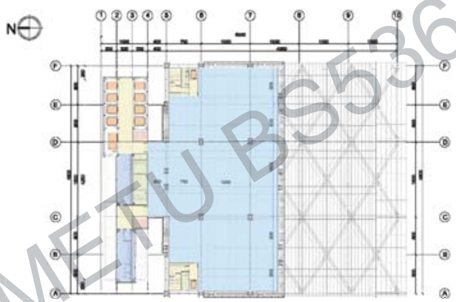
Fig. 25: 31th Floor Plan, **drawn by Ozan Taşlı**

Fig. 25: Leadenhall Tower 6th Floor Slab Plan, **drawn by Ozan Taşlı** based on drawings provided by Damian Eley's presentation at CTBUH conference center on 12th June 2013

LEADENHALL BUILDING – MEGAFRAME STRUCTURE

- Although the configuration submitted in planning applications adopted a regular pattern with a diagrid on the inclined face, in the early stages of the project a large number of bracing configurations were sketched by structural designers.[11]

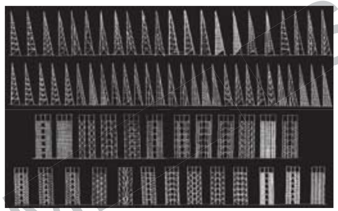
Fig. 26: Bracing configurations by structural designer, retrieved From PhD Thesis of Baldock, I. (2007)


Fig. 27: Structural Model, **drawn by Ozan Taşlı**

11: Baldock, I. (2007). "*Structural Optimization In Building Design Practice: Case Studies in Topology Optimization of Bracing Systems*", PhD Thesis, University of Cambrige, pp. 33-34

LEADENHALL BUILDING – MEGAFRAME STRUCTURE

- The mega frame structure is a braced diagrid, surrounding all four sides of the Office zone and typically located within the externally ventilated façade. It is arranged on a large scale, dividing the building elevations into the eight, seven- story modules. Each mega frame story is therefore 28m above the previous one.[8]


Fig. 28: South-East perspective view of Structural Model, **drawn by Ozan Taşlı**

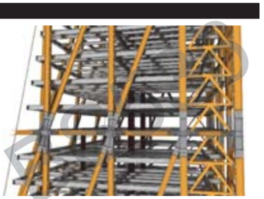
Fig. 29: West perspective view of structural model, **drawn by Ozan Taşlı**

- The long internal floor spans direct much of the office floor load to the perimeter. As a result, the mega frame columns are designed to carry a substantial portion of the building's weight and can therefore naturally also resist the wind loading with minimal additional material.[8]

8: Annereau, N., Thonger, j. & Eley, D. (2012) *The Arup Journal.* Issue 2, pp. 67-77

MEGAFRAME STRUCTURE

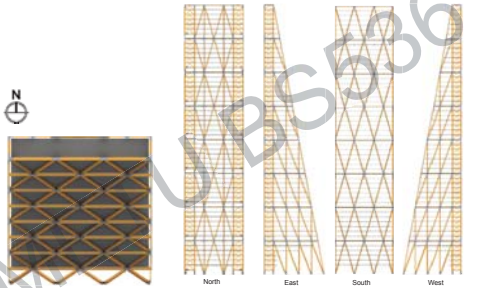

Fig. 30: Top view of mega frame structure, **drawn by Ozan Taşlı**

Fig. 31: Elevations of mega frame structure, **drawn by Ozan Taşlı**

MEGAFRAME STRUCTURE

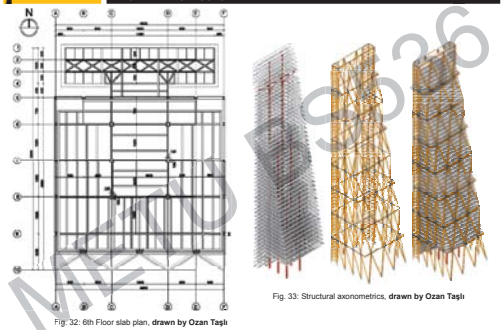

Fig. 32: 6th Floor slab plan, **drawn by Ozan Taşlı**

Fig. 33: Structural axonometrics, **drawn by Ozan Taşlı**

Fig. 32: 6th floor slab plan, **drawn by Ozan Taşlı** based on drawings provided by Damian Eley's presentation at CTBUH conference on 12th June 2013

MEGAFRAME STRUCTURE

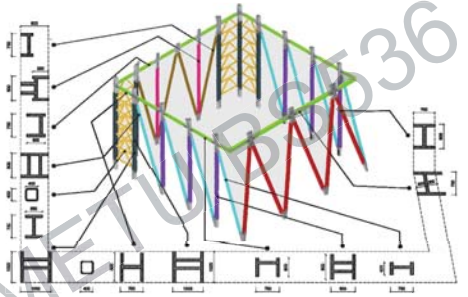

Fig. 34: Size of steel profiles at first mega level, **drawn by Ozan Taşlı**

Fig. 34: Steel Profiles, **drawn by Ozan Taşlı** based on drawings provided by Damian Eley's presentation at CTBUH conference center on 12th June 2013

MEGAFRAME STRUCTURE

- The Leadenhall Tower consists of 39,283 total components, 11,252 pieces of steelwork, with some individual sections being 70 tons in weight. (Eley, D., 2013)

Fig. 35: Construction of 6th mega level, retrieved from http://www.skyscrapercity.com/showthread.php?p=91021330

Fig. 36: Topping out of first mega level, retrieved from http://www.skyscrapercity.com/showthread.php?p=91021330

Fig. 37: Construction of second mega level, retrieved from https:c1.staticflickr.com/9/8077/7421652950_a4ddb958e0_b.jpg

MEGAFRAME NODE CONNECTIONS

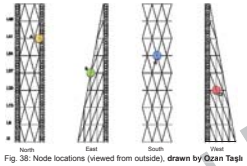

Fig. 38: Node locations (viewed from outside), **drawn by Ozan Taşlı**

Fig. 40: Node connection (A) at North facade, **drawn by Ozan Taşlı**

Fig. 39: Node connection (B) at the South-East corner, **drawn by Ozan Taşlı**

Fig. 41: Node connection (C) at South facade, **drawn by Ozan Taşlı**

MEGAFRAME NODE CONNECTIONS

- Typically, six mega frame elements come together at each joint, in a variety of geometries, and the connections transfer forces of up to 6000 tones in at least three different directions simultaneously. [8]
- Typically 6m x 3m and weighing up to 30 tones, the nodes provide the geometrically complex transitions between the different elements through welded joints between carefully oriented plates. [8]
- The bolts themselves are actually high strength threaded bars, up to 76mm in diameter, pretensioned by <200 tones to ensure that the joints never open up under the design loads. [8]

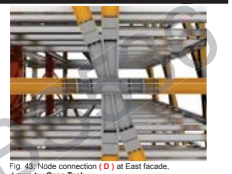

Fig. 43: Node connection (D) at East facade, **drawn by Ozan Taşlı**

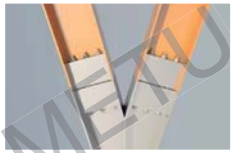

Fig. 42: Bolt box connections, **drawn by Ozan Taşlı**

Fig. 44: Bolts connections, **drawn by Ozan Taşlı**

8: Anne reau, N., Thonger, j. & Eley, D. (2012) *The Arup Journal*. Issue 2, pp. 67-77

MEGAFRAME NODE CONNECTIONS

- There are 11 different types of nodes with each type having various sub-variants according to the forces passing through the joint. Most nodes accommodate six members, although some have up to eight steel sections to connect. [12]
- Using prefabricated nodes has eliminated the need for any complex onsite welding as all of the challenging work was completed at Severfield - Watson's facility. Even so, some nodes took up to 600 man hours to fabricate. [12]

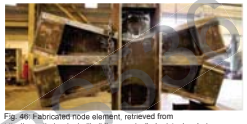

Fig. 46: Fabricated node element, retrieved from http://www.theleadenhallbuilding.com/galleries/steelworks/

Fig. 45: Fabricated node element, retrieved from http://www.theleadenhallbuilding.com/galleries/steelworks/

Fig. 47: Welding work on node element, retrieved from http://www.theleadenhallbuilding.com/galleries/steelworks/

12: Information about node connections retrieved from, http://www.newsteelconstruction.com/wp/city-icon-showcases-steel/ on 30th May 2015

K-BRACING & CONNECTIONS

- To brace the floors and internal columns across the large distances between the mega levels, a secondary stability system was also required. This takes the form of chevron or "K-braced" panels , and is located in the northernmost bays of the east and west faces and in the end bays of the north face around the east and west fire fighting cores. [8]

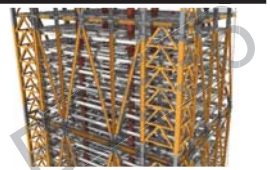

Fig. 49: North facade of Mega frame, **drawn by Ozan Taşlı**

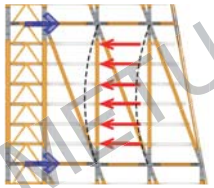

Fig. 48: Load transmission and deform shape, **drawn by Ozan Taşlı**

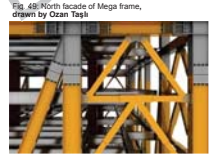

Fig. 50: K-braced panels at the North-East corner, **drawn by Ozan Taşlı**

8: Anne reau, N., Thonger, j. & Eley, D. (2012) *The Arup Journal*. Issue 2, pp. 67-77

K-BRACING & CONNECTIONS

Fig. 51: K-Bracing on North-West core, retrieved from http://wirednewyork.com/forum/showthread.php?t=6580&page=14

Fig. 52: Connection work for K-Braces, retrieved from http://www.theleadenhallbuilding.com/wp-content/uploads/2014/07/TheLeadenhallBuilding_Broadsheet01.pdf

Fig. 53: K-Bracings vies from ground level, retrieved from, http://www.theleadenhallbuilding.com/wp-content/uploads/2014/07/TheLeadenhallBuilding_Broadsheet01.pdf

NORTH CORE

- The north core contains the passenger lifts, toilets and most of the services risers and on-floor plant in a slender structure separated from the main offices by narrow linking floor plate, thus maintaining the legibility of the mega frame around all four sides of building. [8]
- The passenger lifts are arranged in three banks: four low-rise, and eight high-rise lifts. [8]
- The high-rise passenger lifts will travel at speeds of up to 28.8 km/h, making them the fastest panoramic lifts in Europe.

Fig. 54: Aerial view of North core, retrieved from http://www.ibtimes.co.uk/jason-hawkes-aerial-photos-london-show-rapidly-changing-face-capital-1473339

Fig. 55: North core, retrieved from http://www.theleadenhallbuilding.com/gallery/

8: Anne reau, N., Thonger, j. & Eley, D. (2012) *The Arup Journal*. Issue 2, pp. 67-77

NORTH CORE

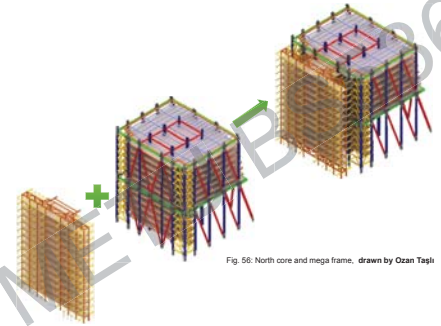

Fig. 56: North core and mega frame, **drawn by Ozan Taşlı**

NORTH CORE

- For speed and ease of construction most of the components for the core were prefabricated into 'tables', three for each level. [12]
- On the north elevation, the primary beams, columns and cladding of the core form a backdrop to the 20 passenger lifts and two goods lifts, which travel up to 200m-high within cantilevered suspended glass shafts. [12]

Fig. 57: Prefabricated 'tables' for North Core , **drawn by Ozan Taşlı**

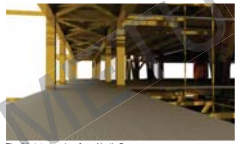

Fig. 58: Interior view from North Core, **drawn by Ozan Taşlı**

Fig. 59: Structure of North Core, **drawn by Ozan Taşlı**

12: Information about North Core retrieved from, http://www.newsteelconstruction.com/wp/city-icon-showcases-steel/ on 30th May 2015

NORTH CORE

Fig. 60: Construction of the North Core, retrieved from http://www.newlondonarchitecture.org/docs/dr_john_stehle_-_laing_orourke_plc.pdf

Fig. 61: Construction of the North Core, retrieved from http://www.newlondonarchitecture.org/docs/dr_john_stehle_-_laing_orourke_plc.pdf

Fig. 62: Construction of the North Core, retrieved from http://www.theleadenhallbuilding.com/wp-content/uploads/2014/07/TheLeadenhallBuilding_Broadsheet01.pdf

45th FLOOR & TREE COLUMNS

- The two columns left at Level 45 perform one additional function at the apex of the tower – to resist the tendency for the structure to expand and contract, which is particularly marked on the south face when the sun heats the steel. Here they branch at the treetops into diagonal bracing, reaching up to join the primary north and south steelwork and hold the mega frame in place by resisting the thermal movement of the stretching and contracting structure. [13]

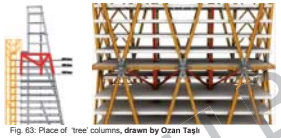

Fig. 63: Place of 'tree' columns, **drawn by Ozan Taşlı**

Fig. 64: 'Tree' columns at the 45th floor, **drawn by Ozan Taşlı**

Fig. 65: Interior view of 45th floor, retrieved from http://www.archdaily.com/548696/top-of-the-city-the-leadenhall-building-inside-and-out/

Fig. 66: Interior view of 45th floor, retrieved from http://www.designcurial.com/news/inclined-to-agree-4463095

13: Information about North Core retrieved from, http://www.ribaj.com/buildings/now-you-see-it on 30th May 2015

MECHANICAL FLOOR - ATTIC

- All the base building services that require outside air for aspiration or heat rejection are at the top of the building. These include the 100% backup generators, the cooling towers, the boilers, and the tenants' kitchen extract fans. Together with high-level electrical switch rooms and the water system pressurization units, these systems make up the extent of the "attic" plantrooms. [8]
- The building is designed to have just one tenancy per floor, which has made it possible to provide the office fresh air supply on a floor-by-floor basis instead of more conventional centralized supply typical in tall buildings.

1. L46 Substation
2. 2 x 11Kv to 415v Tx
3. 4 Generator sets
4. 3 LTHW boilers and pump sets
5. MCCPs
6. Cooling towers
7. Attenuated generator discharge
8. Boiler and generator flues
9. Loadbank
10. SMUs

Fig. 67: Mechanical Floors, retrieved from http://www.newlondonarchitecture.org/docs/dr_john_stehle_-_laing_orourke_plc.pdf

8: Anne reau, N., Thonger, j. & Eley, D. (2012) *The Arup Journal*. Issue 2, pp. 67-77

STRUCTURAL BEHAVIOUR

- Just due to self weight, the effect of biased steel diagonal members on the East and West elevations accounts for up to 180mm of movement towards the North at the top of the building, based on finite element analysis predictions. [14]
- Uneven settlement of foundations accounts for up to 140mm of movement towards the North at the top of the building, based on finite element analysis predictions. [14]
- The prevailing Southerly wind accounts for up to 240mm of movement towards the North at the top of the building, based on finite element analysis predictions. [14]
- Heat from the sun causes the South face to expand and induces a movement of up to 210mm to the North at the top of the building, based on finite element analysis predictions. [14]

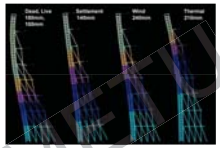

Fig. 68: Structural behavior deform shape, retrieved from Damian Eley's presentation on CTBUH conference on 12th June 2013

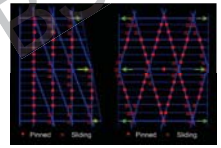

Fig. 69: Pinning and sliding points of Mega frame, retrieved from Damian Eley's presentation on CTBUH conference on 12th June 2013

14: Information about structural behavior retrieved from Damian Eley's presentation at CTBUH conference on 12th June 2013

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