New Civil Engineering Building, University of Cambridge, Cambridge, UK

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A state-of-the-art engineering laboratory designed to strict vibration criteria. Includes a post-tensioned RC strong floor slab for structural material testing as well as a suite of building sensors. Designed using the novel Energy Cost Metric tool.

Summary

The New Civil Engineering Building for the University of Cambridge provides new laboratory facilities, workshop, office and seminar spaces within the West Cambridge campus as part of the overarching masterplan. The building is a 3-storey structure and comprises a steel frame supporting precast hollowcore floor planks on a RC raft foundation and a part basement. Options for the building structure and envelope were tested against the Energy Cost Metric which was a tool that drove decision making by balancing Whole Life Cost and Embodied Energy.

1. *The completed building*

Introduction

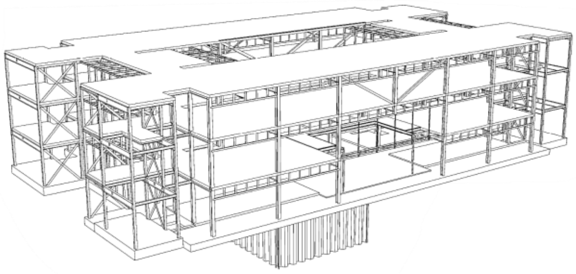
This is a 4280m^2 3-storey university building with single-storey part basement. It is the first building of the Engineering Department plans to relocate to the West Cambridge Campus.

The building was funded jointly by the Engineering and Physical Sciences Research Council (EPSRC) through the UK Collaboratorium for Research in Infrastructure and Cities (UKCRIC) and by the University of Cambridge.

It houses the National Research Facility for Infrastructure Sensing (NRFIS) which is a leader in sensor development in civil engineering and infrastructure.

The building provides state-of-the-art laboratory facilities as well as workshop, seminar and office spaces.

The brief for the project was clear in that it required the design response to be 'very low energy, pleasant, zero-bling, upgradeable, and well measured'. With that in mind, detailed studies were undertaken at the early design stages to determine the appropriate structural grid and materials for the building taking guidance from the Energy Cost Metric which was a tool devised by Professor David MacKay aimed at bridging the gap between cost and energy considerations.



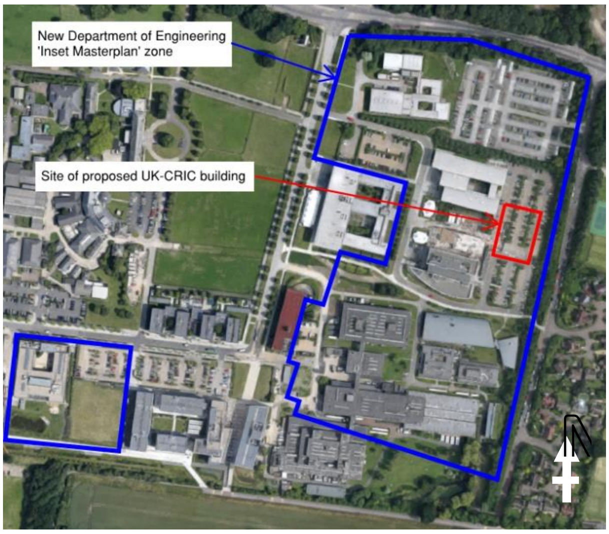
2. *Structural 3D model*

The project procurement was Design and Build and Smith and Wallwork developed the civil and structural design to RIBA Stage 3 and then performed client monitor role during Stage 4 and construction stages when the design was handed over to the contractor SDC.

Works on site started in September 2017 with the building completed in April 2019.

Site

The proposed site of the Civil Engineering building is on the east perimeter of the West Cambridge site, approximately 1 mile west of Cambridge city centre. It is centrally located within the zone of the inset masterplan for the new Engineering Department campus. The site was occupied by a car park area and soft landscaping to the periphery. Its altitude is approximately +15m AOD.



3. Site plan

Historically the area in the immediate vicinity of the Civil Engineering building was agricultural land. The University of Cambridge started developing the West Cambridge site in the mid-20th Century, beginning with the Veterinary School in 1955, followed by the Whittle Laboratory (N of the Civil Engineering building site) in 1973 and the Cavendish Laboratory (S of the UK-CRCI building site) in 1974.

Other buildings adjacent to the Civil Engineering building site include the Roger Needham building (2001) the Electronic Engineering Division building (incorporating the Centre for Advanced Photonics and Electronics, or CAPE) in 2006 and its extension, now known as the Graphene Centre, in 2013.

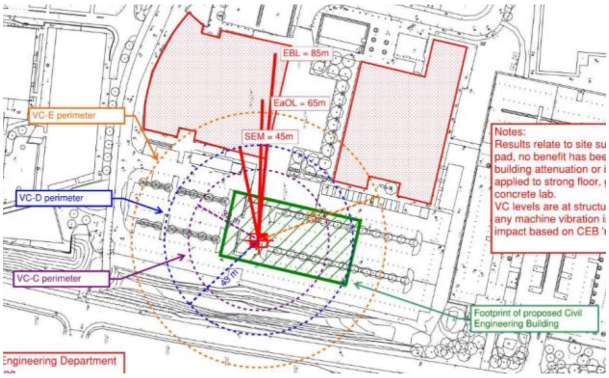
The site is a hub of research into the physical sciences as well as furthering the application of research by having strong presence of industry links.

The geology of the site comprised of made ground to depths between 0.6m-1.8m below ground level over River Terrace Deposits found to depths between 0.9m-1.7m below ground level overlying Gault clay that was proven to at least 25m below ground level in both deep boreholes.

One of the initial considerations was the precise location of the new building within the site as there are several buildings nearby that house equipment sensitive to ground-borne vibrations. Since structural testing was a key function of the new building, this meant that vibrations would be generated and would need to be controlled to appropriate levels so as not to affect the function of the surrounding buildings.

4. Early-stage weight drop tests to measure resultant vibration levels in surrounding buildings.

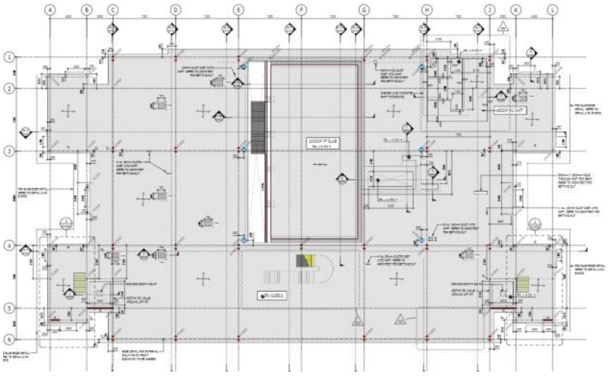
As such, early-stage vibration site testing was undertaken with specialist vibration input from Sound Space Vision. A mass concrete pad foundation was poured in the vicinity of the proposed structures lab and a series of weight drop tests were carried out, each calibrated to exert similar magnitude of energy as normal activities in the building would. The vibration sensitive labs were instrumented in the perimeter buildings and the vibration recorded and compared to the required limits. This then provided confidence that the day-to-day testing within the proposed building would not adversely affect the function of the existing buildings.



5. *Plot of VC-criteria achieved at different distances from early-stage weight drop tests across the site.*

Sub-structure

The sub-structure of the building was a 750mm thick RC raft foundation at ground floor level with a 200mm concrete topping that was polished to give the finished floor surface. The part basement below the strong floor comprised of 300mm thick RC walls and a 500mm thick RC raft foundation. A sump was provided in the basement to capture any future water ingress.



6. *Ground floor plan*

7. *Basement and ground floor reinforcement*

Superstructure

The superstructure of the building comprises of a primary steel frame with 200mm precast hollowcore floor slabs. The structural grid is 10.8m x 7.2m and the same bay repeats 36no. times throughout the building. This allowed the design team to spend more time optimising the structural sections and simplified the procurement and manufacturing of the frame.

The steel frame lateral stability system is a combination of braced bays in the North-South direction and semi-continuous moment frames in the East-West direction. This avoided the need for bracing within the main volume of the building and allowed open plan spaces to be realised.

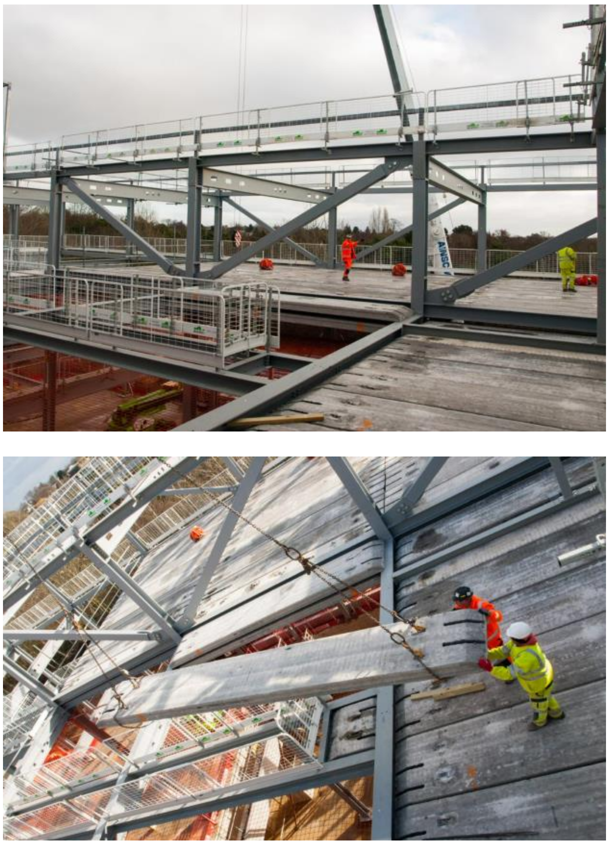
Level	Repeated Bays	Repeated Primary Beams UB 610x305x149	Repeated Columns UC 305x305x158
Ground	12	18	24
First	10	16	22
Second	14	18	28
Total	**36**	**52**	**74**
Length		**10.8**	**4m**
Tonnage		**84t**	**47t**

8. Structural bay standardisation across the building

The semi-continuous frames required careful design and detailing as the connections required to be designed to meet design moment, shear, rotation and rotational stiffness criteria whilst maintaining a ductile failure mode.

9. Steel column cast-in baseplate detail

The steel frame includes 3no. storey-height transfer trusses spanning 14.4m and 21.6m to form column free spaces within the structures laboratory and at the foyer area. The chords of the trusses carry some very high forces in the order of 3MN and they needed temporary restraint in the temporary case up until the precast planks were in place and grouted.



10. 3-span (21.6m) storey-height truss and precast plank installation

Vibration Criteria
The function of the building included some vibration generating operations in the form of the structural testing and at the same time included lab spaces that were vibration sensitive themselves.

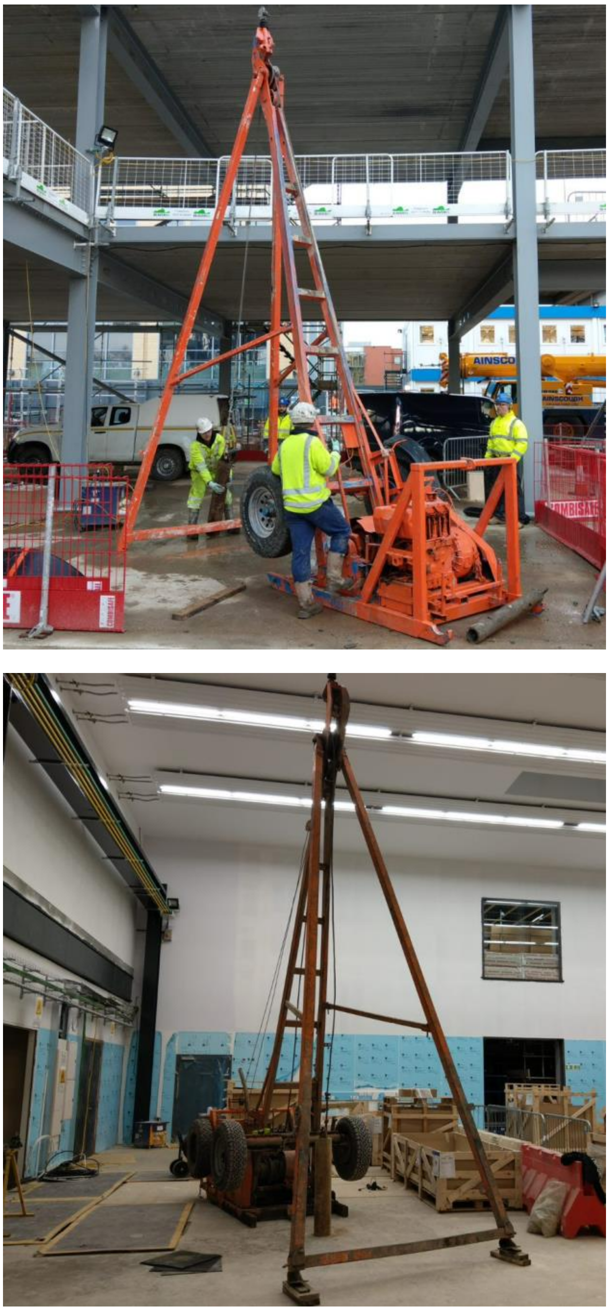
All vibration generating and sensitive labs were positioned on the ground floor to utilise the ground bearing concrete raft to minimise the effects.

Discussions with the academics in charge of the labs were held at early stages to understand the performance criteria for each lab. The majority of the labs had VC-A criteria with 1no. lab requiring VC-B. All upper floors were designed to achieve a Response Factor of 4.

The vibration performance of the building was tested upon completion of the primary steel frame and upon completion of the finishes. This was done via the same tests undertaken prior to construction by weight drops on the raft and on the strong floor.

The vibration isolation of the strong floor, gantry crane and concrete lab are explained later in this document.

The vibration issues were studied by Michael Polack in his 4th Year project 'Building Response to Ground Vibration at the West Cambridge Campus' published in May 2017 and supervised by Dr James Talbot.



11. *Vibration testing of building on raft and strong floor*

Energy Cost Metric (ECM)
The Energy Cost Metric was a tool devised by Professor David MacKay as a way to bridge the gap between cost and energy (both embodied and operational) for a project.

The objective was to minimise the Objective Function, U, for the whole life of the building. This tool was used from early stages and through to construction by the design team and the contractor to make design decisions ranging from the materials of the structural frame, architectural finishes and the operational energy strategy.

An academic paper on the application of the ECM during the project was led by Prof David Cebon and can be found on-line here.

$$U = E + \frac{C}{\alpha}$$

where:

E - total whole-life energy (in kWh), defined below

$$E = E_E + E_{MT} + E_{IU} + E_T - E_R$$

E_E - Embodied energy

E_{MT} - Material Transport energy

E_{IU} - In-use energy

E_T - Occupants' energy for transport

E_R - Reclaimable energy thanks to design for disassembly and reuse

C - the building cost (in p)

α - cost weighting of energy (in p/kWh)

12. *The Energy Cost Metric*

Building sensors

As the building housed the NRFIS, it was the perfect candidate to install and test the latest technologies of sensors for building monitoring.

As such, sensors were installed in a number of locations such as: the concrete strong floor, basement concrete raft and basement walls, the primary steel frame, within the blue roof, ground source heat pump boreholes and within the different spaces.

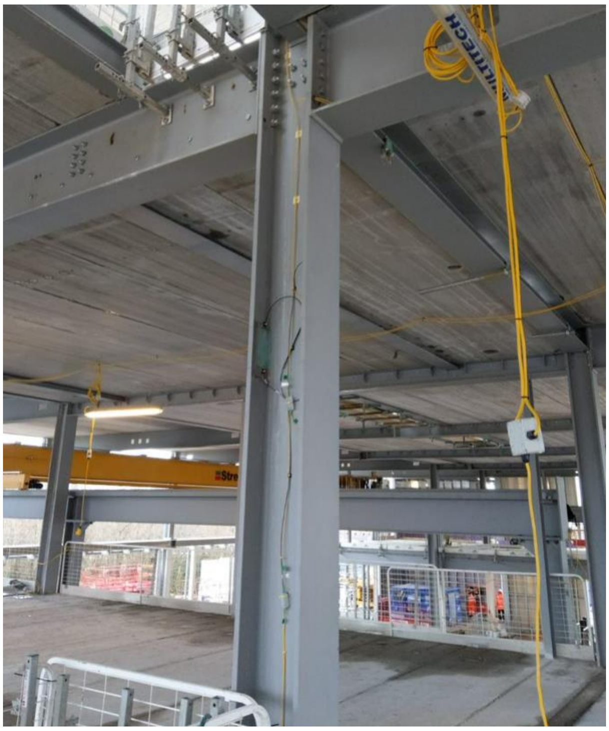
The sensors provided data of concrete curing, slab bending, column and beam loading, information on the water attenuation within the blue roof, energy generated from the GSHP and environment quality within the building.

The final specification and installation of the sensors was undertaken by EPSIMON, which is a specialist part of the Engineering Department.

The link below provides access to the dashboard where the live readings of the sensors can be obtained.

http://www.csiclivingbuilding.eng.cam.ac.uk/index.html

13. *Strong floor instrumentation with fibre optic cables*



14. *Instrumented primary steel frame*

Design for Deconstruction and Manufacture

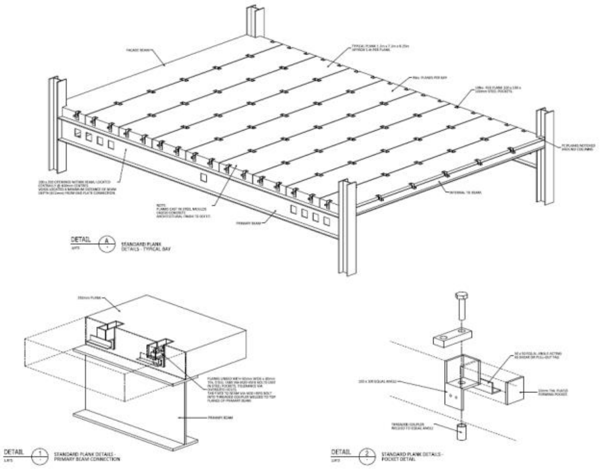
As part of the ECM study, two areas that were identified that were able to reduce the total whole life cost and energy were designing the frame for deconstruction and ease of manufacture.

The design has focused on maximising the possibility of steel reuse by utilising bolted connections rather than welded. Approximately 45% of the steelwork is designed to be easily unbolted and reused. Due to the standardised bays, a large quantity of the structure is repeated aiding manufacture and procurement.

Builderswork through steel beams was also rationalised to avoid large variety of different cases which would make them more attractive for reuse. A soft joint has been introduced in the finishes around all column baseplates to allow ease of dismantling.

15. DfD column baseplate detail

Standard precast planks have been used for the floor slabs. Even though in the early stages, a bespoke plank with bolted connections was proposed for ease of deconstruction, the cost to produce and install was prohibitive when tested through the ECM.



16. Concept for bespoke demountable concrete slab

The building is also designed to receive future extensions to both the North and South sides. Allowance has been made for this in the perimeter structure by providing pre-drilled bolt holes in the columns to receive equivalent beams in the future as well as couplers installed in the ground floor raft to allow shear transfer between the future raft foundations.

17. Couplers to edge of raft for future extension.

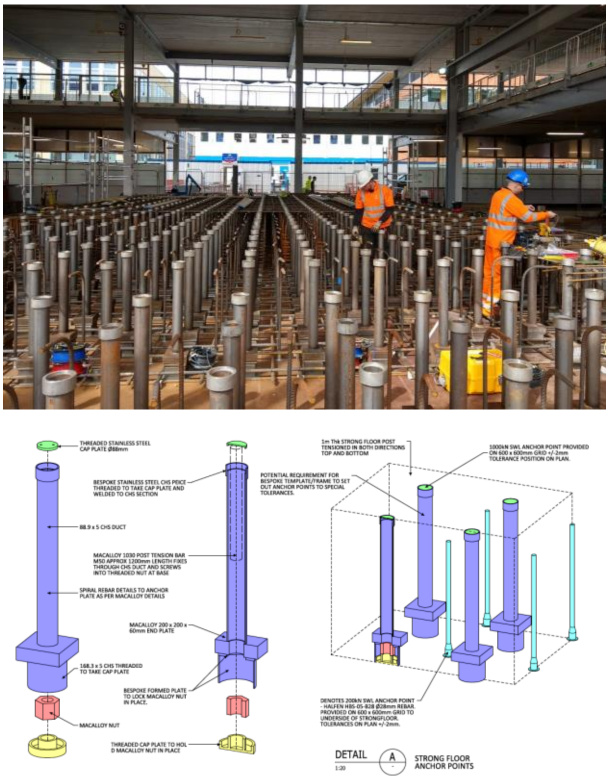
Strong floor

One of the main features of the building is the new strong floor which is a 20m x 10m, 1m thick 500t post-tensioned concrete slab that will be used for structural testing of components.

The slab includes 480no. anchor points to the top surface rated to 1000kN safe working load in tension and 400no. anchor points to the bottom surface rated to 200kN safe working load in tension.

The slab is post-tensioned to 10N/mm^2 from both directions to achieve a ‘no tension’ case when subject to different structural testing scenarios.

The slab was constructed after the primary frame was installed and as such was taken off the critical path. Since the sub-structure around it was already constructed, it was built 1m high and lowered into position using 4no. hydraulic jacks, one at each corner. The strong floor final design, post-tensioning, and lowering operation were undertaken by the specialist sub-contractor VSL.



18. Strong floor anchor points (top and bottom)

19. Hydraulic jack to lower strong floor into position.

The strong floor is supported on the RC sub-structure by elastomeric bearings, designed to minimise vibration transmission from the strong floor to the sub-structure. The bearings were designed by specialist sub-contractor Mason.

20. Strong floor elastomeric bearing

A by-product of the lowering sequence was the possibility to re-use the jacking positions in the future to allow raising of the slab for elastomeric bearing replacement.

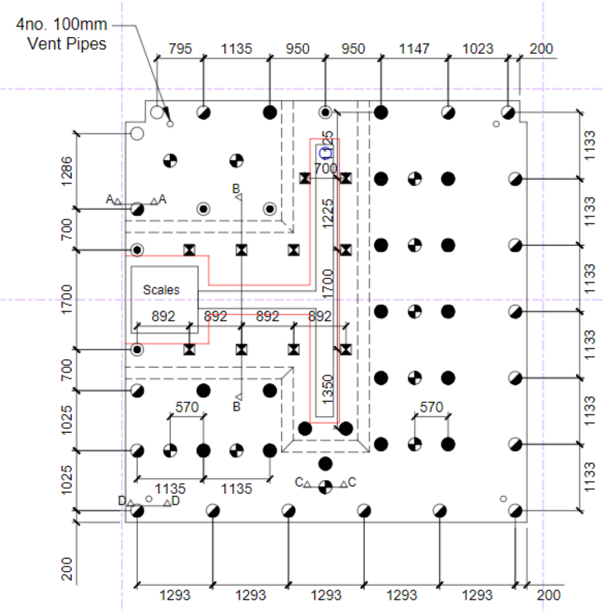
Despite the magnitude of post tensioning to the slab there was still significant rebar (200kg/m^3) with the slab. This rebar comprised anti-burst links at anchor and stress points as well as rebar to control shrinkage cracks. A self-compacting concrete was used RC40/50 with 70% cement replacement and the concrete pour was one of the most significant operations of the project with back-up concrete plants secured by the contractor to ensure uninterrupted supply.

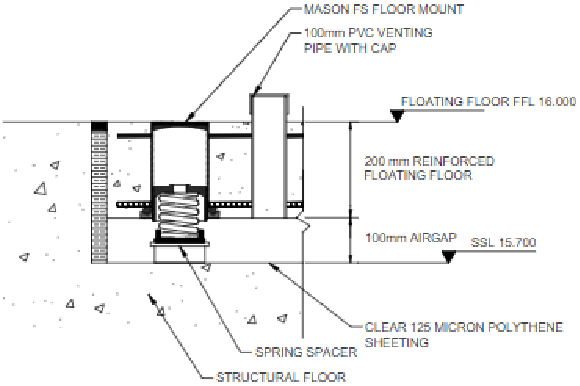
Concrete lab

The ground floor to the concrete laboratory was a 200mm thick RC slab, isolated from the main raft foundation via a 100mm air/spring gap. This was deemed necessary as significant vibration generating activities would be undertaken in this room such as concrete mixing, on a regular basis.

The slab was supported by a series of springs and dampers with each tailored to the load it was carrying. The slab was designed by specialist sub-contractor Mason.

The slab was folded/stepped to include a drainage channel linked to a sump in which scales would be positioned that needed regular washing out.





21. *Concrete lab sprung floor.*

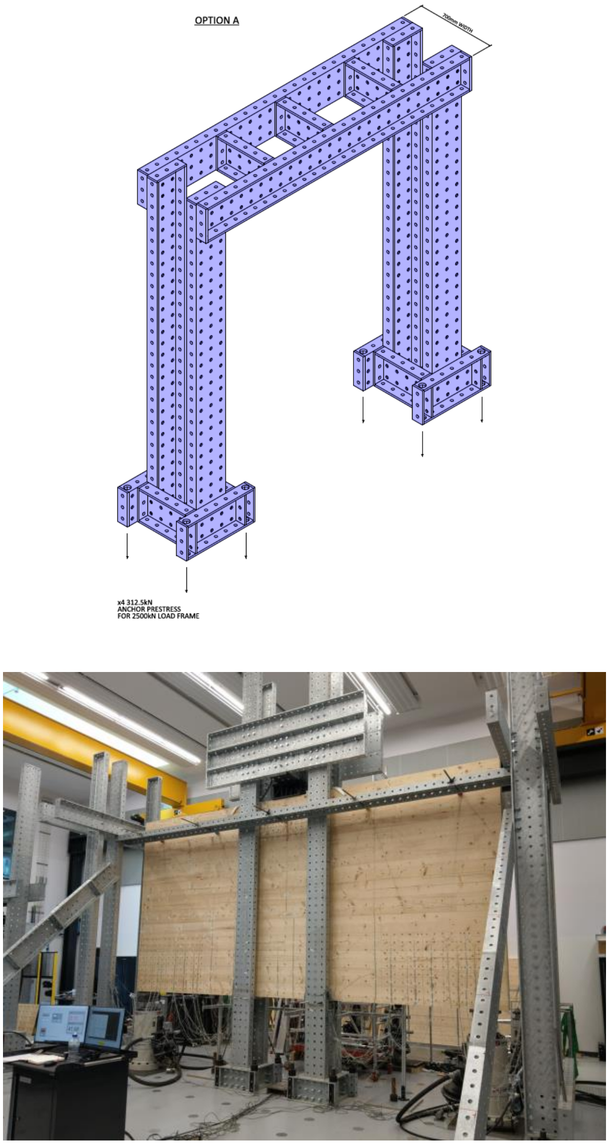
Gantry Crane
In the main structures lab, 2no. 10t gantry cranes were included. The cranes are supported on their one steel frames linked back to the primary frame with acoustically separated washers.

The achievable hook coverage (which is slightly smaller than the structures lab footprint) was reviewed with the client throughout the stages in order to enable maximum utilisation of the space as well as allowing the cranes to fit within the building footprint.

22. *Structures lab with 2no. 10t gantry cranes and strong floor.*

Meccano testing frames
Further to the main building project, Smith and Wallwork was commissioned by the client to provide structural engineering services for the design and manufacture of the steel reaction frames for the testing on the new strong floor.

Detailed design calculations for the steel frame were undertaken using a series of possible testing arrangements and a detailed parts list created for procurement of the materials. These were specified as a series of galvanised PFCs with multiple pre-drilled holes.



23. Isometric of Meccano and in-use

Civil Engineering
The Environment Agency flood map showed that the site was located within Flood Zone 1, with a less than 0.1%, 1:1000 year probability of flooding from rivers and the sea. However, it was in proximity to an area at low/medium risk of surface water flooding and as such a detailed assessment of the topographic survey was undertaken. This identified that the area at risk was confined to the south of the site away from the building; however, additional mitigation was provided by utilising the new access road to the east as an overland flow path should any ponding occur.

Although the risk of flooding to the site was low, there is a known risk of watercourse flooding downstream and therefore the Local Authority placed a very tight restriction (below that of the equivalent greenfield run-off) on surface water drainage flow rates discharging from the site. This required a large volume of attenuation storage to be provided within a very tight development area.

To overcome this it was proposed that a blue/green roof be incorporated utilising shallow depth Permavoid geocellular units placed beneath a meadow grass surface. The green roof element would minimise flows off-site during ‘normal’ rainfall events through water absorption within the vegetation and evapotranspiration, with the geocellular units providing storage during storms up to the 1:100 year event including climate change. Small easily maintainable orifice plate flow controls were provided with numerous overflows incorporated to avoid any build-up of water should blockage occur. This approach was a first for the UoC Estates Department and numerous discussions were held to explain the proposals and obtain the relevant derogations from the design standards. This approach has subsequently been used on other buildings at the West Cambridge site.

Due to the minimal amount of data available for assessing the water management performance of green roofs a number of sensors have been embedded within the various green/blue elements. These record moisture content, water depth, soil temperature and discharging flows rates, and when combined with the adjacent weather centre data will validate the parameters used in the design, potentially enabling a more refined system to be developed in the future.

Foul water was designed as a standard gravity based piped system with final discharge to the Anglian Water sewerage system. Consideration of washwater disposal from the concrete laboratory was a key consideration to minimise downstream blockage and siltation, with the design solution of formed trenches with removable flexible liners, silt traps and filter buckets developed in association with the University Technicians.

The design of infrastructure around the building (carried out as part of a separate project) included access roads, an enhanced junction onto Clerk Maxwell Road, car parking, foul water drainage, SuDS (incorporating a large under-drained attenuation storage swale) and re-provision of geocellular attenuating storage serving adjacent buildings. This was all designed in accordance with the principals of the inset masterplan. This approach enables future buildings to connect into the required service provision with relative ease and prevents the need for costly and disruptive works.

Conclusion

This project was a challenging exercise in coordination, procurement and construction due to its multiple facets and array of specialist input required consistent with a high-end laboratory building.

The use of the ECM and the sustainability principles included in the project brief provided a new way of thinking to the designers and contractors to create a building that was and is a test for future developments.

Project Information

Job no. 000193
Project Value £20m
Project GIA 4520 (m^2) incl. basement
4280 (m^2) excl. basement
Start of design June 2015
Start on site September 2017
Completion April 2019
Procurement Two Stage Design and Build

Client Lynxvale Limited (Cambridge University Estates Management), Cambridge, UK
Project Manager AECOM
Architect Grimshaw
Structure and Civils Smith and Wallwork
M&E Max Fordham
Contractor SDC
Contractor deisgn team RH Architects, Ramboll, KJ Tait
SI Contractor Ground Engineering
Steel frame contractor (+ connection design) B&K Structures
Strong floor designer, installer VSL
Vibration specialist Sound Space Vision
Elastomeric bearings contractor Mason
Building sensors contractor Epsimon

Smith and Wallwork Team

Structures Simon Smith, Katie Symons, Sam Oldfield, Panayiotis Papastavrou
Civils Stuart Arnold
CAD/BIM Alex Palmer

Awards

RIBA East 2022: Short-listed (outcome pending)
Greater Cambridge Design and Construction Awards 2022: Short-listed (outcome pending)

Keywords

Semi-continuous steel frame, Vibration, Gantry Crane, Strong floor, Laboratory, Energy Cost Metric

Materials Used

Frame	Steel frame with precast floor slabs					
Foundations	Ground Bearing Slab					
Building GIA	4280	m2				
					Carbon A1-A5	
Material quantities					t CO2e	g CO2e/m2
Superstructure					809	189
Concrete	503	m3	0.12	m3/m2	263	61
Rebar	12	t	24	kg/m3	18	4
Steelwork	275	t	64.3	kg/m2	528	123
Timber	-	m3	-	m3/m2	-	-
Masonry	-	m3	-	m3/m2	-	-
Substructure					768	179
Concrete	1,765	m3	0.41	m3/m2	508	119
Rebar	171	t	97	kg/m3	260	61
Steelwork	-	t	-	kg/m2	-	-
Timber	-	m3	-	m3/m2	-	-
Masonry	-	m3	-	m3/m2	-	-
Total Structures					**1,576**	368
Concrete	2,268	m3	0.53	m3/m2	771	180
Rebar	183	t	81	kg/m3	278	65
Steelwork	275	t	64	kg/m2	528	123
Timber	-	m3	-	m3/m2	-	-
Masonry	-	m3	-	m3/m2	-	-
Civils						
Pipework length			254	m		
Pipework diameter			100-150	mm		
PCC manholes			10	no.		
PPIC manholes			5	no.		
Geocellular storage (blue/green roof)			106	m3		
Attenuation tank			15	m3		

Carbon figures are based on industry standard figures and not specific EPD data from steel or concrete contractors. Carbon data provided by SDC calculated A1-A3 carbon figures of 266kgCO2e/m^2.

Panayiotis Papastavrou is a Structural Engineer at Smith and Wallwork