Retrofitting the Castle Meadow campus, Nottingham

STUART MCNASH

MEng, MICE

Senior Engineer, Arup, Nottingham, UK

STEPHEN FERNANDEZ

CEng, FIStructE, MICE, Conservation Accredited Engineer

Director and Global Building Retrofit Leader, Arup, Nottingham/Birmingham, UK

SYNOPSIS

The award-winning 1990s buildings at Castle Meadow, Nottingham, which previously served as offices for HM Revenue and Customs, have been repurposed and transformed for the future as a University of Nottingham campus.

The structural engineer had an influential role on the project to define the principles for retrofitting the existing buildings. The differing levels of retrofit, including a complex tensile-fabric roof replacement, have given the site a new lease of life, demonstrating that existing buildings and spaces can be innovatively transformed and reused using a variety of approaches.

These buildings set the benchmark for low-carbon developments in Nottingham, with an embodied carbon of 80kgCO_2e/m² for the central building works.

Introduction

A unique opportunity presented itself to the University of Nottingham to open a new city-centre campus when HM Revenue and Customs vacated the site at Castle Meadow in 2019. The potential new campus needed to be aligned with the City of Nottingham's ambition to become carbon neutral by 2028, a goal which the university has supported with its own zero-carbon plan. Arup assisted the university, developing a robust retrofit strategy at an early stage, enabling the client to sustainably develop this new site, and provided specialist engineering input for the works to replace a complex, listed, tensile-membrane structure.

Existing buildings

Historically, the Inland Revenue campus in Nottingham **(Figure 1)** was developed on an area adjacent to the Nottingham Canal and Castle in 1991, led by architects Michael Hopkins & Partners and engineers Ove Arup & Partners.

The buildings were a pioneering sustainable development for the time, becoming the first project to achieve the highest possible credits under the BREEAM environmental assessment system, established in 1988.

The development consisted of seven blocks of three and four storeys – a Central Building and six office blocks – to create a new urban quarter. The office blocks comprised L-shaped or rectangular buildings on plan, formed from loadbearing prefabricated masonry

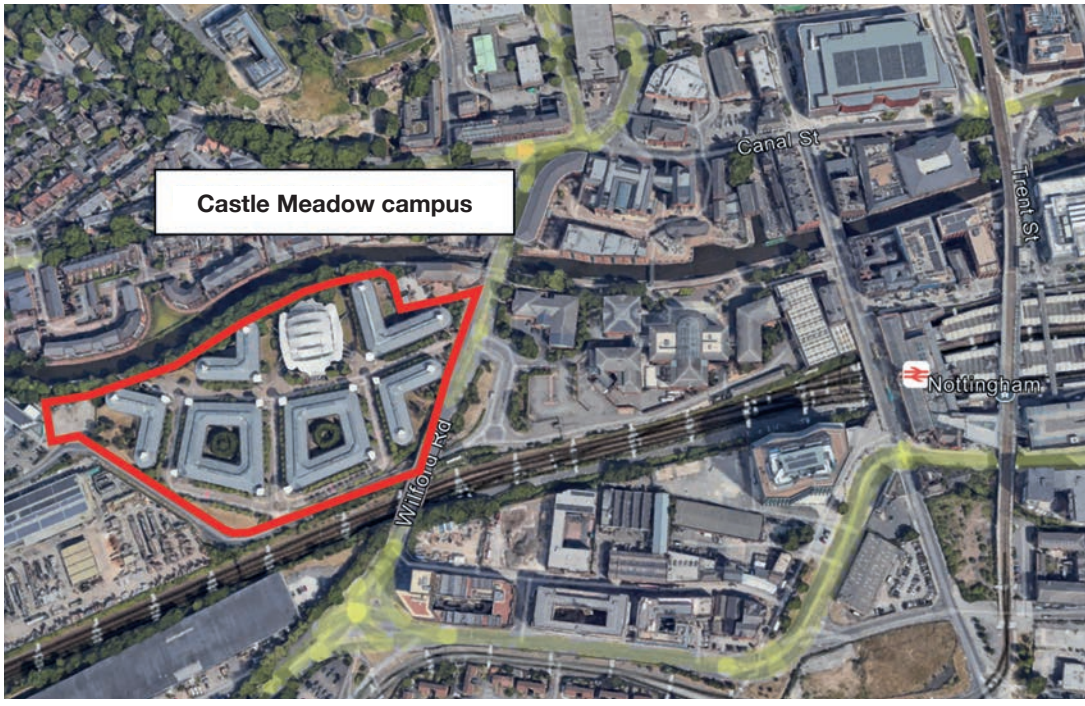

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FIGURE 1: Castle Meadow campus

Project credits

Client	University of Nottingham
Contractor	G F Tomlinson & Henry Brothers
Architect	Hopkins & Bond Bryan
Structural, building envelope and MEP engineer	Arup
Tensile fabric contractor	Base Structures & Tensys

piers along the perimeter and bespoke precast arched concrete floor units spanning the full width of the building to create a column-free floor plate **(Figure 2)**. Translucent stair towers, formed from a lightweight steel frame infilled with glass blocks located at the corners of the building, were key parts of the natural ventilation system.

The vaulted precast concrete floors provide thermal mass to regulate the internal temperature. Projecting horizontal glass 'light shelves' provide external shading and reflect daylight onto the vaulted exposed concrete. The windows are also triple glazed with an integrated Venetian blind in the outer cavity.

The focal point of the original development was the Central Building **(Figure 3)**, which housed cafes, meeting spaces and a sports court. The building was covered by a complex polytetrafluoroethylene (PTFE) membrane roof, with large, glazed elevations at each end and exposed reinforced concrete waffle slabs framing the perimeter of the central sports court.

Due to their high quality and significance, the buildings were awarded Grade II listed status in 2023, making them one of the youngest listed buildings in the city.

Vision

Castle Meadow offered a ready-built campus of energy-efficient and open-plan buildings in good condition, allowing the proposed university development **(Figure 4)** to utilise the much less carbon-intensive 'Build nothing' and 'Build less' tiers of the IStructE's hierarchy of net-zero design.

The University of Nottingham engaged both original designers for the development, Arup and Hopkins Architects, to produce a series of 'design guides' for each of the building types. The goal of these design guides was to communicate the key principles of the existing buildings and the challenges they presented for any potential retrofit scheme to prospective architects, engineers and contractors. The design



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FIGURE 2: Construction of original office buildings

> **DUE TO THEIR HIGH QUALITY AND SIGNIFICANCE, THE BUILDINGS WERE AWARDED GRADE II LISTED STATUS IN 2023**



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FIGURE 3: Central Building with PTFE roof



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FIGURE 4: Vision for new Castle Meadow campus

guides presented a series of vastly different potential spaces, including large 200-seat lecture theatres, meeting rooms, offices and lab spaces **(Figure 5)**.

A key challenge for the multidisciplinary design team was how to communicate the complexity of updating and enhancing the service provision for the buildings on site. As the power and data requirements for the buildings would increase, a key aspect of the design guides was conveying the constraints and how best to route new services within the buildings with minimal structural intervention.

The site is located by the canal on an old flood plain, with a significant band of alluvium present at shallow depth within the ground. The buildings are, therefore, founded on a network of ground beams supported by 15m deep piles, which were an obstacle to the routing of new services. This was overcome by creating service trenches passing beneath the perimeter ground beams, threading through these obstructions.

In general, the structural design team was able to justify a 'do nothing' approach to the retrofit of the existing office buildings. This highlights the important role that the structural engineer can play, as a 'do nothing' approach can save a significant amount of carbon without significant structural intervention. Of course, 'do nothing' doesn't actually mean that the structural engineer 'does nothing': sometimes the structural engineer needs to 'do a lot more', as it is much quicker to design something new from scratch than to justify an existing building.

The existing structure was visually inspected and assessed for its condition and to ensure that no defects were present. Once this was completed, and following a review of the original structural design calculations and historic construction drawings, the engineers were able to confirm that, for parts of the structure which were not being modified, no strengthening works were required. The original design loading allowance of 5kN/m² for office areas allowed for flexible reuse of these buildings **(Tables 1 and 2)**. Therefore, the works to the office buildings were best able to maximise the opportunity for retrofit and the carbon savings this afforded.

The brief for the Central Building was for a deeper retrofit, creating a year-round event space in place of the existing sports court. The weight of any additional structure on the sports court had to be carefully considered due to the logistical complexities and high embodied carbon of installing new piles within the existing building. To maximise the building's potential, the existing pile capacities were assessed via a design review of the historic piling records; this allowed for the development of 'build less' options.

Embodied carbon was treated as a key differentiator of various structural

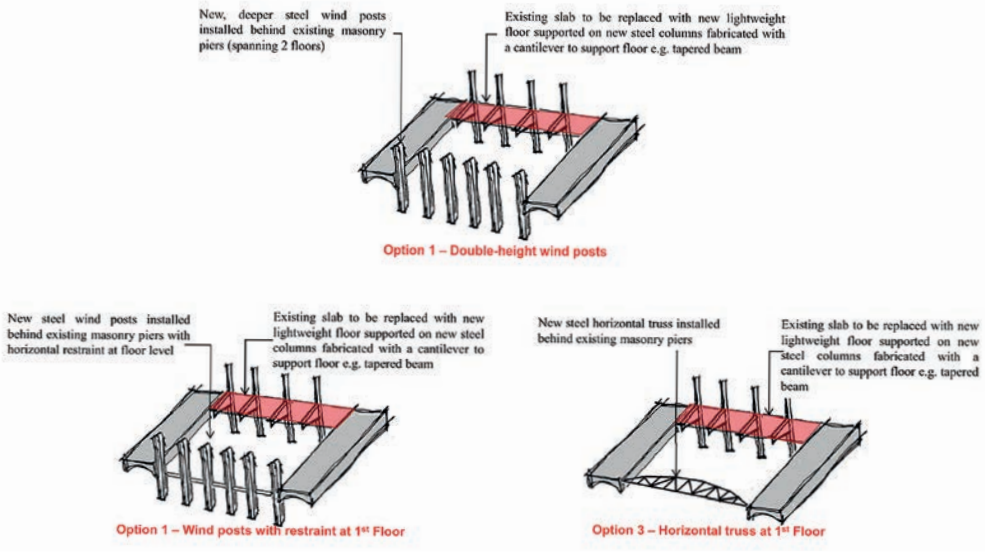

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FIGURE 5: Extract from design guides communicating key principles of existing buildings and retrofit challenges

Table 1:
Superimposed loads used in original design

Floor loads	
Office areas live loads	5.0kN/m²
Office areas partition allowance	1.0kN/m²
Corridors	5.0kN/m²
Staircases	4.0kN/m²
Plantrooms	7.5kN/m²
Teledata equipment rooms	5.0kN/m²
Toilets	2.0kN/m² + fixed partitions
Kitchens	3.0kN/m²
Restaurant/dining areas	5.0kN/m²
Sports areas	5.0kN/m²
Changing areas	2.0kN/m² + fixed partitions
Reception area	5.0kN/m²
Shop	4.0kN/m²
Creche	4.0kN/m²
Ceiling, raised floors and services	
Raised floor and floor-level services	0.65kN/m²
Suspended ceiling and/or services	0.1kN/m²
Plant platform levels	1.5kN/m²
Roof loads	
Offices (maintenance access only)	0.75kN/m² in plan

Table 2: Loads for different space types

Space type	Load category	Loading (kN/m²)
Lecture theatre	C21	4.0
Seminar rooms	C13	3.0
Offices	B2	3.0
Kitchen	C11	2.0

schemes at an early stage. The structural engineers worked with the sustainability consultancy team to report the embodied carbon of the design options being considered as a percentage of the equivalent embodied carbon which would be emitted by constructing a new-build structure of the same floor area **(Figure 6)**. This approach helped clearly communicate the benefits of a cross-laminated (CLT) and glued laminated (glulam) timber frame to the interdisciplinary design team and client. This option could provide a winter garden space capable of supporting planters and mobile elevating

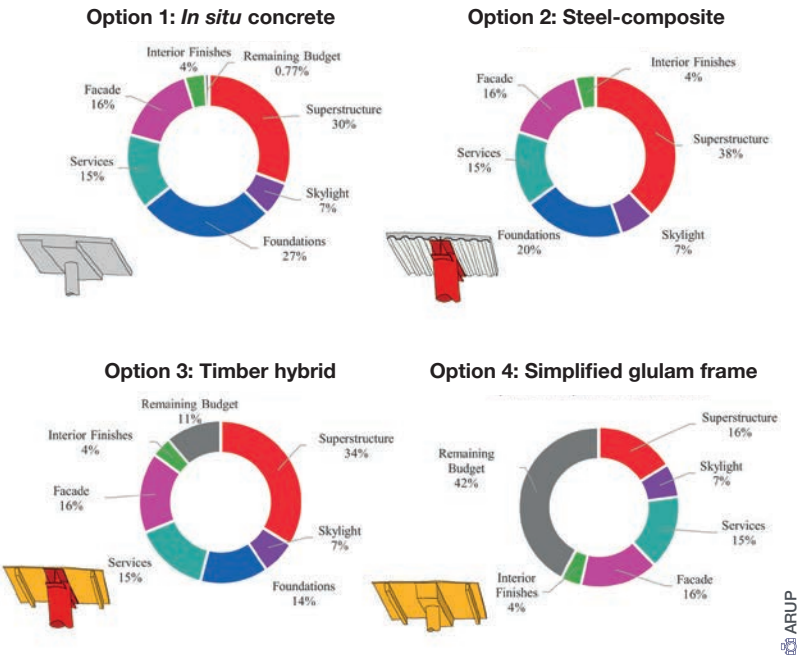

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FIGURE 6: Embodied carbon comparison of four retrofit options versus equivalent new-build scheme

work platforms (MEWPs) for the maintenance of the fabric roof, without the need for additional foundations.

Following the development of this guide, the university packaged the site into a series of smaller retrofit projects tendered as two-stage design-and-build projects for each of the office buildings and the Central Building. The structural interventions to the office buildings were minimised to achieve a 'build nothing' low-carbon approach for the site, only requiring updated servicing provisions.

A key aspect of the works to the Central Building was the replacement of its tensile-fabric membrane.

> **THE STRUCTURAL INTERVENTIONS TO THE OFFICE BUILDINGS WERE MINIMISED TO ACHIEVE A 'BUILD NOTHING' LOW-CARBON APPROACH**

Central Building: roof replacement

Roof form summary

Tensile-fabric roofs are formed by establishing a stable geometric form with a fabric membrane, which is held taught by a supporting structure acting in tension and compression. Typical tensile-fabric structures are composed of a single form, repeated across the structure or supersized to create a large, impressive volume.

The vision of the original designers of the Central Building was for the form of the roof to reflect the different uses of the building. Therefore, the roof comprises five separate tensile fabric elements, utilising two distinct geometric forms **(Figure 7)**.

The largest element is located over the central sports court, suspended from three elliptical trusses which are hung from a cable net supported by four large steel masts at the corners of the building, and two large elliptical trusses at either end of the building, which span the full width of the structure.

At the north and south ends of the building are two smaller external canopies which shade the glazed elevations, held in place via a perimeter tensioning cable connected to inclined columns. On the east and west of the building, above the mezzanines which surround the sports court, are conic tensile-fabric roofs, which are connected to curved 'oculi' trusses supported by a series of A-frames internally and tensioned using a similar system of perimeter cables and inclined columns as the north and south canopies.

The use of multiple geometric forms makes it a very complex example of this type of structure.

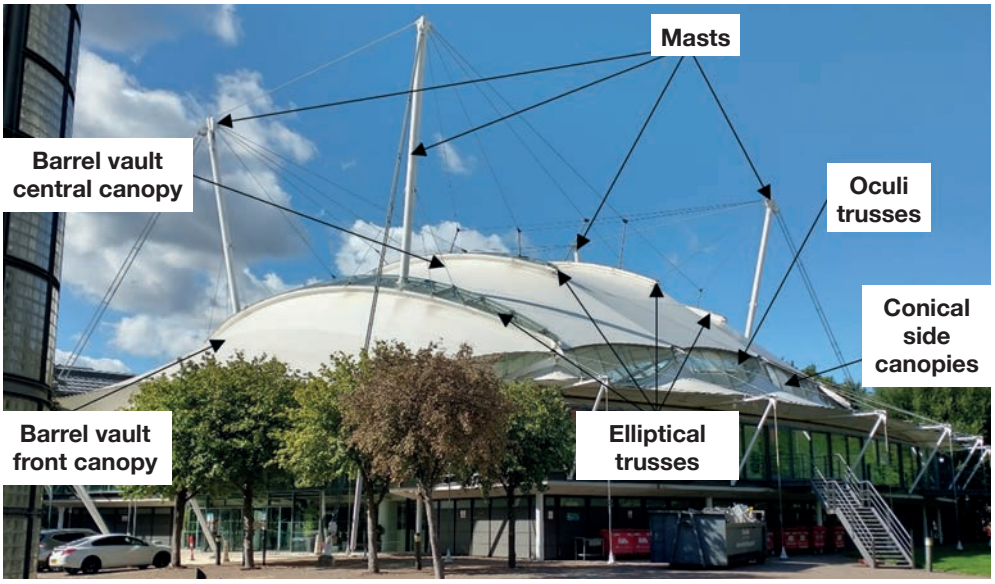

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FIGURE 7: Central Building structure



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FIGURE 8: Condition of tensile-fabric roof

Condition survey

The contractor, GF Tomlinson, appointed Arup and Base Structures as specialists for the works to the roof. These, in turn, appointed Tensys as the tensile-fabric designer (Tensys had also been the fabric designer during the construction phase of the Central Building in 1993).

When constructed, the PTFE membrane had a reported design life of 30 years. However, there have been examples of much older, well-maintained PTFE membrane structures, such as the Sports Science and Athletic Pavilion at the University of La Verne, California, which lasted 51 years before the fabric required replacement.

An assessment of the existing fabric concluded that its condition was poor (significant tearing, leaks and rust on tensioning cables; **Figure 8**), so a replacement fabric membrane was required.

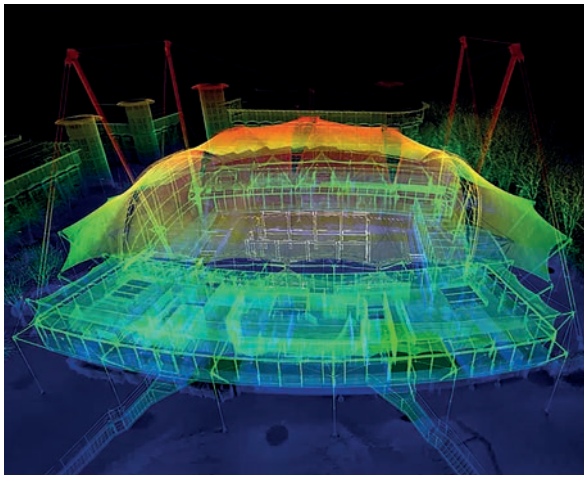

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FIGURE 9: LiDAR scan of building

> **THE PROJECT BENEFITED FROM THE INCLUSION OF THE ORIGINAL DESIGNERS OF THE BUILDING**

Replacement of fabric

The project required a strong collaborative effort from the design team with a clear understanding of each party's scope to create seamless interfaces between the different designers. Arup was responsible for assessing the capacity of, and any required strengthening to, the steel structure supporting the tension membrane. Tensys was responsible for the design of the tension membrane and perimeter tensioning cables, which were all being replaced. Base Structures was the specialist subcontractor responsible for performing the replacement works. GF Tomlinson was the principal contractor with overall project responsibility and responsibility for temporary works.

The design process to replace the tension membrane required five key steps:

- creating design models for the structure
- construction sequencing
- understanding the impact of changing the fabric
- performing capacity assessments
- understanding structural movements.

Creating design models

The project benefited from the inclusion of the original designers of the building and existing drawings, calculations and models. By using digital fabric node maps from the Tensys archive and design drawings from the Arup archive, an initial analytical model for the structure could be quickly created to enable the start of the design process.

However, as always when working with existing buildings, the engineers needed to verify that the existing building correlated to the record information, which may not always capture changes which occurred on site. This was particularly important as, due to the listed nature of the building,

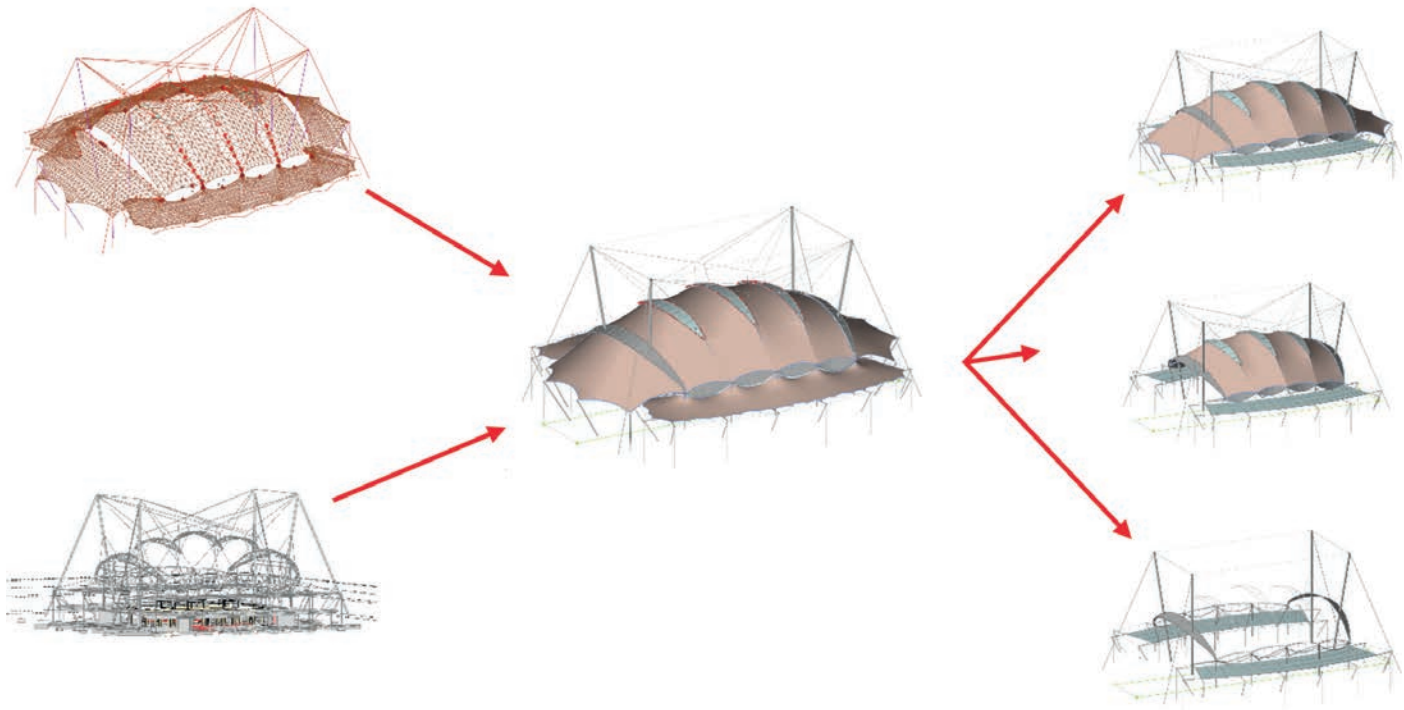

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FIGURE 10: Workflow for creating staged analytical model

the structural form of the roof could not be significantly altered.

A LiDAR survey was performed of the perimeter and inside of the building, along with a measured survey of the mast tips and cable-net node locations. The LiDAR scan **(Figure 9)** could be loaded into Autodesk Revit so that a scan-to-BIM process could be performed to create a full 3D model for the steel structure of the roof.

This Revit model was then exported into Oasys GSA to update the location of the supporting steel structure of the roof in the analytical model.

As Arup and Tensys were performing designs for separate elements of the same roof, using separate non-linear analysis packages, it was crucial that the boundary conditions and stiffness of the supporting structure were consistent for both teams. At the start of the project, the results for every element in both models were cross-compared to ensure the results were within an acceptable margin. Where there were variances due to different supporting conditions, material properties or model loading, a collaborative meeting was held to agree upon a single approach for both models. At the end of this process, the models were reporting the same results within 5% of each other, which was considered acceptable to move the design forward.

Construction sequencing

Due to the detailing of the original PTFE roof, the new fabric membrane could not be installed while the old fabric was in place, which is the preferred replacement sequence for modern tensile-membrane roofs. Instead, the construction sequence needed to be almost completely reversed, with the cable net de-tensioned and the suspended trusses lowered before the new fabric could be installed.

This complex methodology required the installation of Tirfor winches and ratchet straps to de-tension and remove elements of the cable net, as well as winches and fabricated lifted beams to unload and lower the suspended elliptical trusses to a scaffold working platform built on the sports court. These activities significantly modified the load path of the structure, and significantly increased load in local areas during certain activities.

Constant collaboration was required between all four parties during the development of the construction sequence. The design models were updated with staged analysis steps **(Figure 10)** for the fabric-removal and truss-lowering process to assess how

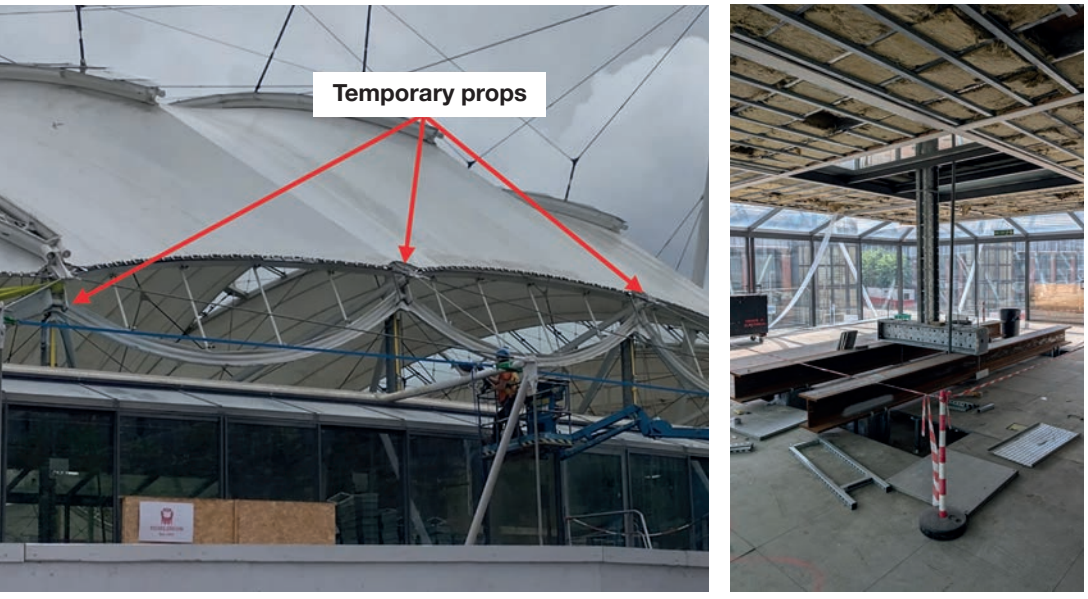

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FIGURE 11: Temporary props to oculi trusses

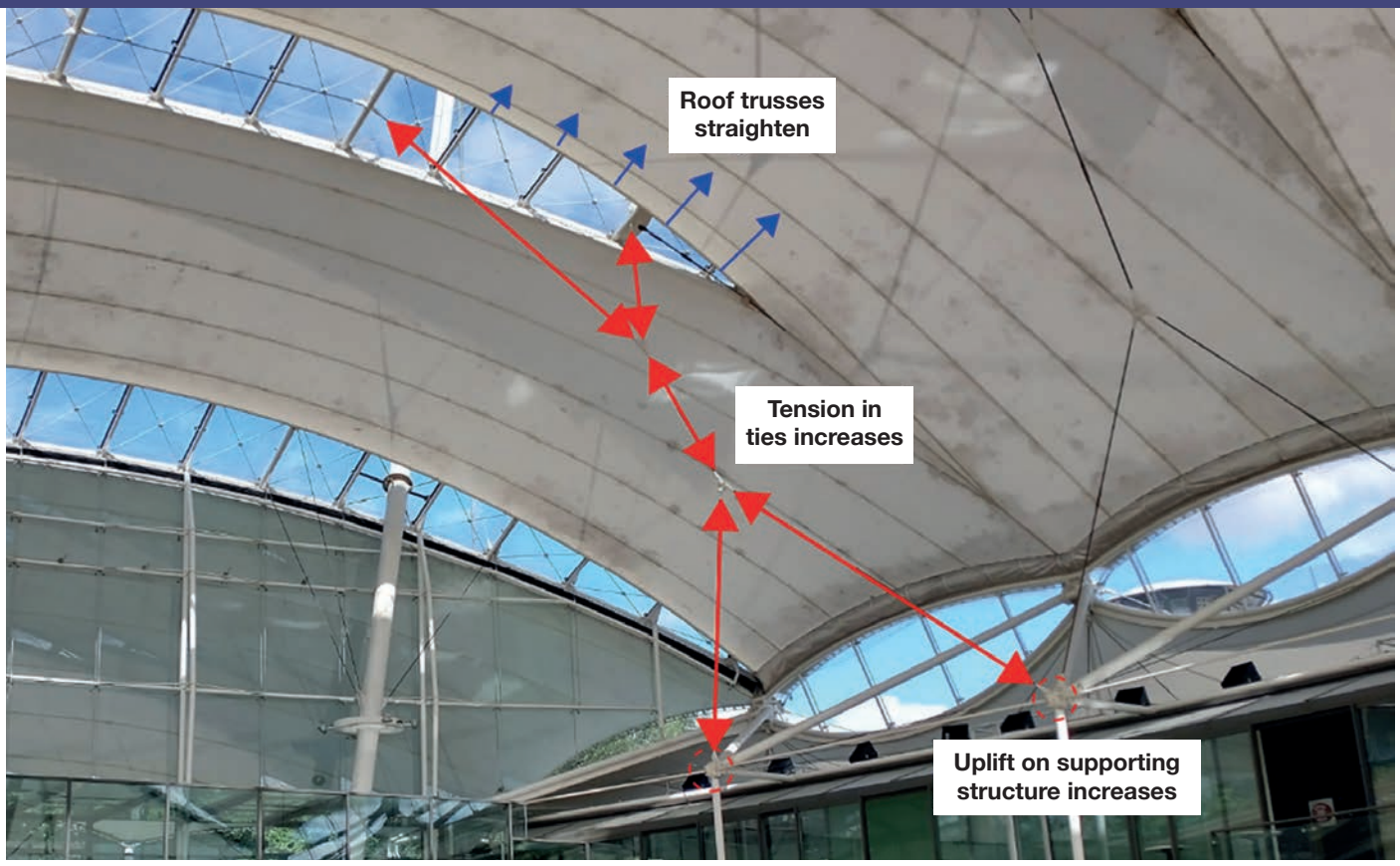

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FIGURE 12: Impact of changing membrane

the construction sequence impacted the load distribution through the structure, which fed into the structural element and connection verification checks.

The staged analysis identified that the side 'oculi' trusses which supported the conic tensile membrane were not stable once the suspended trusses had been lowered, as the nodes of the oculi trusses were held in place via a pretensioned cable connected to the suspended trusses. Therefore, a series of temporary props **(Figure 11)** had to be built from the perimeter concrete mezzanines to support structure. These elements were designed and installed by MGF working for GF Tomlinson.

Impact of changing fabric

The original tension membrane was made of PTFE. Fibres of PTFE are woven together to form a fabric sheet in a process similar to traditional weaving, with one set of fibres pulled tight in the 'warp' direction, and another set of fibres woven across in the 'fill' direction. This process leads to an anisotropic material with a Young's modulus approximately half as big in the fill direction.

In modern tension-membrane structures a polyvinylchloride (PVC) fabric is used. The process of forming PVC fabric leads to a material which is much closer to being isotropic, with a Young's modulus approximately 10% different in the warp and fill directions. As a result, the PVC fabric requires approximately 60% of the prestress and a much smaller thickness to form the same geometry as a PTFE membrane – 2.0kN/m in PVC and 5.0kN/m in PTFE – making it a lighter alternative.

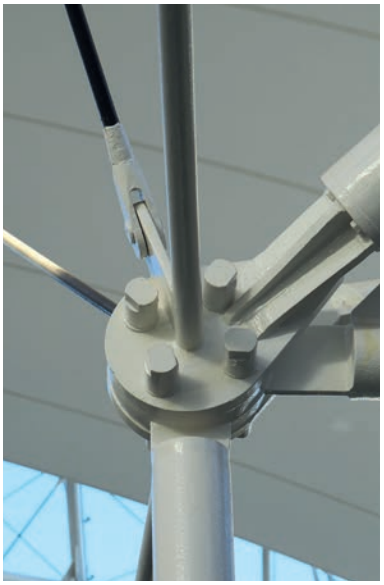

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FIGURE 13: Remediated connection

While the reduction in membrane prestress reduced the overall load on the structure, the assessment of the analytical model showed some local changes in behaviour which required addressing **(Figure 12)**. The suspended curved trusses of the barrel vault roof were held in place by a combination of the fabric membrane and a network of Macalloy bars connected to the perimeter A-frames. By reducing the prestress in the fabric, these curved trusses attempted to 'flatten' under load, increasing the forces in the internal Macalloy bars and supporting A-frame structure, which required replacement Macalloy bars and strengthened connections **(Figure 13)**.

Performing capacity assessments

To assess the capacity of the existing structure, a full condition assessment of the steel frame and its connections was required. Fabrication drawings were available; however, the information on these drawings required verification, as many were in Polish, the design forces for these connections was not on these drawings, and the condition of the connections after 30 years of use required assessing.

A condition and measured survey of the building's connections was performed, and new steel connection drawings for the project were created **(Figure 14)**, which will provide a key record in the future when the fabric is replaced again.

Understanding structural movements

As part of its role as principal contractor for the works, GF Tomlinson wanted to ensure that the works were monitored throughout to give early indication of any

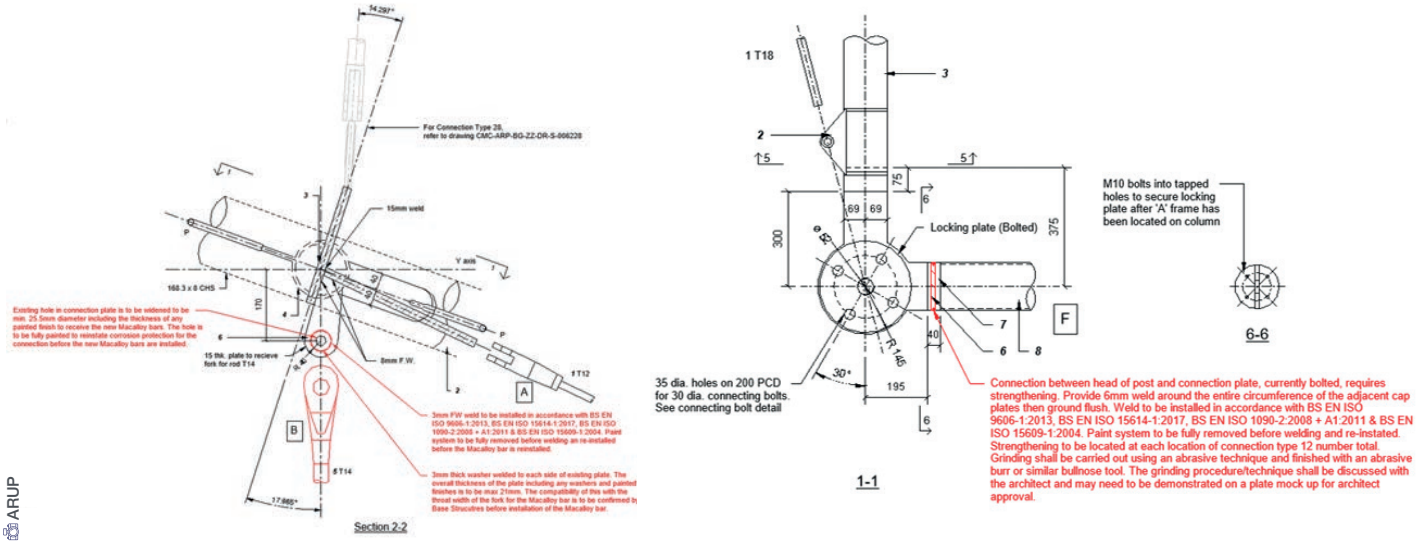

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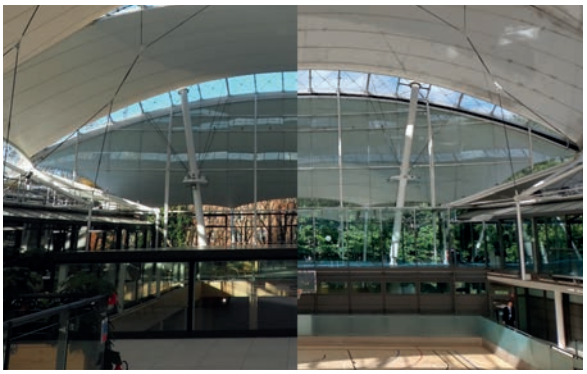
FIGURE 14: Modifications to roof structure (drawings for connection of replaced Macalloy bars)



STEPHEN FERNANDEZ

FIGURE 15: Internal transformation of Central Building

potential failure. It was decided with Arup, Tensys and Base Structures that the deflection of the mast tips should be monitored on a daily basis throughout the full construction sequence. The design team used the analysis models to create a traffic light system in which movement of one of the mast tips relative to the others beyond certain prescribed limits would result in either a pause, if the movement was minor, or a full stop to the works if the movement was large and suggested potential failure. The works proceeded without a single pause.

Summary

The University of Nottingham Castle Meadow project has showcased a full range of adaptive reuse and retrofit principles **(Figures 15–17)** and the importance of the structural engineer's role in delivering them. Condition surveys and investigations of the existing buildings were used to justify 'build nothing' and 'build less' approaches, both of which required significant engineering works.

The works to the Central Building roof highlight the need for close collaboration between all disciplines, the importance of sourcing existing drawings and historic design information, as well as the need for site surveys and constant reassessment and validation of design assumptions throughout the project stages to deliver complex retrofit projects.

The project has continued the strong legacy of sustainability for the development, with the Central Building works having an embodied carbon of 80kgCO_2e/m^2 for all the works, equating to a SCORS rating of A+.



CHANDAN JOSHI

FIGURE 16: New timber mezzanine within existing building



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FIGURE 17: Interface between new and old structure