Research at Dundee and Strathclyde Universities

Dr Nutan Subedi, a member of the Institution's Research Panel, outlines four research projects at Dundee and Strathclyde Universities covering composite structural elements, dynamics of slender structures and predictive models of corneal performance

Fig 1. Aluminium and timber composite beam

Composite structural elements comprising of concrete infill sandwiched between steel plates and described as DSC elements are a robust form of construction with practical applications in many structures. Currently, at Dundee and Strathclyde Universities, research is focused on a number of issues concerning the structural performance of such elements.

1. DSC elements under static and impact loads

Completing the connection between the steel plates and concrete infill are steel shear studs at centres designed to achieve the desired level of interaction. At the University of Strathclyde a program of research was undertaken to evaluate the behaviour of DSC elements under static and impact loads. A model scale of 1:4 was adopted. The initial work determined the behaviour of the shear studs. This was followed by a series of panel and beam tests to establish the performance in flexure under static loads. Finally the beam sections were subjected to impact testing both in their bare state and overburdened with sand. At each stage, the predictive methods and the experimental results were in good agreement. It is hoped to extend the impact work to include panels and to examine more closely the behaviour at serviceability loads. Contact: r.cairns@strath.ac.uk

2. Dynamic behaviour of slender structures

Dynamic behaviour of slender structures has become of concern to many designers following the increasing awareness of the negative human perception to slender structure vibrations. A theory based on modelling the composite beam as a sandwich construction with visco-elastic filling is currently being developed. The numerical analysis is also being compared against scaled model experimental tests (Fig 1) which use an aluminium and timber composite beam connected using various neoprene membranes. Eventually it is hoped to recommend an alternative forms of connection that will reduce the perception of vibration in slender composite beams. Contact: r.cairns@strath.ac.uk

Fig 2. (below) Steel-concrete-steel cantilever shearwall

3. Impact resistance of DSC shearwall elements

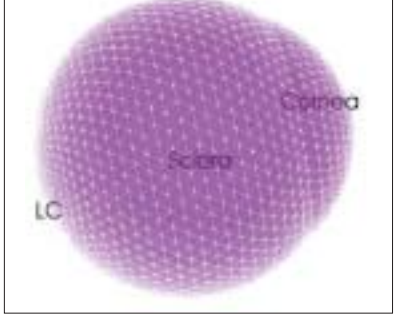
A possible application of double skin composite construction is in shearwalls of tall buildings. Current events have shown that large impact forces could become an important consideration in the design of shearwall structures. A preliminary study carried out at the University of Dundee using small scale cantilever walls representing shearwalls has shown that the resistance of DSC shearwalls subjected to in-plane impact force effected by using a dropped object is considerably higher that those of plane concrete walls (Fig 2). The work has prompted further research using more representative scaled models and proper instrumentation. Ductility and deformations under impact loading would form some of the important parameters in this study. Contact: n.k.subedi@dundee.ac.uk

4. Predictive models of corneal performance

Interdisciplinary research with particular application in biomedical science is a growing field where structural engineering has a tremendous scope for contribution.

An interdisciplinary research project into the behaviour of the human cornea is currently under progress at the University of Dundee utilising the finite element technique. The aim of the mathematical model is to predict the bio-mechanical performance of the cornea when subject to disease, injury, surgery or abnormal increase in intra-ocular pressure. The models (Fig 3) are being developed to be used as predictive tools for the assessment and development of clinical and surgical methods and lead to improved patient care. Important specific applications include clinical management of glaucomatous eyes, myopia treatment and tonometry modelling. Contact: a.i.h.elsheikh@dundee.ac.uk

Fig 3. (below right) Finite element mesh of a human cornea



The Domestic Finishing Mill, Anchor Mills, Paisley

How a multi-disciplinary approach is meeting the challenge of making an historic but derelict building suitable and safe for modern residential use

Built in 1886, the Domestic Finishing Mill is part of the Anchor Mill Complex. One of the few surviving buildings from Paisley's industrial heritage, this massive and beautifully constructed building is category A Listed (see fig 1). Although the building was in continual use for more than a century it has stood derelict for over 10 years.

One of the main architectural features is a 11 × 28m high central light well or atrium. This atrium is covered by an ornate glazed lantern roof light and is surrounded on each level by 'Victorian' timber and glass screening (see fig 2 and 3).

Whilst the building has lain derelict it has been victim to numerous arson attacks, the most serious of which occurred approximately 6 years ago. A fire was deliberately raised on the fourth floor of the building, which caused major structural damage to that floor.

The design proposals

The UK Historic Building Preservation Trust, in conjunction with Bryant Homes, have complied an ambitious phased regeneration and conversion programme aimed at restoring the building. It is intended that this will guarantee the future of this historically significant building.

One of the most important drivers for the project identified, by both funders and Historic Scotland, is that the important features such as the atrium are restored in a sympathetic fashion. The detailed development proposals are:

- conversion and formation of a naturally ventilated car park for residents and business users at ground floor level;
- conversion and restoration of the first floor of the building to form lettable small business units;
- restoration of the central atrium space to form a naturally ventilated circulation and hub space for the public and users to enjoy;
- conversion and formation of luxury residential apartments and maisonettes on the second, third and fourth floors, stacked around the atrium;
- repair and restoration of all areas of the building

The Domestic Finishing Mill awaiting refurbishment

Consulting engineer Buro Happold was appointed on a multi-disciplinary commission to facilitate the development programme. Part of the brief was to:

- Inspect, test and appraise the building in terms of structural engineering and building services.
- Formulate detailed design proposals for structural engineering and building services.
- Formulate a detailed and comprehensive fire strategy which would complement the existing building, deliver the overall architectural objectives and satisfy the regulatory authorities.

These services have been delivered and development approvals have been received from Historic Scotland, Renfrewshire Council Planning and Building Control authorities and Strathclyde Fire Brigade.

The fire engineering brief and scope of work

Buro Happold FEDRA was charged by the client to:

- Develop a fire safety strategy to the complete satisfaction of the local authority Building Control Department and Fire Authority.
- Produce fire safety technical reports to justify and substantiate relaxation of Technical Standard requirements.
- Assist in all necessary value engineering exercises to conclude an affordable guaranteed maximum price for the client.

The key issues

A number of important issues had to be assessed and overcome throughout the development of the fire strategy.

Prescriptive regulation

Although Fire Safety Engineering has been recognised by the Scottish Executive since 1998, its use in Scotland has remained somewhat restrained in comparison to other parts of the UK due to the prescriptive regulatory framework.

As the conversion proposals would change the use of the building and significantly alter the interior, the requirements of the Building Standard (Scotland) Regulations 1990 as amended had to be applied and satisfied. However wholescale application and compliance with the prescriptive requirements of the Scottish Technical Standards could not be achieved without conflicting with the key conservation objectives for the project. An alternative approach, which sought to provide an adequate and reasonable standard of safety and impacted least upon the architectural quality and character of the building, had to be implemented. The aim was to strike a careful and reasonable balance between safety and preservation. A fire safety engineering approach ideally suited these requirements.

Contemporary / bespoke design

The architectural objective was to produce a sensitive design, which complemented and had little impact upon the aesthetic quality of the historical building. As part of these proposals the architect, in conjunction with Persimmon Homes, produced a series of contemporary designs for the proposed residential apartments.

A building services strategy was also derived which utilises the qualities and benefits of the existing atrium space. Within the residencies, inner rooms such as the bedrooms etc., would be provided with natural ventilation and daylight gained directly from the atrium space. This strategy would however provide a route for fire and smoke spread between differing areas of the building unless the risk was adequately mitigated. This also conflicted with residential fire separation and compartmentation requirements.

Atrium

With a height of 28m and open to all storeys of the building, the existing atrium provided an obvious route for fire and smoke spread within the building. This risk was further compounded by the fact that the atrium was totally sealed and there was no existing means of suppressing a fire or relieving smoke from the space. The existing timber Victorian screening around the atrium also represented a significant

fire load and flame spread route.

Despite these factors the designers wished to:

- use the atrium base for general circulation and business accommodation;
- retain the Victorian screening;
- have the atrium open on all storeys to the accommodation;
- have all apartment openings to the atrium non fire rated and openable;
- retain the ornate glazed rooflight above the space.

Cast iron structural frame

As expected for a building of this age the structural frame was cast iron. Suspended filler joist composite floors supported on iron beams are in turn supported from iron columns via an open saddle box arrangement. The initial concerns with the frame were fire damage to a large area within the top storey of the building and localised fire damage within the top storey of the south stair tower.

Strathclyde Fire Brigade had major reservations about cast iron and its performance in fire, borne out of experience in real fires where the cast iron had suddenly collapsed when water was applied. From a structural engineering perspective, residual stability and robustness, particularly in the fire damaged areas, had to be resolved.

Structural fire performance

Due to the building height and size, the Scottish Technical Standards required existing elements of structure to be fire protected for 90mins. However there was no evidence of any fire protection materials existing. The fire protection requirements also applied to fire separation walls between the proposed apartments and the atrium, as well as between the business units and the atrium. These onerous requirements contradicted the overall design objectives, so an alternative structural fire engineering approach had to be applied.

Approach and proposals

There were four stages to development of the fire strategy.

Stage 1 involved a desk-top study of the design proposals and objectives for the project which identified the highest risks in terms of life safety. This review also looked at ways to address the identified risks through prescriptive guidance and alternative approaches. A schedule of risks and potential solutions was presented to the design team for consideration along with the regulatory approvals risk associated with each.

A detailed fire scenario and hazard assessment identified the consequences and effect of differing fires on the building and its potential occupants and fire fighters. This was carried out quantitatively and qualitatively. A literature review of the fire performance of cast iron revealed contradicting results.

Stage 2 involved consultation and negotiation with the local authority. Throughout

The existing atrium ***(courtesy Buro Happold)***

the design process, consultation with both Building Control and the Fire Authority ensured a package of measures was developed which adequately addressed the risk and which they were comfortable approving. It allowed the regulatory relaxation process to be negotiated in the early stages of the project. This removed a large risk to the project and allowed a degree of cost certainty to be reached for the fire safety package.

Stage 3 involved a site inspection with the Fire Authority. The structure was carefully examined, the fire damaged areas inspected and ultimately led to the Fire Authority having confidence that the stability and robustness of the existing cast iron frame was good.

Stage 4 in the fire strategy development was the production of a comprehensive fire strategy report which designers and regulators could easily translate. This document clearly stated the performance requirements to be achieved by the design. It provided Building Control and the Fire Authority with the confidence necessary to buy into and approve the proposals. The following innovative features are vital components of the proposed fire strategy:

- domestic sprinklers will be installed in all apartments;
- a natural smoke control/ dilution system will be installed in the atrium space;
- automatic fire detection will be installed throughout the atrium and business units;
- the cast iron structural frame will be treated with a thin coat intumescent coating to achieve 60mins fire resistance.

These features allowed relaxation of Technical Standard requirements to be granted by the local authority.

'the project will help to prolong the life of the historically important building and guarantee its future'

The benefits

There were several key benefits of the fire strategy developed by Buro Happold FEDRA and the approach implemented. Application of a holistic risk-based approach allowed the hazards presented by the existing building and the proposed design to be identified and assessed. A package of safety measures was recommended which would adequately address and mitigate the identified risks. In this way the fire strategy was tailored to suit the particular building and not based on a rigid or generic set of prescriptive standards.

The project will help to prolong the life of the historically important building and guarantee its future. It enabled the building services concept and natural ventilation proposals to be realised.

The approach helped to inform the regulatory process at an early stage of the project. It achieved relaxation/ dispensation of Scottish Technical Standard requirements for:

- reduction of the overall structural fire protection requirements for elements of structure from 90 to 60mins fire resistance;
- reduction of the period of fire resistance required for the fire separation wall between the business accommodation and atrium space;
- dispensation of fire resistance requirements for openings in the fire separation wall between all apartments and the atrium;
- dispensation of compartment height restrictions in relation to the atrium;
- relaxation of operational fire fighting provisions;
- relaxation of ventilation requirements for fire fighting shafts;
- dispensation for the requirement to provide alternative exits from the upper storey of maisonettes;
- relaxation for the open-plan design configuration of galleried apartments.

The project achieved a balance between active and passive fire protection measures which does not detract from the existing architectural quality of the building, but which adequately mitigates the risk presented by the conversion proposals. It achieved an optimum design solution which represented best value and an affordable solution within the clients overall budget.

The Domestic Finishing Mill is at the forefront of fire safety as the completed domestic sprinkler installation will be one of the first of its kind in a new-build residential development in Scotland. This project is a prime example of how the application of good fire engineering practice in Scotland can benefit the built environment by allowing this unique old building to be restored and converted.

Taking into account the complexity of the conversion project, the multi-disciplinary approach by Buro Happold FEDRA on the project was extremely effective. Building Control and the Fire Authority were involved in producing the fire strategy which resulted in the client, design team and regulators being completely satisfied with the outcome. se

Credits

Client: The Phoenix Trust (UK Historic Building Preservation Trust)
Architect: James F Stephen Architects
Structural and building services engineer: Buro Happold
Fire safety engineer:Buro Happold FEDRA
Quantity surveyor: Davis Langdon and Everest
Residential developer: Persimmon Homes
Planning Supervisor: J R Queenan Partnership

Royal Naval College

How do you make a building as historically important as the Royal Naval College in Greenwich fit for a future catering for 8000 staff and students? Michael Eatherley and Malcolm Brady of Michael Barclay Partnership explain

The Royal Hospital for Seamen was founded by Queen Mary as a home for veterans of the Royal Navy with, as Hawksmoor put it, a 'fixt intention for magnificence'. It was conceived as a home for up to 2000 men on the site of the Tudor palace of Placentia, by the River Thames at Greenwich, and it was built in four phases of work between 1696 and 1751. Remnants of the old palace lie buried under the central lawns and as parts of the vaults under the Queen Anne quarter.

Sir Christopher Wren laid out the original plan, set out as four quarters which are known as King Charles, Queen Anne, King William and Queen Mary. The group was divided by a strip of land that remained in the Crown's possession leading down to the river from Inigo Jones' Queen's House. Wren continued overseeing the work, free of charge, until well into his 80s; but leaving much of the detail design to his assistant, Nicholas Hawksmoor. In the ensuing years other architects, notably Thomas Ripley, John Vanburgh and James Stuart, made major contributions. The Painted Hall at the north end of the King William quarter was decorated by Thornhill between 1708 and 1725. The chapel which forms the corresponding wing of the Queen Mary quadrant was rebuilt by James Stuart after Ripley's original had been destroyed by fire during the New Year celebrations in 1779.

After the Napoleonic Wars, the increasing popularity of 'out-pensions' led to a gradual decline in the numbers of veterans and eventually to closure of the hospital in 1869. Four years later the Admiralty's Naval College transferred from Portsmouth. The College adapted the buildings over the years, dividing the wards into small residential cabins introducing classrooms, lecture theatres and ablutions. During the Second World War bombs caused localised damage. Later there came further developments – a large lecture theatre in Queen Anne, and in King William specialist laboratories, lecture theatres and a small nuclear reactor for training purposes. In spite of all this, it has to said that, a least below the surface, much of the original fabric remains intact. The Royal Naval College left Greenwich in 1998 and the site was made the responsibility of the new Foundation for the Royal Naval College.

The fifth major building, to the west of the four quarters, is the Dreadnought Seamen's Hospital. It was built by James Stuart between 1764 and 1768, originally as The Infirmary for Hospital Pensioners, and extended during the 19th century. It was badly damaged by incendiary bombing in 1941, but remained as a hospital until its closure in 1986 and subsequent neglect.

Above: Dreadnought building before refurbishment Below: After work was completed

Below: Aerial view

Approach to refurbishment

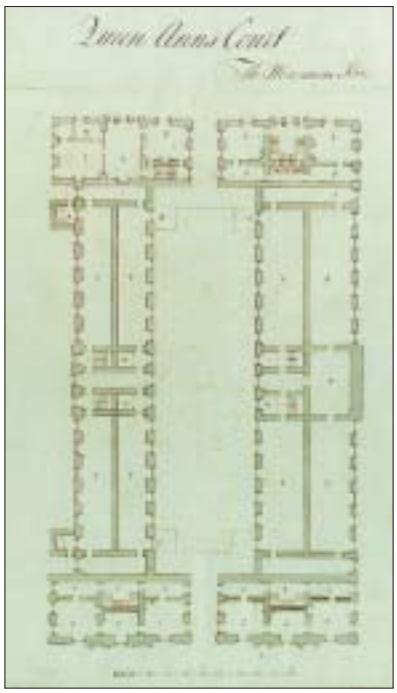
After a period of negotiation the University of Greenwich acquired first the Dreadnought Seamen's Hospital in 1997 and then, successively, Queen Anne, Queen Mary and King William; subsequently, Trinity College of Music took over King Charles. Dannatt Johnson Architects was appointed to draw up a master plan for the University's new campus and later for the restoration and adaptation of the interior spaces. Giles Quarme and ST Walker and Duckham acted as historic building architects to the Foundation for the Royal Naval College. They were responsible for the external fabric of the buildings.

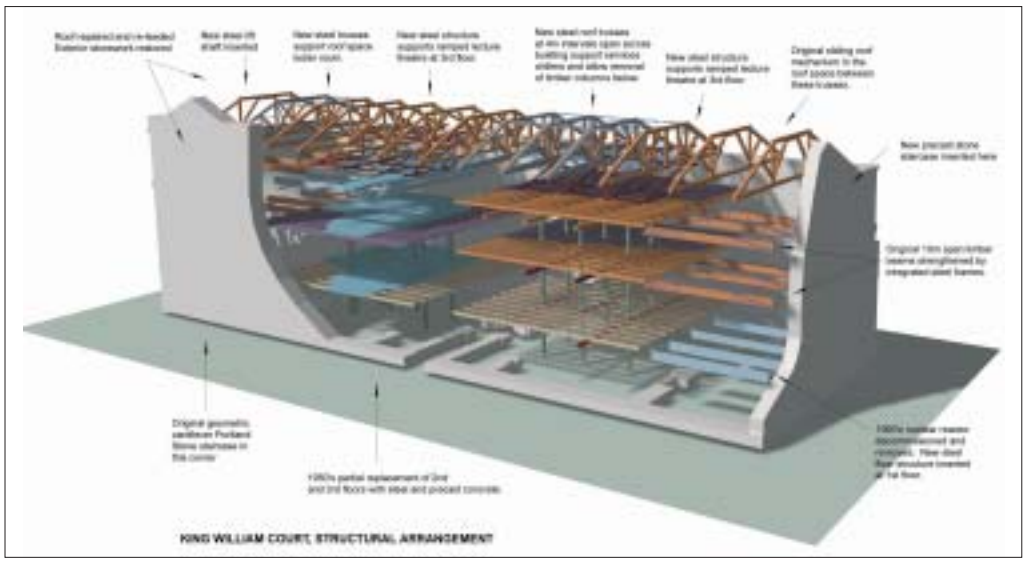
With the exception of the Dreadnought, the group of buildings is a Scheduled Ancient Monument and listed Grade 1. Needless to say, their architectural and historical importance demanded a special approach to the structural engineering, where respect for the fabric of the buildings is all important. Structural interventions were a last resort and, if repairs proved to be essential or where structural adaptations were vital to the university, the first consideration was to make the design sympathetic to the quality of the buildings.

The approach adopted and agreed by English Heritage and the local authority was broadly as follows:

- Determine the nature and physical condition of all the main elements of structure – walls, vaults, roofs, floors, staircases and foundations.
- Assess the strength and serviceability of these elements in relation to existing and reasonable new conditions.
- Repair damaged parts and strengthen structures only where safety might be at stake or where deformation or dynamic effects might be unacceptable.
- Adopt repair and strengthening measures to be least invasive, to be sympathetic to the original materials and design and, as far as possible, to be reversible.
- Record what was found and how the buildings had been left.

Not very much documentary material relating to the structure of the buildings could be found – little more than a few drawings of work carried out or proposed following damage during the Second World War. Archaeological reports helped with information on the ground conditions and there are some intriguing contemporary accounts of the familiar tribulations of construction. The initial physical investigation at feasibility stage took place almost literally under the Navy's feet. The process was continued until the end of the work by which time all areas had been examined and a complete picture of all the





Left: First floor plan (c.1700)

Above: King William cutaway

structures developed and recorded.

It might be argued that there is little difference between the use made of the buildings by the University from that of the Royal Naval College and that the construction was generally acceptable on the basis of prior use. However there are important distinctions in the use of individual rooms and particularly in the number of occupants. There are times when there will be as many as 8000 staff and students in the buildings – almost certainly many more than at any time in the past.

Another factor was the obvious evidence of distress in some of the larger rooms – large deflections, liveliness and earlier attempts to strengthen and make good. It was agreed that the building should be fully checked for safety and serviceability generally in compliance with current Building Regulations and Fire discipline. Structurally, a consequence was the need to make an analysis of the strength and behaviour of all the floor and stair structures. The normal categories of imposed floor loading were adopted in all critical areas. In less sensitive parts these were relaxed and drawings were prepared for each room showing the safe loading and the largest number of people who might safely occupy it. The university has already made use of these to assess whether a particular room might be suitable for a large party.

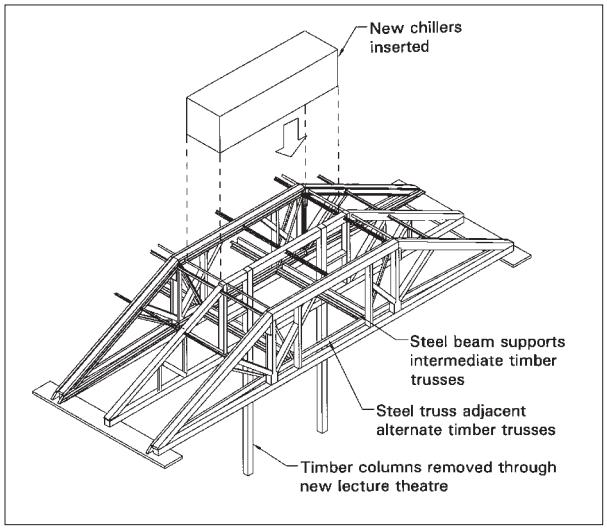
The original structures of the buildings are similar and in line with other contemporary buildings. The 19th century adaptations were mostly reasonably sympathetic to the buildings, but some of the more recent ones have been much more intrusive. The most significant is a large lecture theatre carved out of the west range of Queen Anne replacing the length of the spine wall with heavy steel beams, and in King William old floors were removed to accommodate a small nuclear reactor and associated laboratories. However, sometimes under the surface, much of the original fabric is intact.

Original walls are in thick brickwork faced either in Portland Stone or gauged brick. They are founded on chalk blocks over a dense gravel formation. Mostly the walls were found to be in reasonably good condition. An exception was one of the cross walls in the north pavilion of Queen Anne which was damaged as a result of differential ground movement – possibly where there are accounts of Hawksmoor, procuring 200 tons of chalk from Kent to dump in a soft area of what was then the river bed. The outside stone facings needed attention as did chimney stacks and parapets. Some of the stone was badly weathered and iron cramps tended to have corroded with the effect of loosening the areas of facings.

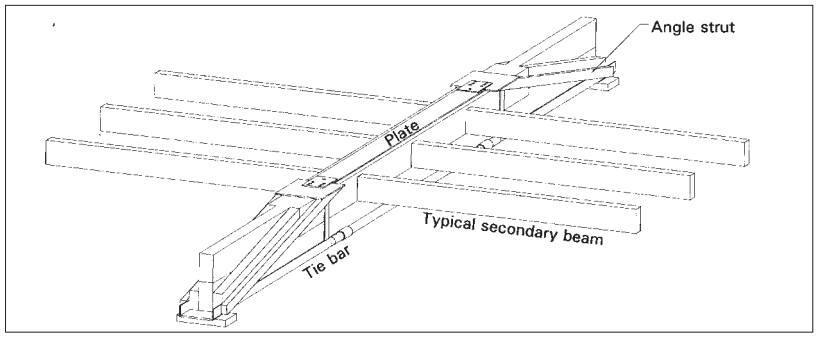
The lower levels and some of the upper circulation areas are structured in brick masonry vaulting, typically one brick thick. Except where disrupted by occasional service penetrations, these structures remain in good condition and are easily capable of supporting their loads.

Timber floors typically are in the form of light floor joists spanning about 1.2m onto secondary beams (100mm × 225mm) spanning 4m and double notched into primary beams. The primary beams (350mm × 350mm) generally span up to 7m onto thick masonry walls, but there are instances of spans of up to 11m in Queen Anne and King William witnessed by previous attempts to mitigate the excessive deformations. Much of the timber is original Baltic Pine and in reasonably good dry condition. Where there were defects these included historic woodworm attack, occasional dry rot below old roof leaks, fire damage, services notching and accidental impact breakages. A common feature was a separation of the secondary beam tenons from their notches in the primaries. Local repairs were usually by bolted steelwork – resins were only used occasionally because of the irreversibility of the technique. Where a primary beam had to be strengthened as far as possible this was achieved by inserting steelwork in such a way that as little as possible of the surrounding fabric was disturbed. One of the solutions in the areas of 10m span in King William is illustrated in the cutaway drawing.

Roof trusses repeat the lower grid of 4m spacing. In most areas the trusses are



Above: Roof modifications over the new lecture theatre



Right: Floor strengthening

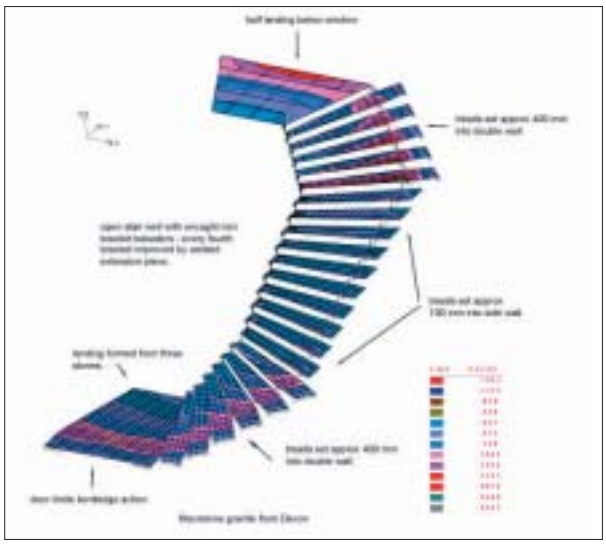
either original, often suffering from decay at the eaves, or are 19th century replacements. The only 20th century replacement was a result of war damage in the south wing of Queen Mary.

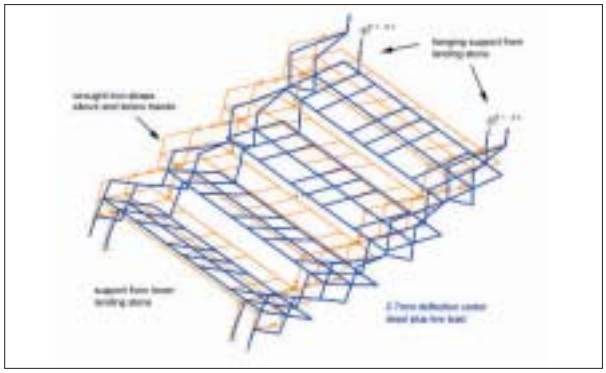
Concealed at one end of the attic space in King William is an ingenious sliding roof thought to have been built in the 18th century above an observatory telescope. The adjoining area is the site of one of the new major interventions. The roof seems to have been constructed in two stages, first with heavy roof trusses spanning across the full width of the building still in place at about 4m intervals, followed by the incorporation of later intermediate trusses spanning on to a double row of central columns running up from the ground and supporting the floors below. The cutaway illustration shows the principal structures. The top storey of the columns has been removed to provide space for one of the two new large lecture theatres in the building. New steel trusses span alongside the later of the timber ones and support both the roof and concealed platforms containing the new chiller units. The theatres themselves are framed in light steelwork designed to distribute loads to the existing timber columns below.

There are 23 staircases in the three 'quarter' buildings, mostly of geometric stone design with a few in timber. Geometric stairs are of particular interest. The concept may have been used first by Palladio. Stone slabs at landings are deeply embedded into the supporting walls but individual stair treads may be set no more than 100mm into the side wall. Stability is achieved by the action being shared between the treads transferring up to half the load tread by tread to a lower level with the side walls resisting shear and torsion forces; in theory there may be no cantilever action at all. The landings are the critical elements and are very often complicated by the way they may be divided into several separate stones. A significant feature is the manner in which many of the more used stairs have had new surface stones of up to 30mm thick cut into the original worn stone – thereby weakening the structure.

The strength of each stair was assessed by structural analysis based on close inspection, measurement and physical testing of discrete samples of material. Vertical load testing was avoided because if the analysis left a doubt as to the strength, the risk of breaking a stair was considered unacceptable. In the event only two of the original stone stairs had to be strengthened. One was in Queen Anne, where one of the half landings was reinforced within the thickness of the stone. The other was in King William where the long cantilever landings at the south west corner had already shown signs of distress. The stone is mostly Portland limestone and tests showed material properties in the middle of the normal range. Others were 'Moorstone' granite from Devon: here properties varied depending on the degree of weathering (from lying for millennia on the surface of the moors). Two examples of the approach are illustrated. The first is Ripley's oval stair in Queen Mary, where the diagram illustrates the theoretical principal stresses on the top surface. Clearly there are many uncertainties in the modelling, and to overcome this, upper and lower bound options were considered with a variety of assumptions on support conditions and interactions between treads. The second in the same building shows the stair where flights 'fly' past windows, on an ingenious system of iron straps.

The balusters supporting the handrails were of two kinds: either square section wrought iron bars set about 25mm into leaded sockets on the top surface of the stone or, the slightly later cast iron bracket type into the side edges. Because of the number of people who might be escaping in case of fire and recent research by the Building Research Laboratory, the lateral loading criteria were considered very important. In the case of short flights there was little doubt that the handrail was safe and this was confirmed by loads tests. However in longer flights it was clear that the criteria could not be met. To satisfy them a hidden detail was devised of a steel shoe which was welded onto pairs of balusters at about 1200mm, with the shoe set down into the wearing stone and anchored into the structural stone below.





Top: Queen Mary oval stair diagram

Above: Flight of stairs in front of windows

Left: Restored oval stairs

Right: Restored timber roof trusses

Dreadnought building

The Dreadnought building had suffered badly from neglect after its closure as a hospital. The roof had been leaking and there were rooms where areas of floor had collapsed as a result of dry rot. The first phase of work was an enabling contract for which Bylander Waddell and Partners acted as structural engineer in securing the building by installing a temporary roof, cutting out defective timber and making structural repairs. The subsequent approach to the structure was similar to that adopted on the principal buildings. In addition the two central courtyards were enclosed with glazed roof structures. The original ablution blocks within these courtyards are of considerable archaeological interest; they are a very early example of new advances in hospital design which took account of the need for hygiene. The shells of these are retained under the new roof. se

- Further information: Malcolm Brady, Michael Barclay Partnership (tel: 020 7240 1191; email: malcolm.brady@mbp-uk.com)

Credits

Client: University of Greenwich
Structural engineer: Michael Barclay Partnership (Michael Eatherley, Malcolm Brady)
Architect: Dannatt, Johnson Architects
Project Manager & Q.S.: Fanshawe
Principal Contractors: Wallis, James Longley, Sunley Turrif, Wates
Foundation consultancy: Giles Quarme Associates, ST Walker & Duckham
Structural engineer King Charles quarter: Arup
Photos of completed work: Peter Cook