King’s College Chapel

Roof Covering Renewal

Covering Paper to Faculty Application

MARCH 2022

CAROE ARCHITECTURE

KING'S COLLEGE CAMBRIDGE

CONTENTS

1.0 Introduction:

Jurisdictions and consultation:

The Chapel falls under Faculty Jurisdiction and is exempt from Listed Building Consent. The Chapel remains subject to secular Planning Approvals where applicable. This Paper supports a Faculty application under the 2015 RULES.

The urgency of the roofing problem

Attention was drawn to the Chapel roofs following the latest Quinquennial Inspection in 2018 and in the two previous QIRs by Freeland Rees Roberts. The 2018 report highlighted significant problems of continuing a*nd rapidly worsening* failure of the leadwork. In order to emphasise the concern and call for action, the QI plotted water ingress and where rot (brown and 'dry' rots) had established locally, threatening the roof timbers. At the request of the College Fellowship, the need for replacement was also validated in a subsequent Assessment and Report by the Lead Contractors Association in 2021 (included in Appendix A). Emergency repairs have been undertaken to the roofs (with Faculty) over the past three summer seasons to address serious decay and water ingress. Each time we undertake these 'holding' repairs we find that the splits and slips in the leadwork are worse and also that the more recent temporary repairs are not holding.

Access and temporary roofing:

Safe access to undertake the major works is an essential pre-requisite. The question of how renewal of the leadwork with associated repair of roof structure, parapet gutters and rainwater goods could be carried out safely - with respect to H&S and protection of the historic structure - was given close consideration from the outset of this project. As shown on roof plaques, past re-roofing was undertaken in phases over a number of years and, it is assumed, without a temporary roof. For many reasons, which we hardly need to spell out in detail, it is an axiom of this project that there must be a temporary roof. Divine worship in Chapel has to be maintained; we cannot cancel the nationally significant BBC broadcasts; there has been a major refurbishment and re-building of the organ. Thus for these any many other practical reasons a major access scaffold for materials and personnel is required, with a protective temporary roof. We also need a loading bay 7m away from the roof to undertake 'hot works' away from the listed structure. We have established a strict fire-safety protocol in this scheme for conducting the works with control of risks.

Any project of this scale will involve some disruption to the College and Chapel. Given the expected life span of a well-detailed lead roof covering (100 years plus), access provision on the scale envisaged is not anticipated again for multiple generations and we seek to maximise its value. Hence the project scope includes strategic matters such as climate change adaptation and mitigation measures. However, based on the QIR findings, we have judged that this is not the time to undertake a full scaffolding of the entire chapel. We are not embarking on a stone-repair or major glazing conservation programme.

We have conducted a comprehensive options appraisal for scaffolding and temporary roofing solutions: the solution which has been expertly evaluated by scaffold designers and structural engineer is for the temporary roof which is supported on the chapel structure, not built up from the ground. There has then been a second round of options and design development on this preferred solution to come up with the current detailed design which has now been engineered without major fixings into historic fabric.

The climate crisis and Carbon Zero targets.

There are now pressing targets for carbon zero, some enshrined in legislation and some as institutional priorities and policies. Kings College Chapel itself and the domus estate of the Fellowship is subject to UK government legislation; the Church of England Synod 2030 Carbon Zero target; the University of Cambridge 'Cambridge Zero' targets of 2038 and 2048 respectively; The City of Cambridge Climate Change Strategy. The College body – Students and Fellows – have also defined commensurate targets for responding to the IPPC reports on anthropocentric climate change and the crisis faced by the planet, societies and eco-systems.

The College Fellowship have already taken very extraordinary steps to address carbon emission reduction in its built estate, with new buildings and refurbishment projects of existing buildings now required to make dramatic improvements in energy performance. However the hard-to-treat, highly significant historic estate presents a major problem in reaching carbon zero.

The college chapel has recently benefited from a major new low-energy lighting scheme. However the chapel is still heated with (efficient, condensing) fossil-fuel burning heating plant. As part of the project development process, feasibility assessments for sustainability measures are being explored; these include the installation of PV arrays to the Chapel roof, and consideration of rainwater harvesting infrastructure. We have also been looking closely at essential climate change adaptation requirements – especially the capacity of rainwater disposal systems.

The college has an intrinsic need to address the carbon footprint of its built estate, functions and operations. But the Fellowship is also deeply aware of the emblematic nature of the built estate, especially the internationally recognisable College Chapel. The Fellowship has to be taking steps itself, but also can in this instance be helping with 'thought-leadership', and leading others by example.

The design team looking at this proposal for PV generation on the chapel roof are equally aware of a profound responsibility for the fabric of the historic chapel and the need for holistic long term thinking – as well as putting forward the best possible case for this PV installation with the right degree of support, detail and justification.

2.0 Concise Architectural Description

King's College Chapel is a fundamental element of the Founder's intentions for his college as '*a place of education, religion, learning and research*.' The Chapel continues to play a vital role as part of the College's founding principles, making a valid contribution to the active life of the community and a significant contribution to the financial health of the College, derived from visitor income. Indeed, the Chapel's history and significance contributes not only to the overall spirit of place at King's College but to the College's reputation as an institution of exceptional significance with an international profile.

Founded by King Henry VI, who laid the first stone on 25 July 1446, King's College Chapel is a 12 bay, limestone building designed in the Perpendicular Gothic style of the late medieval period. It lies on the north boundary of Front Court oriented east to west, with its east façade of stained glass windows facing King's Parade. Its building history, which was marked by long periods of inactivity, reflects a politically turbulent era around the War of the Roses. For this reason the Chapel went through three phases of construction, under four separate master masons, and was not completed until 1515. It has been said that its historical significance cannot be measured, *'a work in which the principles of the newest, and last, phase of Gothic architecture were, for the first time displayed upon an important scale*.'[1] The Chapel has the largest fan vault in existence, at 289 feet long, 40 feet wide and 80 feet high.[2] These dimensions were specifically detailed by King Henry in 1447, when he laid out his original plan that the Chapel, '*… shall contain in length two hundred four score and eight feet of assize without any aisles, and all of the wideness of forty feet…*'[3] The end result is an impressive structure that is both an architectural and engineering marvel, and with a history and richness in detail that is as complex as its fabric and design.

The first phase of construction began in 1448 under master mason Reginald Ely, who laid out the plan and sections of the elevation.[4] The original intention was for the Chapel to be one part of a wider scheme of adjoining buildings surrounding a principal college courtyard. However, this scheme was never realised and the Chapel was built as a solitary structure, separate from those that came later. The first phase of construction moved swiftly, working from east to west, with annual funding of £1000 per year provided by King Henry until he was overthrown in 1461.[5] The progress achieved by this first period of construction can be seen in the predominant use of white magnesian limestone, sourced from two quarries in Yorkshire: Thevesdale near Tadcaster and Ruddlestone, near Sherburn in Elmet.[6] After 1460, oolitic limestone was sourced from several Northamptonshire and Rutland quarries such as King's Cliffe, Weldon, Barnack, Clipsham and Ketton.[7] Thus, this first phase of building work is visibly discernible. It reached its highest and most developed point on the north side of the east front where it rises 68 feet from the ground level, and continues at various, lesser heights throughout the rest of the building.[8] Building accounts suggest that at least one, but possibly two

[1] George Gilbert Scott, *An Essay on the History of English Church Architecture Prior to the Separation of England from the Roman Obedience*, (London: Simpkin, Marshall and Co., 1881), p. 172.
[2] John Saltmarsh, *King's College Chapel: A History and Commentary*, (Peterborough: Jarrold Publishing, 2015), p. 276
[3] Ibid, p. 28.
[4] Francis Woodman, *The Architectural History of King's College Chapel and its Place in the Development of Late Gothic Architecture in England and France* (London: Routledge & Kegan Paul, 1986), p. 3.
[5] Saltmarsh, p. 33.
[6] Ibid, p. 44.
[7] This belief has been challenged by Francis Woodman who argues that both types of stone were used during this first phase, with the finer, white magnesian used as facing in all visible areas of the choir, whilst the brown, less expensive oolite was used as backing. See Woodman, p. 44.
[8] Saltmarsh, p. 45.

spaces had been completed before work was halted, known as the Provost's chapel, with glazed windows, located on the north side of the east end.[9]

The second phase of construction took place between 1476 and 1485 after a lull of 15 years, supported by funding from Edward IV in 1480. For a very short period the Chapel master mason was John Wolrich, before the job passed a year later to Simon Clerk. It is believed that Clerk was responsible for changing the intended design of the Chapel vault from a lierne vault, which Ely had envisaged, to a fan vault design, a change made possible by reshaping the window arches.[10] Other progress included completion of the first five eastern bays, with walls and a simple roof. However, with the death of King Richard III in 1485, funding ceased and building works once again stopped.

The third and final phase of construction began in 1508 under John Wastell, a mason who once worked for Simon Clerk and succeeded him after his death. With funding secured by Henry VII and subsequently Henry VIII, Wastell was able to complete the Chapel including the antechapel, vaults, towers, and battlements by 1515. This phase of work is perhaps most easily identified through the use of heraldic symbols and coats of arms carved into the buttresses and interiors. The master carver at this time was Thomas Stockton.

The Chapel's twenty-six stained glass windows depicting Old and New Testament scenes was designed by the King's glaziers, Barnard Flower and later, Galyon Hone and designer Dirk Vellert of Antwerp, from 1515. A large number of glass painters were employed, many of them Flemish, to the consternation of the English Guilds. With the exception of the west window (which was not finished until 1879), all of the windows had been completed by 1547. They are a work of art in their own right and notable for having survived, 'largely intact, the biblical literalism and the iconoclastic ferocity of the sixteenth and the seventeenth centuries.' The north-east side chapel contains remnants of the most historic stained glass. Other historic fragments of considerable interest are found in chapels on both the north and south sides.

It is the fan vault that is the most striking architectural feature of King's College Chapel, constructed primarily of Weldon stone. '*Mason's marks number the major pieces of each bay and line up with adjacent stones, suggesting that the stone locations were assembled and verified prior to their final installation in the Chapel.*' The end result is a feat of complex engineering that continues to astonish the public and amuse engineering professors and their students.

The original flooring of the Chapel varied slightly. The choir was laid with grey English marble, whilst the antechapel may have had a combination of tile and brick, with a processional path of marble and Ragg.[11] There are reported to be fragments of brick paving under the choir stalls. Today the Ante-chapel is paved in smooth honed modern marble, with under-floor heating. The Quire is paved in a chequered design of black and white marble. The stepped high altar footpace and sanctuary paving is modern from 1968.

There are eighteen side chapels, which Henry VI's Will of 1448 referred to as 'closets,' or places for private worship. Only the two north-east chapels were vaulted by Reginald Ely prior to 1461. The rest were not finished until after 1513. These side chapels serve today as spaces of worship and remembrance: on the north side there is a sequence of spaces presented for visitor interpretation and the corresponding vaulted rooms on the south side serve as ancillary vestries.

[9] Ibid, p. 46.
[10] Ibid, p. 54.
[11] Woodman, p. 197.

3.0 Designations and Listing

The Chapel of Kings College Cambridge.
King's Parade
Cambridge CB2 1ST

Diocese: Ely (Diocese ID 14)
Archdeaconry: Cambridge (ID 141)
Benefice: Cambridge, St Edward King and Martyr (ID 14/975 R)
Deanery: Cambridge South (ID 14110)
Local Authority: Cambridge City Council

Listing

Grade I. The Chapel was built between 1446 and 1515, and the glass was added between 1515 and 1531. The woodwork was made between 1532 and 1575. The woodwork was made between 1532 and 1575. The building is an outstanding example of the craftsmanship of the period and all the fittings are noteworthy. The fan-vault of the roof was designed and built by John Wastell, master-mason 1512-15. The timber roof was built by Martin Prentice and Richard Russel 1508-15; it is of 24 bays. The east end and altar were remodelled in the general internal restoration of 1968. There are several good C16 doors with fine locks and other iron fittings. C18 font. The windows form one of the finest and most complete sets of late medieval stained glass in Europe. The side-chapel glass is, however, mostly modern.
Brass eagle lectern, early C16 with candle sconces added by Butterfield and a base by Rattee in 1854.
Organ by Renee Harris, 1688. Screen of magnificent oak carving, 1533-36 with the central doors of 1636.
Choir stalls of oak, 1533-6.
The Chapel was paved with marble 1702 and Portland stone 1775.
Monument to John Churchill, only son of Duke of Marlborough, died 1702. (RCHM).12

[12] https://historicengland.org.uk/listing/the-list/list-entry/1139003

4.0 Project Objectives and Priorities

The project objectives are:

- Main chapel roof:
    - Renewal of the lead roof covering on the main chapel roof to make the building water and weather tight, with adaptation of the parapet gutter steps and falls to achieve code compliance.
    - Conservative repair of the roof structure where required, including assessment of existing areas of brown and dry rots.
    - Judicious treatment of insect attack (DWB and other) as part of a long term programme and monitoring exercise.
    - Review capacity of current rainwater disposal system and performance requirements in anticipation of climate-change adjusted rainfall increases.
    - Subsequent repair and/or adaptation of rainwater goods as required following the above.

- Additional opportunities:
    - Investigate feasibility for installation of PV renewables to the main Chapel roof.
    - Conduct viability assessment for rainwater harvesting infrastructure.
    - Dependent and necessary works to the below-ground drainage serving the Chapel.
    - Consider increased scope of repairs to the external fabric to maximise use of the scaffolding access.
    - Fire-risk mitigation, including lightning protection flash-over and surge measures.

Many of the south side Chapel roofs are also in poor condition exhibiting severe underside lead corrosion and resultant loss of integrity of the water proofing lead. Caroe Architecture, in consultation with Tobit Curteis Associates, have developed designs for renewal the roof on south side Chapel N with improved ventilation to respond to these issues. A Faculty has previously been granted for these works (ref 2020-055090). The current proposal is to complete renewal of all south side Chapel roofs to this design, as part of this project.

This project does not include any works to glazing or the façades of the Chapel building.

5.0 Repairs and Renewals to the Main Chapel Roof

5.1 Existing Conditions (mostly as transcribed from 2018 QIR)

The Chapel roof is nearly 300 feet long and laid without steps in mini-roll lead, falling to lead parapet gutters. The mark-up of the roof below records the defects identified during the Quinquennial Inspection of 2018 above an overlay of the survey taken during the preceding Quinquennial in 2012. The condition of the lead has clearly deteriorated rapidly, and continues to do so. There are new splits, the lead is creeping or pulling, there are nail holes, sheets are tracking down the roof slope and older and more recent repairs have failed again. Regular emergency holding repairs are not sustainable and cannot reverse the failure of the leadwork generally.

South Roof Slope

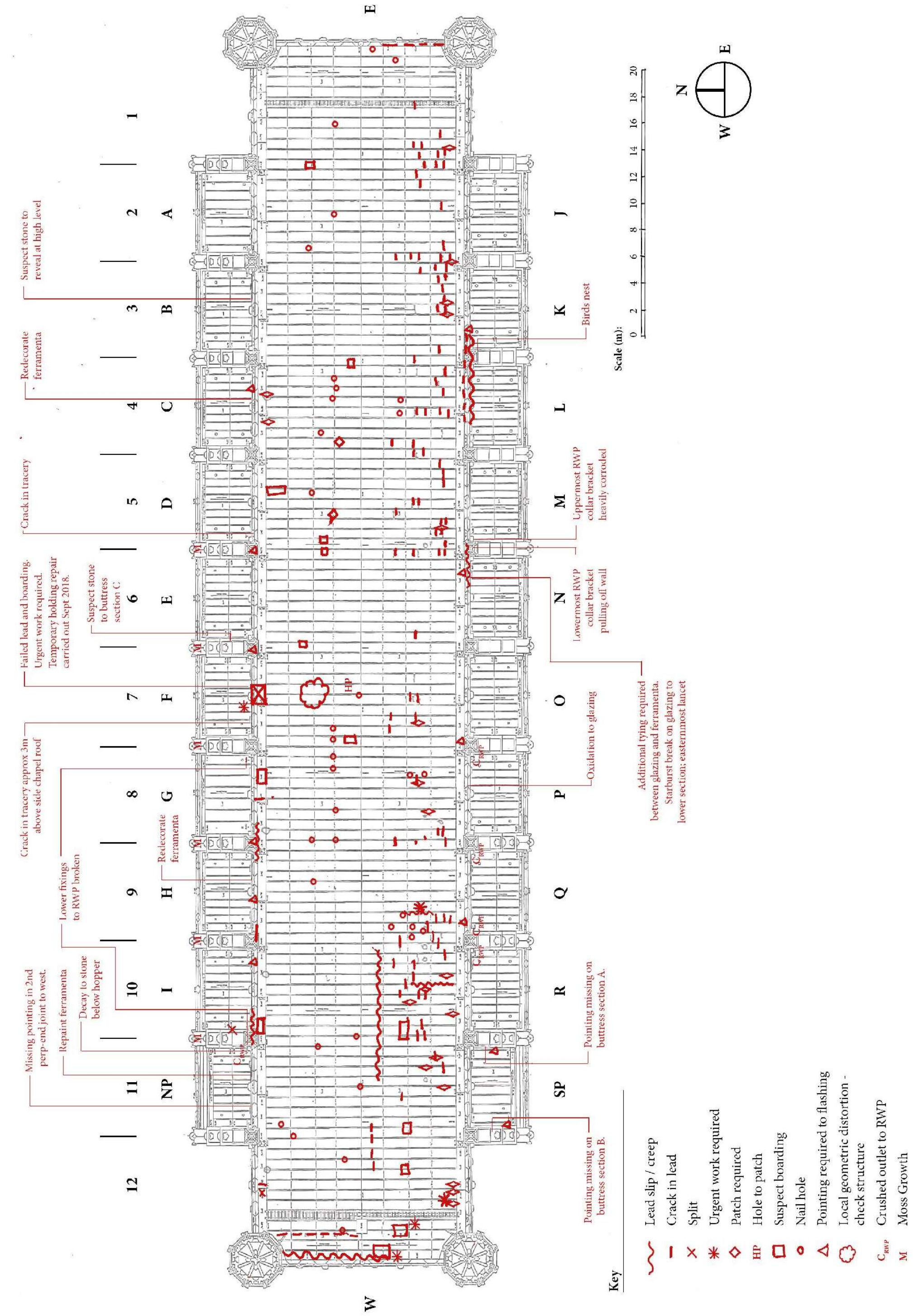
Although the south roof slope has basically identical detailing to that of the north, in subtle ways, the materials and workmanship differs. This has contributed to the early failure of the materials. For example the wire-cut nails are too thin, so act like cheese cutters, and the heads of the nails are too small and don't provide support to the lead. They are also nailed too close to the heads of the sheets. Thus the heavy sheets in many places have slipped down the roof slope, as evidenced by the tails of the lead sheets where there is a lot of variability - one can see the lead sheets which have variously travelling southwards and down the roof slope. When this occurs a strain is put on the rolls themselves. I have found that that both at the head and in the length of the rolls, the nails can be pulled out of the boarding and thus they pierce the lead above: they also pull out of the roll and pierce the lead work over the roll. This type of failure is better or worse in various parts of the roof. The general creep of the lead work causes other consequences and strains, with a major number of longitudinal splits across the sheets, caused by the inability of the lead to move thermally over the slightly sticky treated sarking boards, which has no building paper or underlay. At the Western gable one sheet had actually slipped nearly 200 mm allowing water to enter the roof space freely [this defect has been remedied temporarily]. There are significant areas of emerging and well developed rot and timber decay in the roof boarding. In the worst areas this was starting to attack structural timber; immediate intervention by way of interim repairs has been undertaken, which the DAC endorsed [three rounds of emergency repairs have been undertaken over the last three years]

North Roof Slope

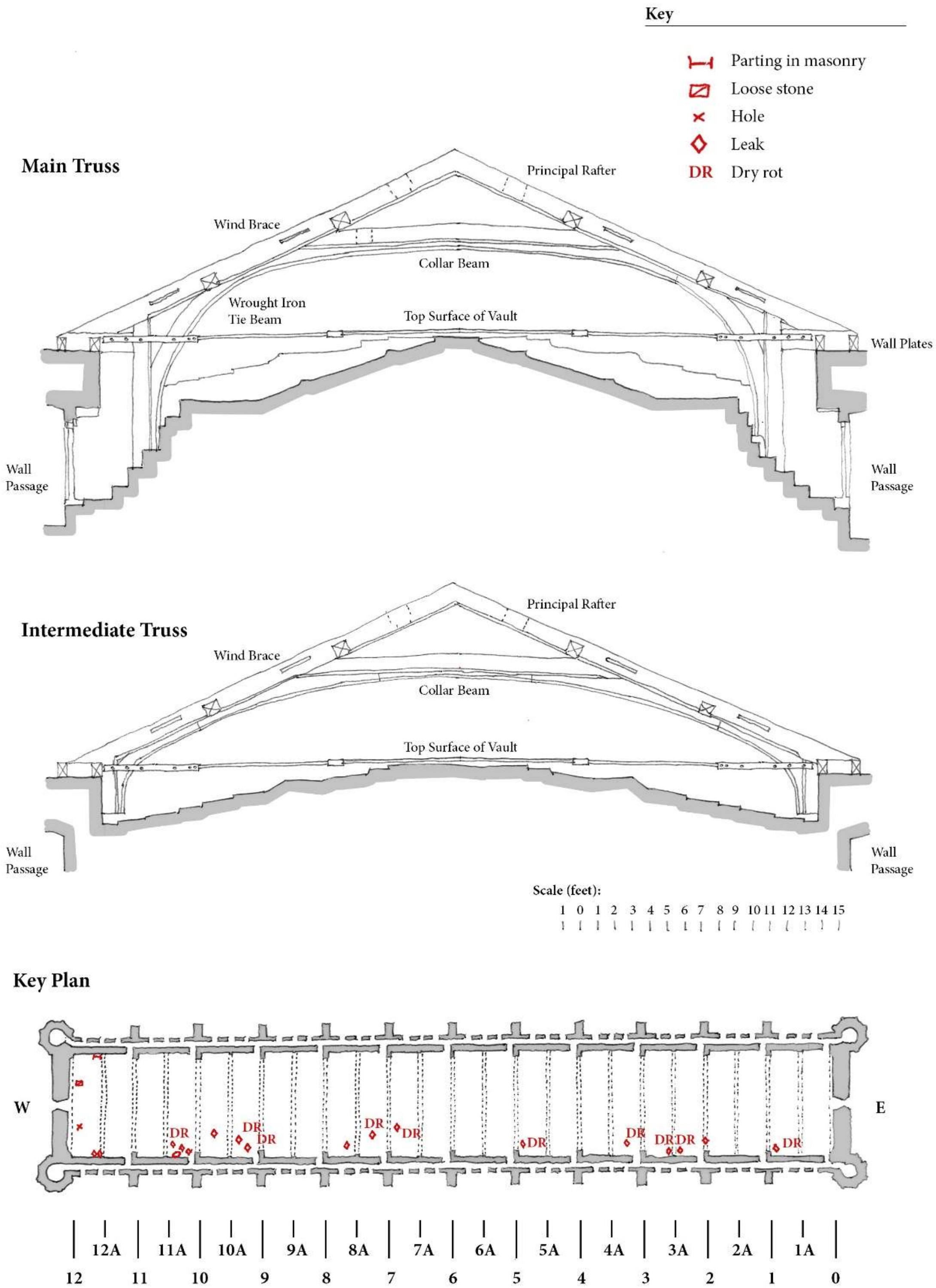
The lead work of the north side has performed well in the main and, for such an old roof, at over 155 years, the lead is now thinning quite considerably at the leading edges due to underside lead corrosion. There are many brazed-on patches and filets to the lead showing that it has been subjected to cycles of maintenance, especially at the ridge where the roll travels in a swept fashion over the apex.

The nailing of this roof is now at life end. The nails were iron nails of a relatively slender section and head and these are now corroded. In many areas of the roof there is actual or incipient nail head failure resulting in the beginnings of penetrations in the over cloak. Ultimately this failure route is a one-way street in terms of further degradation.

There are also a number of areas where the boarding creaks or moves suggesting that there could be detachment or nail failure to the substrate sarking board. This is to be expected due to the age of the roof, but will require attention when the leadwork is renewed.



Mark up of defects identified during the 2018 Quinquennial. Note those shown in red are defects which have developed since the 2012 inspection.



Plan of Main Chapel roof space with mark-up of internal defects identified during the 2018 Quinquennial Inspection

Phases of holding repairs with further buckling (precursor to tears) evident.

Urgent holding repairs in progress. Note rotten and decayed boarding.

Rotten boarding and structure below defective gutter.

Saturated timber and rotten boarding.

Dripping wet boarding with rot starting to establish.

Damp staining below leaks in the roof covering. Water now pools within the roof space.

5.2 Detailed Scope of Repair Works

Please refer to drawing GA 200 Scope of Work – Roof and Roof Space Plans Rev 4.01.

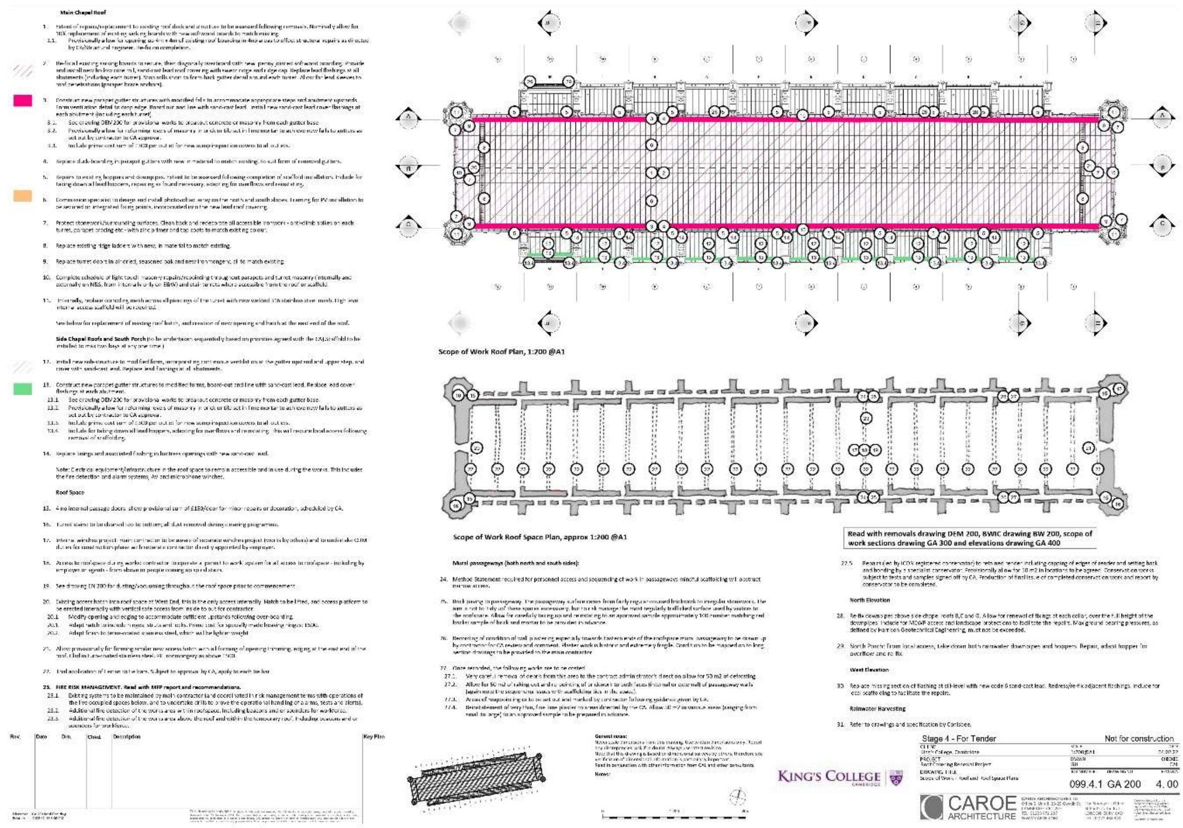


Image included for reference. Please find copy in Appendix B

External and other Works

- Renewal of the lead roof covering on the main Chapel roof which is leaking and can no longer be patched. This must address the underside lead corrosion on the south slope and may require incorporation of ventilation when re-detailing. Modern batten rolls are much larger than the existing mini-rolls and would require the installation of a king roll at the ridge, altering the form and look quite dramatically along the length. Instead it is proposed to renew the roof covering with traditional hollow roll details in sand-cast lead and maintain the swept ridge as would have been seen originally. A continuing scheme of environmental monitoring will determine the need for additional ventilation, which can be incorporated into this form at the eaves and ridge.
- Renewal of the parapet gutters and substructure with re-profiled steps and falls to ensure efficient discharge of rainwater, with lead detailing codes.
- Overhaul of all associated abutments with repair or replacement of existing cover flashings and associated remedial works to the parapets stonework.
- Conservative repair of the roof structure will be undertaken as required, on a like-for-like basis. We are proposing to retain the existing sarking boards to the roof, replacing only where rotten. Careful assessment and repair of the sarking boards will be undertaken following removal of the lead. The boards will be re-fixed to ensure they are secure. Where we need to undertake

any repair to structural timber, areas of the sarking boarding will be lifted and the re-cycled boards re-instated. We then are proposing to give a consistent non-acidic surface for the new lead; the entire roof will be over-boarded with new timber laid on the diagonal.

- Repairs to existing hoppers and downpipes. Analysis of rainwater catchment areas has been undertaken to assess the current and required capacities of the rainwater disposal system to accommodate present and future climates. Please see rainwater calculations in Appendix C undertaken by Conisbee. The largest catchment areas are at either end of the Chapel building where the end downpipe serves a bay and a half, rather than a single bay of the main roof. At the east end these discharge to the side chapel roofs below, to further downpipes and ultimately to underground drainage. Whilst the majority of the disposal system is sufficient, the side chapel downpipes serving these, easternmost side chapel roofs would not be able to effectively discharge run-off from a 1 in 50 year event with climate change allowance. Adaptation of the lead hoppers to provide overflows is proposed.
- Creation of new maintenance access hatch at the east end of the roof, to match that as existing at the west end.
- Repair or renewal of roof access doors to the stair turrets.
- Review of maintenance access and procedures generally, including replacement of the existing inlaid walkway boarding within the parapet gutters, and roof crossing ladders.
- Review of the temporary and permanent lightning protection requirements.
- Light touch masonry repairs where accessible from the scaffolding. Works to the main corner turrets, where accessible from the roof or by steeple jack, which may include access and repair to the slender parapet gutters, redecoration of anti-climb spikes; pointing and weatherproofing of cap-stone stonework and addressing any unsafe high-level masonry as may be encountered. Only limited renewal to be undertaken where unavoidable.
- Renewal of south side Chapel and South Porch roofs and parapet gutters to modified forms - incorporating improved ventilation in response to issues of underside lead corrosion. This will be in accordance with designs for south side Chapel N, which have already been granted Faculty approval. Associated works to repair hoppers and adapt with overflows to address capacity issues. Repair of hoppers and downpipes serving the North Porch.
- Replacement of missing section of flashing above the West Porch.

Note: the proposed scope of work includes Installation of PV arrays to specialist design on the north and south slopes of the main roof, and installation of rainwater harvesting facilities – both with associated infrastructure. Please refer to detailed descriptions later in this paper, and the specifications provided.

Internal Works

- Address all brown rots and dry rots, all water ingress to be rectified and all affected timbers (sarking) to be either treated, repaired or replaced as required.
- Masonry repairs and repointing within the roof space and the north and south mural passageways, including conservation works to extant plaster and repair of the brick paving within the passageways.
- Redecoration as required of the truss tie-bars.
- Review fire detection system and upgrade as necessary.
- Works to repair internal staircase doors.
- Replacement of existing bird excluding mesh across the piercings in the stair turrets and apertures along the mural passageways.
- Consider flash-over or surge protection or bonding needs of Lightning protection system to existing M&E services.

5.3 Access and Strategy

Providing safe, practical working access to the Chapel roof is a complex task and one which will have influence the success of the project. Significant effort has been put into the procurement of the scaffolding and temporary roof designs at this early stage of the project. The chosen solution must not only provide safe working access and weather exclusion to the Chapel roof, but it must also minimise structural impact, as well as disruption to collegiate life and public areas.

The Progression Flow Chart below by Rise Scaffold Services Ltd, shows the development process of the scaffolding design, for which the reviewed options are then summarised. The initial considerations informed ground testing which has now been conducted by the Harrison Group to establish the maximum ground bearing capacities. For reference – Scheme 3, fixing option B (1.01) is that which is being proposed. A legible (larger) version of the flow chart is appended.

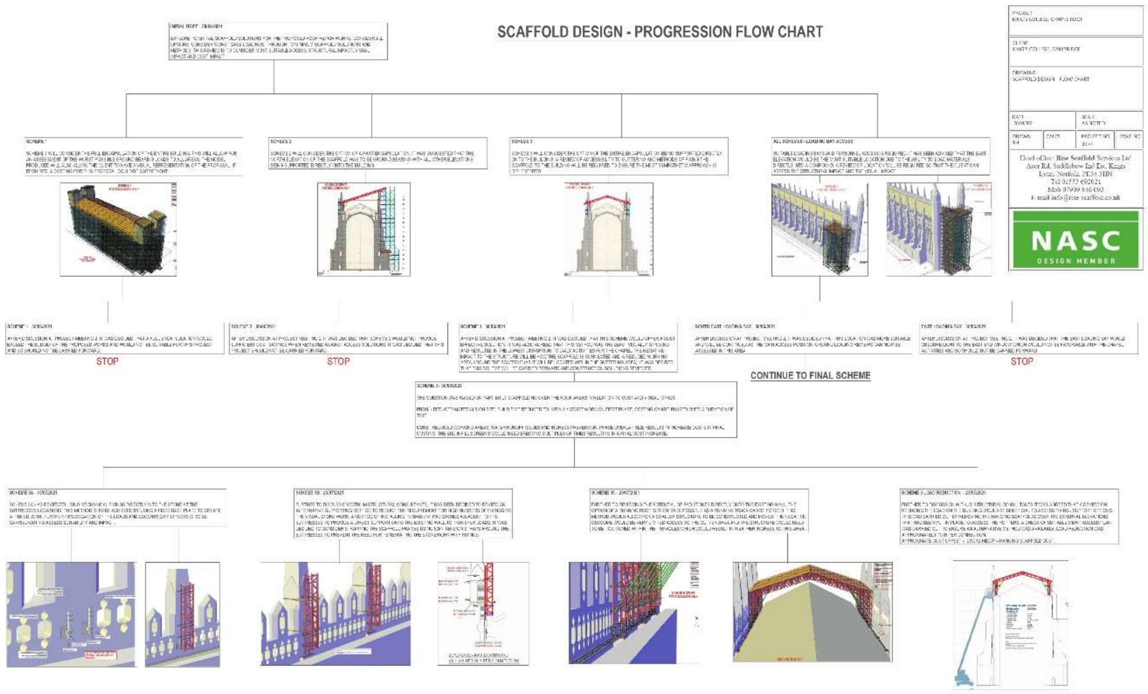


Image included for reference. Please find copy in Appendix D

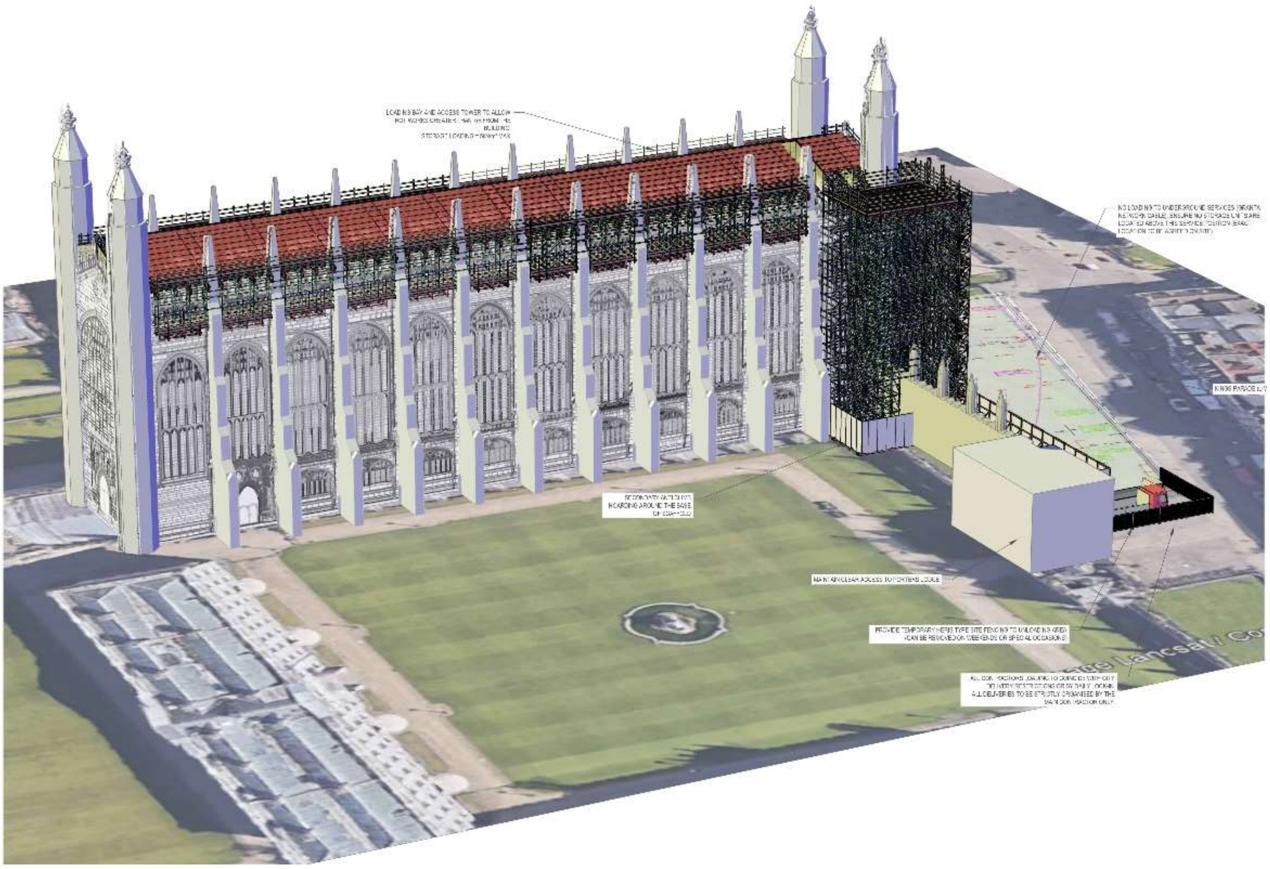
Scheme 1 – Not taken forwards

This study reviewed the full encapsulation of the chapel building with scaffolding from the ground up, allowing for an assessment of the worst possible ground bearing loads to all areas. The model shows the visual impact of such a proposal. The cost of this option and programme duration would be prohibitive and adversely affect the feasibility for the entire project.

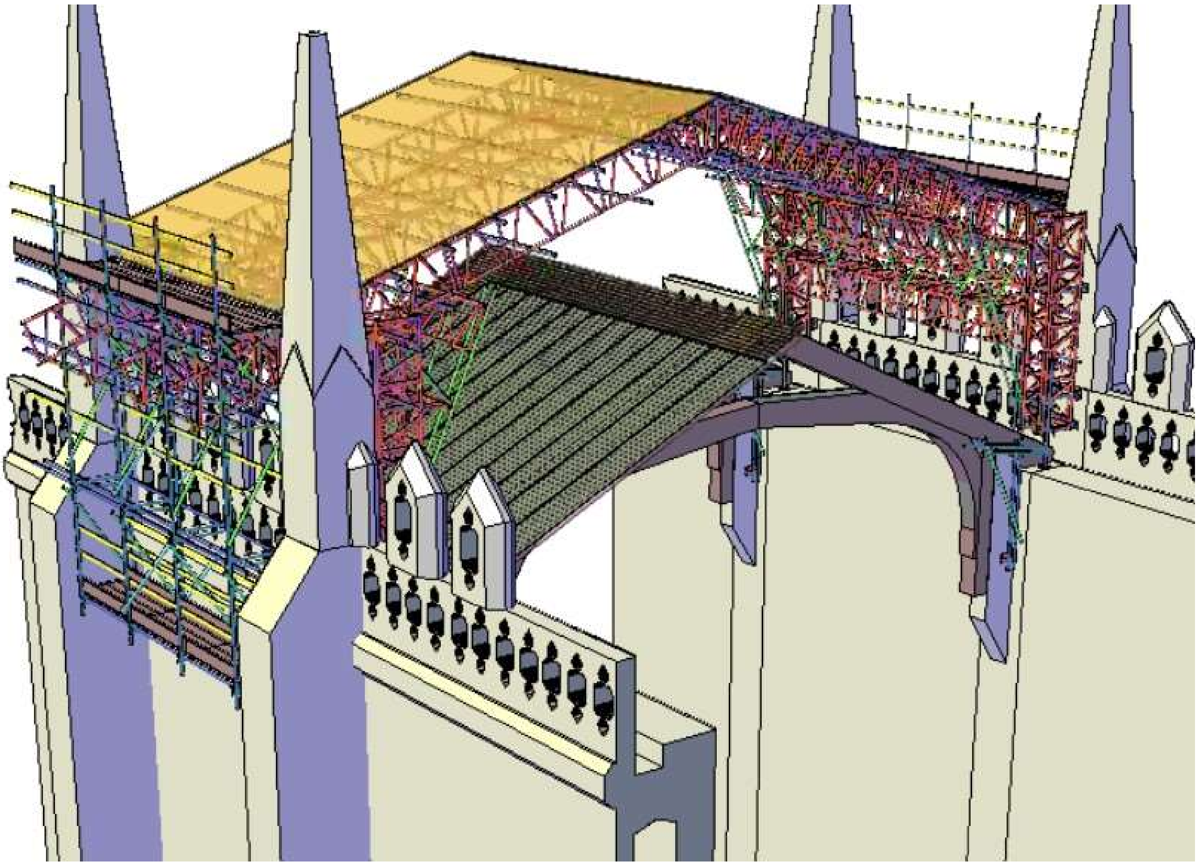
Scheme 2 – Not taken forwards

This study considered the option for part encapsulation, with the less prominent, north elevation of the chapel, chosen as the location for ground bearing elements. Scaffold to all other elevations would be supported directly onto the building. When reviewed against further access solutions, it was determined that sufficient cost savings could not be achieved through this method, which was not taken forwards.

Scheme 3 – As Proposed for approval



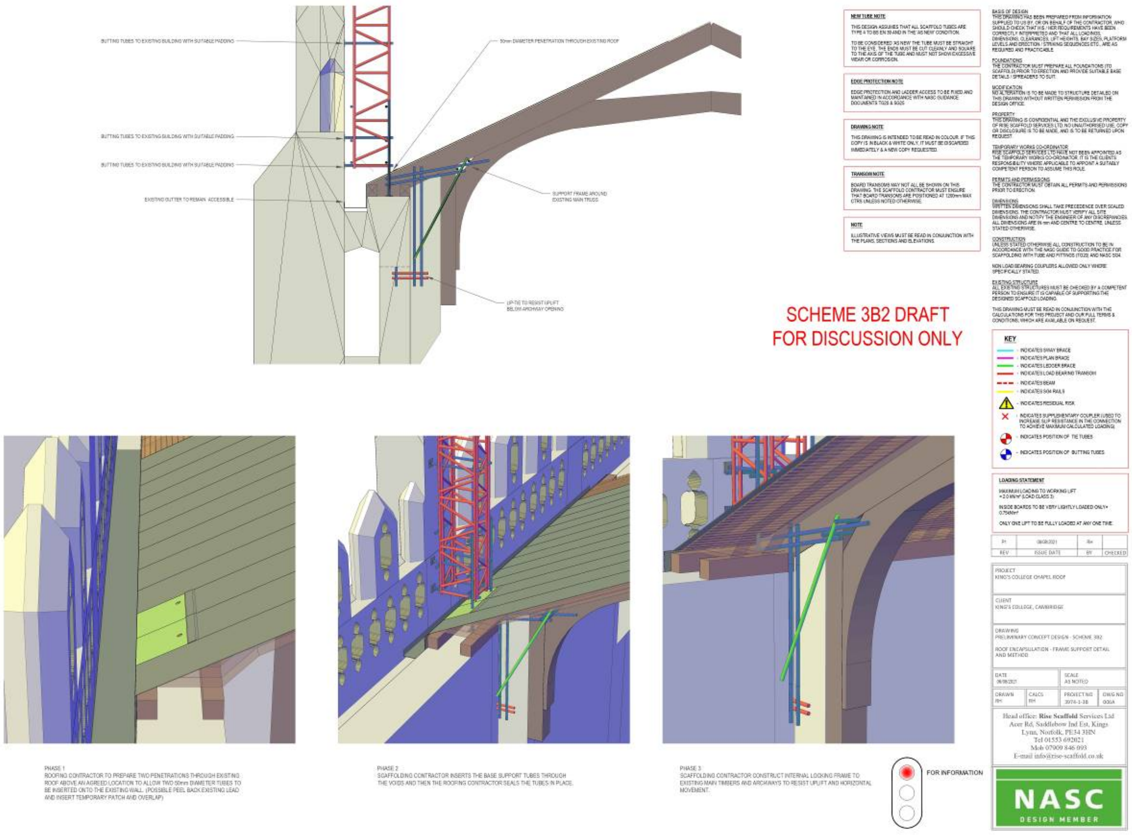
Visualisation of Scheme 3, proposed scaffolding and encapsulation solution



Indicative 3D section showing Scheme 3, the proposed temporary roof

Scheme 3 reviewed the opportunity for the temporary roof to be supported directly onto the building. It was decided that this scheme would offer an effective solution which significantly lowers the windage profile of the scaffolding (with lower loadings as a result). The duration for erection is also more realistic and therefore the disruption to daily activities of the Chapel and College is reduced.

Once we resolved on this scheme for scaffolding as the preferred option, we have then conducted a number of further technical design options to examine the solution which has fewest fixings or impact on the historic fabric and thus the most sympathetic approach for the temporary works.



Drawing showing Scheme 3 included for reference. See Appendix E for further details. Note: discussion on fixings to follow below.

Scheme 3, Fixing Option A – Not taken forwards

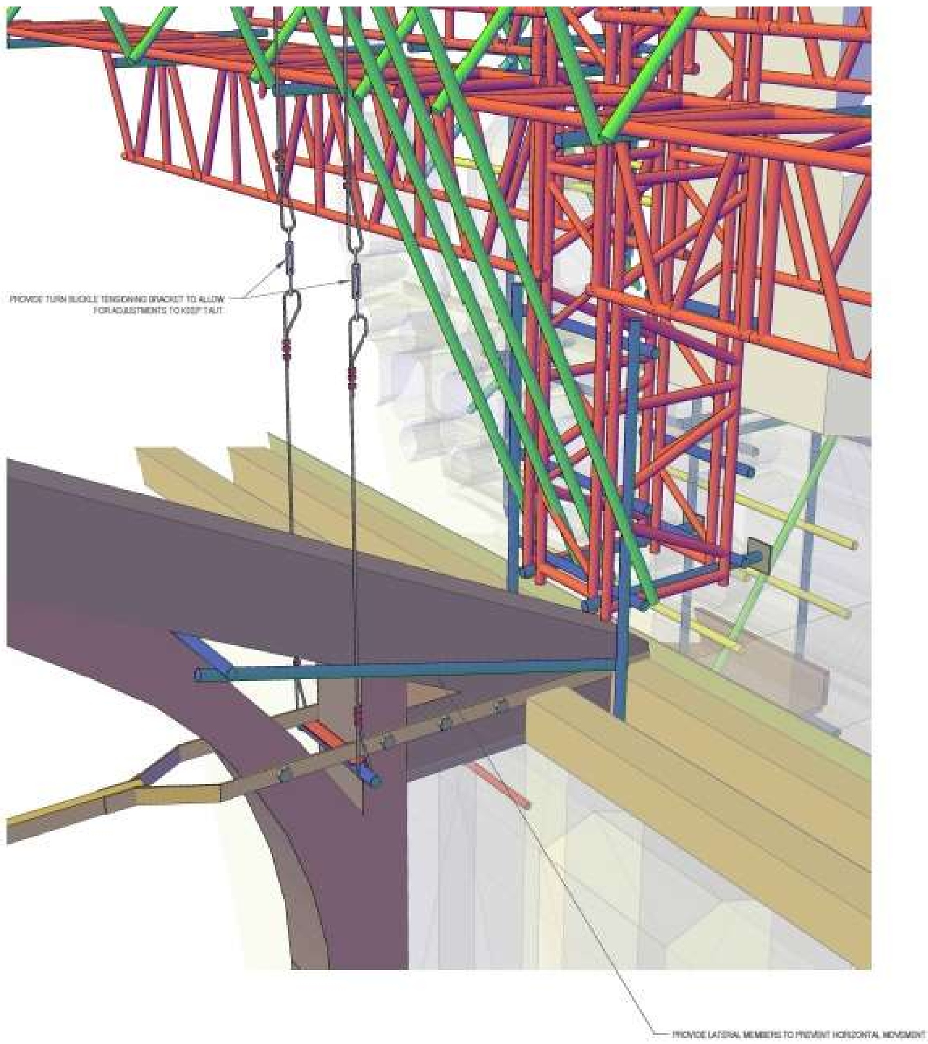
This option reviewed the use of mechanical fixings into the internal faces of the stonework at buttress and pinnacle locations. This would be achieved by using a fixed base plate to create a pinned joint. Following a review by JM Structural Consultants, it was determined that 10no fixings would be required at each location, which would result in harm to masonry.

Scheme 3, Fixing Option B – Not taken forwards

To reduce the need for fixing into the fabric, fixing option B reviewed the potential for installing pad stones, adjacent to the buttresses within the width of the parapet gutter, to provide a direct support to transfer loads. Tension straps would be fitted around (not fixed into) the buttresses. This provided a sensitive approach without the need for penetrations into the stonework, however would obstruct works to the parapet gutters and would result in substantial amount of gutter renewal, having to be completed following removal of the main temporary roof – thereby risking water penetration.

Scheme 3, Fixing Option B Rev 1.01 – PROPOSED

Having agreed with the scaffolding designer that, since the lead roof covering is sacrificial and also repairable, there could be a solution for securing the scaffold in an unfixed, temporary wall to the internal structure. It was subsequently determined that it would be feasible to place the loading positions between wall-plates on the inner wall top, thereby managing to avoid fixings into the fabric and significantly reduce sequencing issues of the works. It is proposed to transfer uplift from wind loads to the existing roof structure using tension cables connected to scaffolding tube inserted behind the braces of each major truss (which would be protected). This detailed design approach is demonstrated in the following image. JM Structural Consultants are currently reviewing whether the dead load of the existing roof structure will be sufficient to combat uplift. If the safety factor is not achieved, it may be necessary for local fixings into joints in the internal brickwork adjacent the truss. Note: To reduce loadings (and therefore fixing requirements) the feasibility of using a Mobile Elevated Working Platform (MEWP) rather than hanging platforms, to undertake high-level repairs outside of the parapet line – namely the rainwater hoppers and downpipes - is currently under review.



Scaffolding Option 3, Fixing B Rev 1.01 – PROPOSED

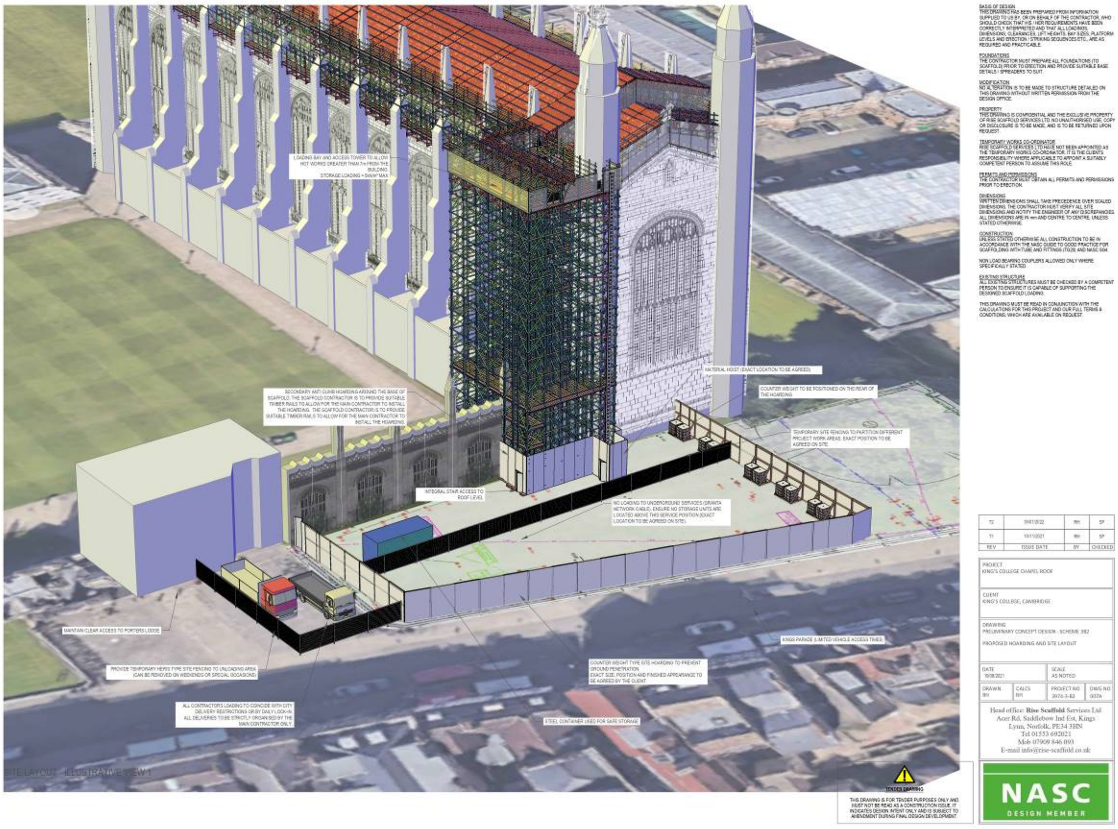
Scheme 3, Fixing Options C – Not taken forwards

Alongside review of the aforementioned the pad stone approach above, the option of a running roof was considered. This would allow for a smaller structure to be constructed and moved, although would result in greater obstruction to the parapet gutters and sequencing issues.

5.4 Site Layout and Compound

For each of the options described above, suitable loading bays and personnel access will be required. The East Elevation is proposed at the most suitable location due to the ability to load materials directly into a compound. This has been located at the south east corner to prevent it from obscuring the east window and any impact on the great Kings Lawn tree.

The compound will extend across the grassed area to the east of the Chapel and Porter's Lodge. It will be enclosed by a 2.4m high hoarding, intended to be used effectively as a means of community engagement by incorporation of a printed display to include information on the history of the Chapel and details of the works. This will be secured using counter weights rather than penetrating the ground, to avoid archaeological disturbance.



Indicative visualisation showing site compound

6.0 Opportunities: Sustainability Measures

6.1 Discussion

With the current climate emergency we have a duty to continually review and explore opportunities to improve sustainability and move towards zero-carbon for the Chapel specifically and the college estate generally. A project of this nature, and associated access provision, will not occur again until the roof is next in need of recovering. It therefore provides a rare opportunity to consider the feasibility and implementation of appropriate environmental strategies which may not arise again for another 100-150 years.

This is a task inherited not just through professional and ethical responsibility but one which has been reinforced by the Church of England's commitment to achieving net-zero emissions by 2030 - an ambitious, but necessary target pledged by the General Synod. The approved Synod motion which follows, places responsibility on all stakeholders to review what is necessary to meet this target, through the following motion:[13]

That this Synod, recognising that the global climate emergency is a crisis for God's creation, and a fundamental injustice, and following the call of the Anglican Communion in ACC Resolutions A17.05 and A17.06;

(a) call upon all parts of the Church of England, including parishes, BMOs [Bishop Mission Orders], education institutions, dioceses, cathedrals, and the NCIs [National Church Institutions], to work to achieve year-on-year reductions in emissions and urgently examine what would be required to reach net zero emissions by 2030 in order that a plan of action can be drawn up to achieve that target;
(b) request reports on progress from the Environment Working Group and the NCI's every three years beginning in 2022 and;
(c) call on each Diocesan Synod, and cathedral Chapter, to address progress toward net zero emissions every three years.

Cambridge City Council have demonstrated similar dedication towards sustainability by the implementation of their Carbon Management Plan and completion of 66 Carbon Reduction Projects between 2016 and 2021, including the installation of a photovoltaic array on the Guildhall roof.[14]

King's College Chapel is of international importance and clearly any proposal to provide sustainability benefits must be reviewed against the potential for impact on the heritage of the building – both in terms of its character and through the works required to accommodate the associated infrastructure. It also therefore has the potential to serve as an important precedent for how suitable schemes may be adopted in a sensitive manner. As part of the Project development works, studies have also been commissioned to review the feasibility of Photovoltaic and Rainwater Harvesting installations.

[13] https://www.churchofengland.org/news-and-media/news-and-statements/general-synod-sets-2030-net-zero-carbon-target
[14] https://www.cambridge.gov.uk/media/9580/carbon-management-plan-2021-26.pdf

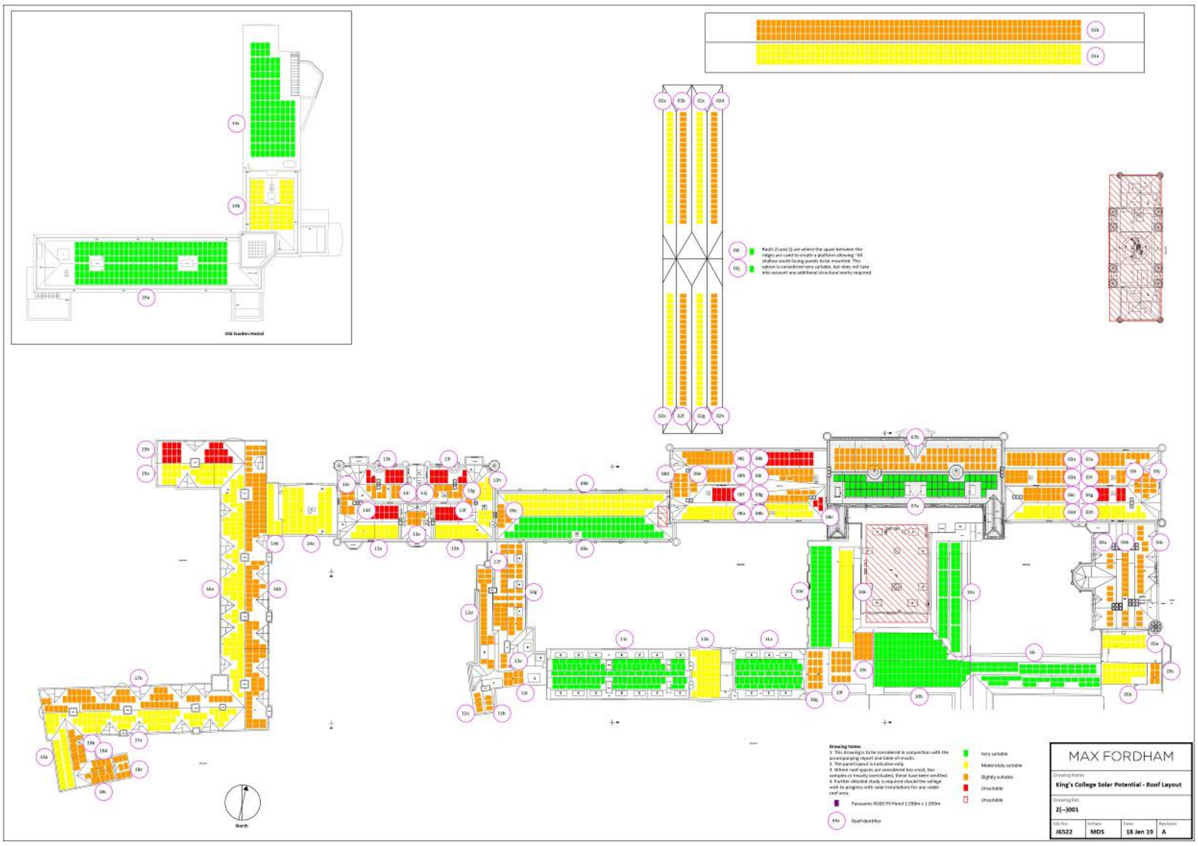
PV Array on the Guildhall roof with King's College Chapel in the background.[15]

[15] Image from Cambridge City Council Carbon Management Plan p. 11
https://www.cambridge.gov.uk/media/9580/carbon-management-plan-2021-26.pdf

6.2 Photo Voltaic Installation

6.2.1 Introduction

In 2019, prior to the inception of the current project, Max Fordham LLP were commissioned by King's College to carry out a high-level survey investigating the potential for photovoltaic and solar thermal installations on the various roofs of the College buildings. This identified the Chapel roof as a potential site. A further feasibility study was commissioned as part of this project to provide a detailed review for the potential installation of PV arrays on the Chapel roof – establishing the business case for installation, and identifying the constraints and limitations imposed by the historic fabric and archaeological implications. By necessity this will include a review of the wider College infrastructure and how any proposal would integrate to existing electrical systems, including lightning protection.



High-level, site wide review for potential PV or solar thermal installations

The Fellowship have already successfully delivered some of the objectives of this high level strategy, most recently on the college hall. However the most important observation which needs to be made about the MFP feasibility strategy is that ALL viable renewables capacity is needed to contribute to the Carbon Zero commitments. Viability in this instance especially includes viability of consents being obtained. Since the 2019 report on renewables detailed analysis on the efficiency and commercial viability of the Chapel project shows it to be highly desirable – subject to consents.

Precedents within the C of E ecclesiastical context

Where suitable, the installation of solar PV panels on roofs is encouraged by the Church of England as part of a package of practical measures.

> '*A practical path to net zero carbon for our churches – Getting to Zero*', December 2020, policy C8: [16] 'Install solar PV, if you have an appropriate roof and use sufficient daytime electricity in the summer'.

The growing number of successful installations at other high-profile heritage assets, such as Salisbury and Gloucester Cathedrals as listed below, serve as precedents for the sensitive introduction and the benefits which may be achieved.

Salisbury Cathedral

- 37kW solar array
- Completed at the start of July 2020
- Provide 33,708 kWh per year
- 93 panel system
- Salisbury Cathedral (2020): 'will provide 33,708 kWh of clean energy to Salisbury Cathedral, reducing its carbon footprint by 11,764 kilograms per year'.[17]

Gloucester Cathedral

- 38kW solar array
- Reduced the Cathedral's energy costs by 25%
- 150 panel system
- REC BLK2 model
- Gloucester Cathedral (2016): 'they have given us more than 25% of our electricity over the year: 31.12MWh of "clean" energy which has effectively meant 12,199.91 kg fewer CO2 emissions or had the equivalent effect of planting over 40 trees. The financial saving to the cathedral is a further blessing given the £4,000 reduction in our bills!'[18]

[16] https://www.churchofengland.org/sites/default/files/2021-01/the-practical-path-to-net-zero-carbon-numbered-Jan2020.pdf
[17] https://www.salisburycathedral.org.uk/news/solar-panels-installed-roof-cloisters-0
[18] https://www.gloucestercathedral.org.uk/first-anniversary-of-solar-panels-at-gloucester-cathedral-.php

6.2.2 Initial assessment of the Chapel roof

The expansive and largely concealed roof of King's College Chapel provides similar potential for vast energy improvements by the installation of a photovoltaic array. This includes the opportunity for locating panels on the north slope as well as the south slope - made viable by the relatively shallow roof pitch and the fact the north side does not suffer over shading from the parapets. It was estimated than an array including both slopes could provide a potential combined annual output of 81,858 kWh/yr and a potential combined CO2 saving of 15,144 kgCO2e/yr.

Following the procurement of more detailed metric survey data as part of this project, Max Fordham have been able to review the possible layouts for the proposed array and the associated benefits more accurately. The accompanying Shading/ Annual Production Reports are included in Appendix F. These conclude that the actual potential is even greater than anticipated from the earlier estimates, as summarised in the figures below.

South Slope:
Annual PV Output (kWh/yr): 62,000
Capex PV (£): £72,328
Elec import offset (£/yr): £8,246
Simple payback (yrs): 8.8
CO2 saving (kgCO2e/yr): 11,470

North Slope:
Annual PV Output (kWh/yr): 38,400
Capex PV (£): £72,328
Elec import offset (£/yr): £5,107
Simple payback (yrs): 14.2
CO2 saving (kgCO2e/yr): 7,104

Potential combined annual output (kWh/yr): 100,400
Potential combined CO2 saving (kgCO2e/yr): 18,574

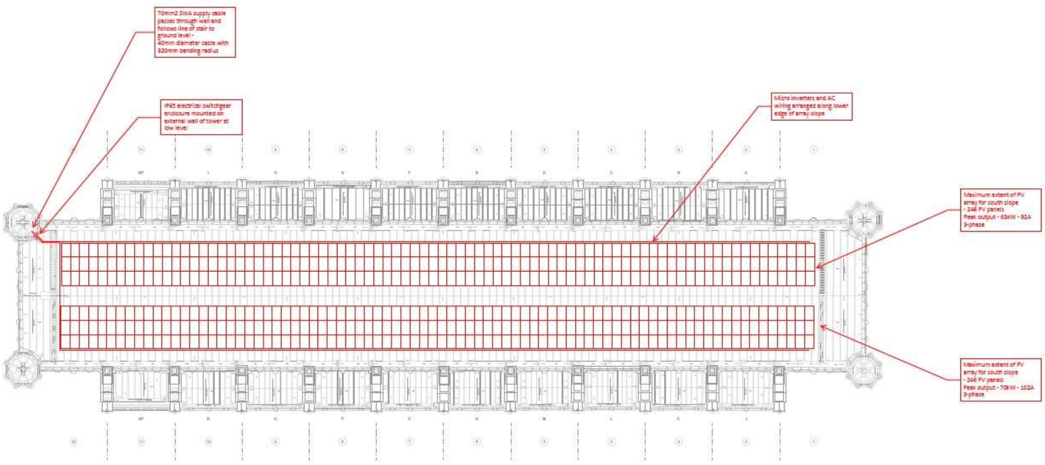


Diagram showing the proposed layout of the PV array. See Appendix G for details

6.2.3 Visual impact of the installation

Clearly given the Grade 1 listing and sensitivity of the Conservation Area, visual impact of a PV array is a paramount concern. We have undertaken here a detailed appraisal of visual sensitivity. The methodology is simply to identify receptor sites (near and far) and then to clearly question what the impact would be. Our findings are described as follow. There would be some (modest) visibility of PV array. The question to be asked of regulators at this juncture is for guidance on the weighting of benefits and possible harms. There is still no national guidance on the weighting of heritage protection with environmental protection, so each case has to be evaluated on its merits.

It can be observed that, in the main, from ground level, the large majority of the chapel roof is obscured. However glimpses of the lead roof coverings can be seen through piercings of the parapets and between the rising pinnacles and turrets from high-level vantage points. The following photographic context analysis have been included to elucidate the limited extent to which the roof is visible and therefore the limited potential visual impact of any proposed PV installation.

We have not commissioned any formal 'verified view' assessment, because we suggest that the sensitivity is more than amply identified in the photographs here, which can be further verified by a site visit. However we do ask our regulators if any more extensive or forensic view sensitivity analysis would be required to proportionately support an application.

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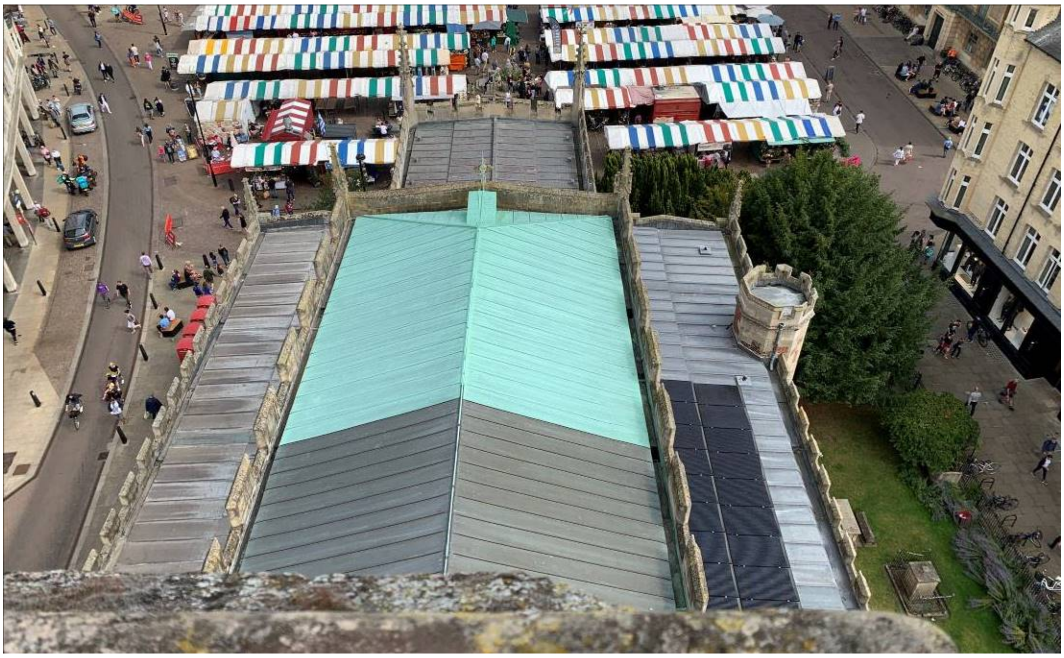
Photograph reference locations

Photograph 1: View from Trinity Lane

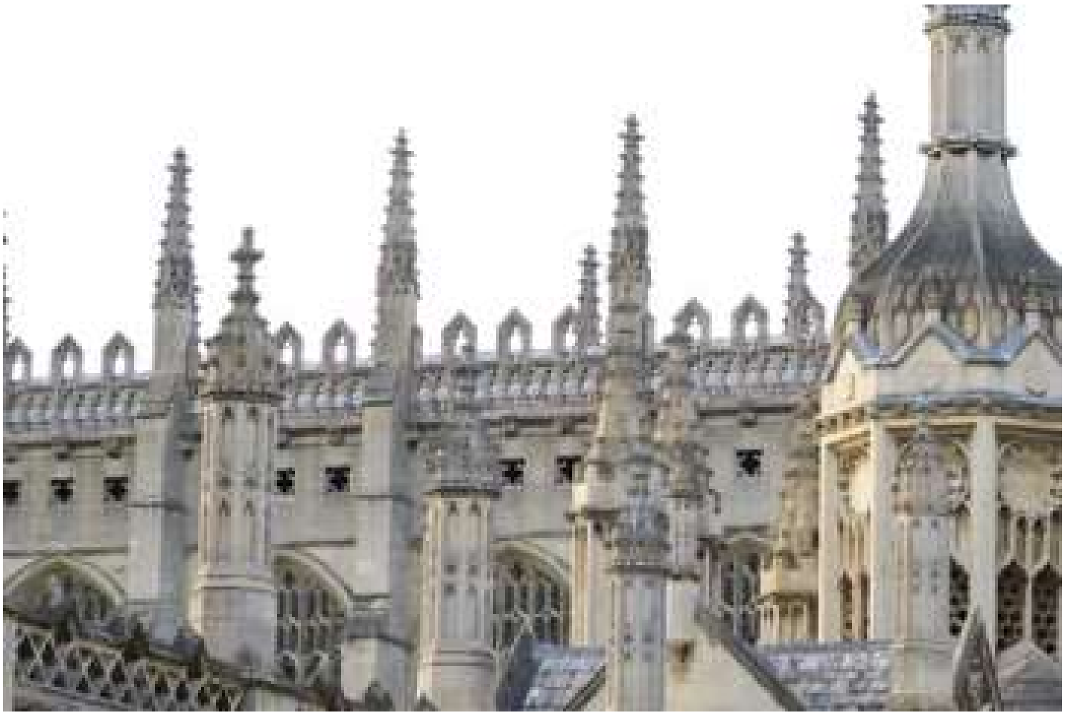
Photograph 2: View from Senate House Hill where Trinity Street and Mary's Street join

Photograph 3: View from the Tower of Great St Mary's Church



Photograph 4: View of existing PV array on the South Aisle of Great St Mary's Church

Photograph 5: View from the Corpus Clock at the conversion between King's Parade, Bene't Street and Trumpington Street.



Photograph 5 (Detail)

Photograph 6: View from the south west corner of the front lawn.

Photograph 6 (Detail)

Photograph 7: View from King's College Bridge

Photograph 8: View from The Backs

Photograph 9: View from Garret Hostel Lane Bridge

Photograph 10: View from the top of the Grand Arcade car park.

Photograph 11: View from Castle Mound.

Photograph 11 (Detail)

Our evaluation of these viewpoints is that the visual impact of a PV array would be almost negligible and would be justified by the benefit.

6.2.4 Fixing Options

Besides the visual impact of a PV array, there is also a physical impact to consider. There are a range of fixing options:

1. Ballast lower edges with saddle strap over the ridge. This could support PVs on one or both slopes of roof. If the array was to one slope only, some ballast would still be needed on the other slope.
2. Ballast lower edge with physical fixing at upper edge / ridge. This could support PVs on one or both slopes of the roof. Precedent: Gloucester Cathedral (shown below).
3. Physical fixings at lower and upper edges / ridge - could support PVs on one or both slopes of roof.
4. Roll clamp option for solid core roll covering only: therefore ruled out.

Following appraisal of the above, ballast options have not been taken forward, in part due to the additional loading which would be placed on the historic roof structure, but primarily due to the unquantified risks of regular and repeat condensation and limited drying where in contact with the lead - which may lead to accelerated deterioration of the roof covering. The parameters for thermal expansion of the lead are known and the risks associated with direct fixings can be mitigated by design. Direct fixings have therefore been proposed.

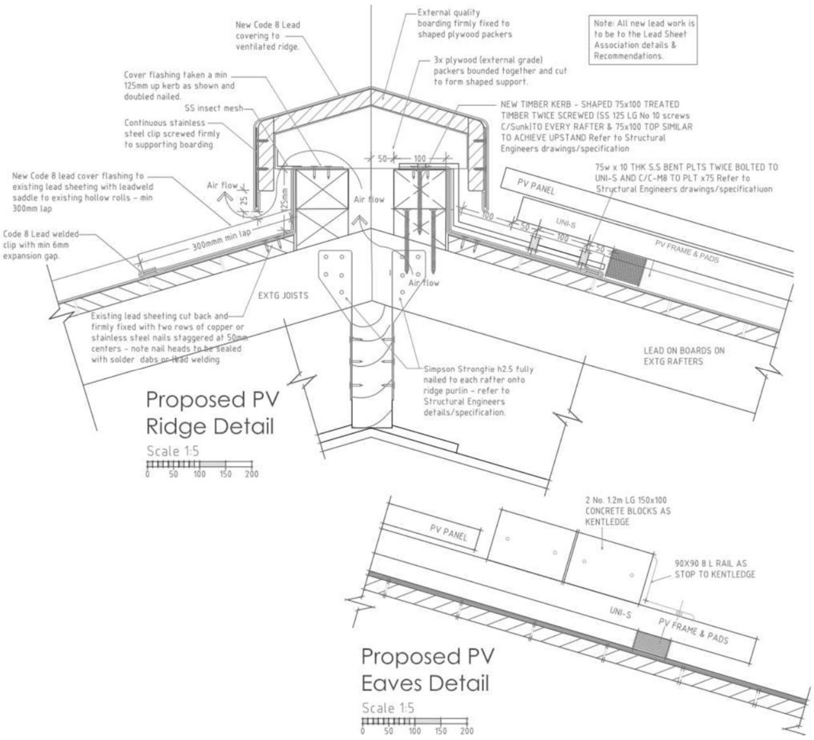
Fixing Precedents

Gloucester Cathedral

Ridge detail was added to allow lead covering to be substantially retained and provide a fixing for the PVs.

Photograph showing roof prior to intervention

Photographs showing new ridge and PV installation



Detail of fixing at ridge and ballast at the eaves

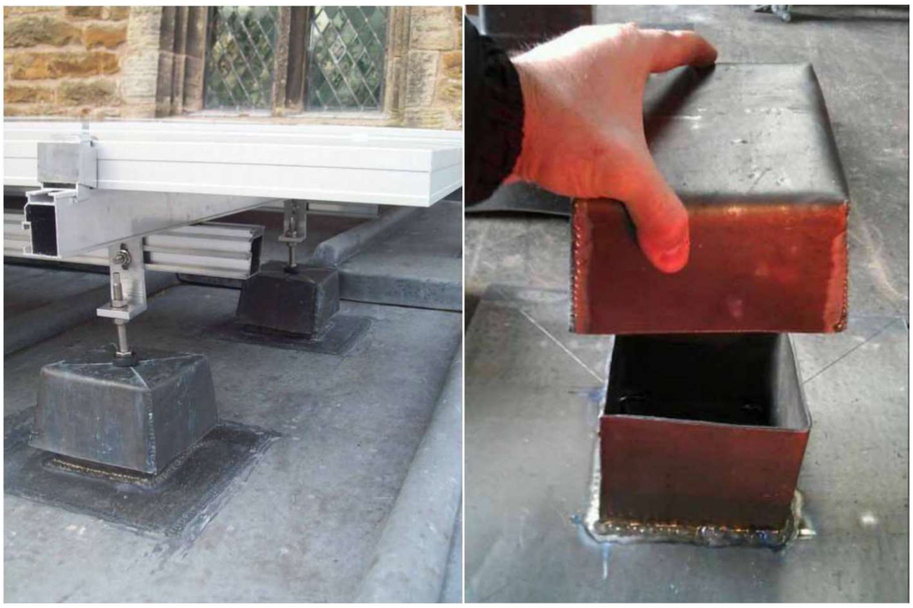
Church of St Michael and All Angels, Withington

Alternative approach to maintain existing ridge detail using ballast on the opposing slope.

Photograph showing the array during installation.

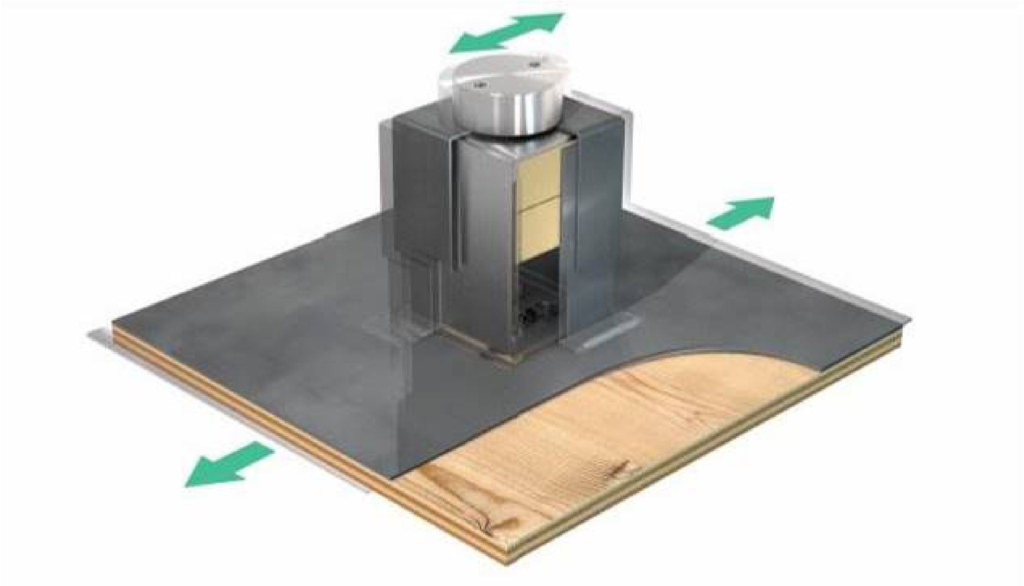
Precedent 3 from Historic England's Energy Efficiency and Historic Buildings document

Alternative approach for direct fixing, incorporating a timber block system capped with lead sheet to support and fix typical hand rail systems, whilst allowing thermal movement of the lead.



Photographs showing block fixing details[19]

[19] Historic England, *Energy Efficiency and Historic Buildings: Solar Electric (Photovoltaics)*, p. 7



Alternative – Nicholson's Integrated Fixing Point for metal roofs

6.2.5 Cable routes and infrastructure

It is anticipated that the routing of cables from roof level to ground, will be through one of the stair turrets at the west end. The existing fire alarm and small power to the roof space is within the south west tower, wrapped around the newel. Distribution from the Chapel building to the College/back to the grid is still under review.

6.3 Rainwater Disposal and Rainwater Harvesting

There are two critical questions in relation to rainwater for this project.

1 Verification of critical capacity for rainwater disposal, throughout the system (from roof to the below-ground drainage network) to safeguard the fabric, particularly in relation to storms and climate change adaptation.

2 Rainwater harvesting for irrigation purposes.
The need for rainwater harvesting under consideration for this project is for a specific purpose, not a generalised consideration for water conservation. However it is noteworthy that the East of England is one of the most water-stressed regions of the UK and this stress is anticipated to rise. One of the first planning applications for new development to be refused in the UK on grounds of water infrastructure deficiency was in the East of England.[20]

The need and rationale for rainwater harvesting relates directly to a concern for the maintenance of the high heritage significance and universal heritage values of the College estate – which includes the maintenance of the green lawns and swards of the courts and open spaces. In several recent years these green spaces have been severely parched by drought – leading to complete failure of the lawns in one instance. Production of new turf has a large carbon and water requirement. Sustainable maintenance of these lawns is therefore essential to preserving the valued qualities of the conservation area and the setting of many heritage assets.

Rainwater disposal capacities:

The expansive main roof of chapel combined with those of the side chapels, provides a total catchment area of approximately 2250m2. With increasing rainfall intensities, a vital consideration of the roofing proposals has been to ensure that the rainwater disposal system has sufficient capacity to accommodate present and future climate-change rainfall. Conisbee have undertaken rainwater analysis to include a 40% allowance for climate change and been commissioned to undertake a feasibility study to review the potential installation of a rainwater harvesting system.

1 in 1 YEAR (60 MINUTE STORM)
Runoff from Main Chapel Roof: 34 l/sec
From Total Roof Area: 50 l/sec

1 in 5 YEAR (60 MINUTE STORM)
Runoff from Main Chapel Roof: 56 l/sec
From Total Roof Area: 81 l/sec

1 in 50 YEAR (60 MINUTE STORM)
Runoff from Main Chapel Roof: 87 l/sec
From Total Roof Area: 126 l/sec

1 in 500 YEAR (60 MINUTE STORM)

20 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/292913/gean0107blln-e-e.pdf

Runoff from Main Chapel Roof: 136 l/sec
From Total Roof Area: 198 l/sec

MAXIMUM EVENT (60 MINUTE STORM)
Runoff from Main Chapel Roof: 248 l/sec
From Total Roof Area: 360 l/sec

At present, the Chapel downpipes connect directly into underground drainage which subsequently discharges to a combination of mains drainage connections and via culvert to the River Cam. The above demonstrates the substantial drainage requirements of the Chapel building for which consideration must be given to how and where it is directed when it reaches ground level. The review of underground drainage capacities is on-going however, with increasing rainfall intensities consideration to the eventual requirement to increase capacities or include a means of attenuation should be considered.

Rainwater Harvesting:

In conjunction with the above, Conisbee have undertaken a feasibility study for the installation of a rainwater harvesting solution which would significantly reduce College water requirements, as well as provide a potential method of attenuation. Harvested rainwater would primarily be used by the grounds staff for maintaining the College Lawns, which in themselves are a large contributing factor the setting of the numerous heritage assets on the College site.

A 10 x 10m RWH tank holding 100,000l would provide water for 3 working days of irrigation, enough to water of 1/3 of the lawns to field capacity (fully saturated). This has been discussed with the Senior Horticulturist who has advised that this level of saturation would not be required and the water from one tank should provide sufficient resource for all lawns. Collected rainwater would be used during the wetter seasons as water is sprinkled on the lawns prior to rainfall to increase the ground's reception to rainwater. The potential for lead contamination through run-off from the Chapel roofs was also discussed with the Senior Horticulturist who confirmed that the amount of lead would be insufficient to cause a detrimental impact.

If capturing all rainwater discharged from the Chapel roofs, an average storm would refill the tank by 13,972 litres and the tank would be refilled 22 times per year. The works storm in every year (1 in 1 year storm) would refill the tank in approximately 40 minutes.

The ground around the Chapel and College site has a high archaeological potential and the location of such a tank must be carefully considered. Usefully significant insight has been established through a combination of ground investigations, historical documentation and analysis of the scorch marks which have presented in 1955 and 2018. A full Desk Based Assessment for this project has not been commissioned as yet – but there are ample records available to understand the archaeological stratigraphy and heritage sensitivity that can be anticipated.

CAROE ARCHITECTURE

KING'S COLLEGE CAMBRIDGE

7.0 Appendix

Appendix A – LCA Report on the Leadwork to King's College Chapel, Cambridge

Appendix B – Drawing GA 200 Scope of Work, Roof and Roof Space Plans

Appendix C – Rainwater Calculations and Drainage (Conisbee)

Appendix D – Scaffolding Development – Progression Flow Chart (Rise Scaffolding Services Ltd)

Appendix E – Scaffold Development - Scheme 3 (Rise Scaffolding Services Ltd)

Appendix Fi – PV Feasibility - Shading Report (Max Fordham LLP)

Appendix Fii – PV Feasibility - Annual Production Report (Max Fordham LLP)

Appendix G –PV Layout (Max Fordham LLP)