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Net Zero Ambitions in Heritage Settings: Reinventing the Heritage Steel Window

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Abstract

Net zero ambitions for London's heritage buildings have long been constrained by conservation requirements that retain poorly performing historic windows or reliance on secondary glazing, limiting gains in thermal performance, airtightness, acoustics, and usability. Between the 1920s and 1960s, single-glazed, non-thermally broken rolled steel window profiles were widely used and are now valued for their slender sightlines and refined detailing. Modern systems are typically considered unsuitable for listed buildings because their proportions and detailing diverge from original windows. An initiative by Eckersley O'Callaghan, The Crown Estate, Royal MHB, and others develops a high-performance window system that faithfully replicates the heritage aesthetic. It operated across three strands: Conservation; close consultation ensured the architectural significance of the original windows was preserved, Whole-building performance; portfolio-wide energy assessments demonstrated a clear whole-life carbon benefit, and Product performance; rigorous design and product testing validated performance. The system has successfully progressed through engagement with Westminster heritage stakeholders, securing planning permission for the installation of a compliant, conservation-sensitive window system in a Grade II listed building with a view to rolling out onto other assets.

Keywords

Steel, Window, Heritage, VIG, Vacuum

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1. Introduction and context

Eckersley O'Callaghan (EOC) had been engaged in the conservation and refurbishment of heritage facades for some time and identified a persistent challenge within the sector. Efforts towards making conservation-sensitive assets more sustainable were being hindered by the absence of modern systems capable of simultaneously meeting modern performance standards and satisfying the specific aesthetic requirements of conservation stakeholders for significant building's facades. This limitation being particularly relevant for heritage steel windows, for which no acceptable alternative was available on the market.

In response, EOC approached The Crown Estate (TCE) to collaborate on this issue, recognizing that TCE's extensive portfolio and sustainability ambitions created a suitable context for research and development in this area. The Crown Estate embraced the opportunity and assembled a multidisciplinary team to work on this initiative, aiming to develop the next generation of high-performance heritage style steel windows that would also meet their aspiration to achieve sustainability targets and reduce energy consumption in its buildings. This paper documents the development process and solution for this new glazing system, which has achieved planning and is in manufacture for the Grade II listed 21-29 Glasshouse Street project in Piccadilly, London.

2. The problem statement

2.1. Portfolio review

A thorough review of the Crown Estate portfolio was undertaken, as well as a broad review of London building typologies within conservation areas. This identified the presence of thousands of poorly performing but conservation-significant steel windows, typically in buildings from the 1920s to 1990s. The Crown Estate portfolio has multiple assets with non-thermally broken steel windows. For the Regent's street portfolio, most steel windows were found to be 70-100 years old and in a varying state of repair.

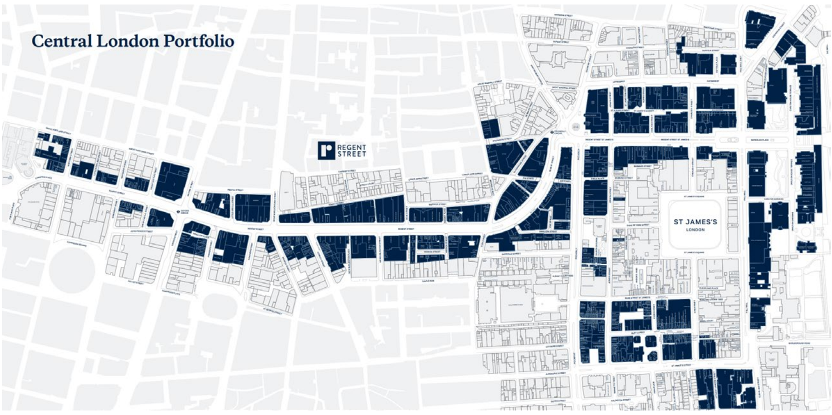

Fig. 1: The Crown Estate London Regent Street and St James' Portfolio.

These existing steel windows are distinguished by their slender sightlines, clear hierarchical configurations, and exposed -often ornate- ironmongery. Together, these features express the craftsmanship of their era and contribute to a strong sense of historic character. However, original steel windows from this period of construction typically present the following challenges:

- Non-thermally broken and typically single glazed: U-value of ~6 W/m^2K
- Poorly sealed: leading to bad air tightness performance and drafts
- Towards the end of their useful life given their age: up to 100 years old in some cases
- Typically incorporate toxic materials: e.g. lead paint layers, putty containing asbestos
- Poor acoustic performance
- Increasing maintenance burden
- Glass typically filmed for safety purposes, with associated aesthetic compromise

2.2. Conservation challenges

Despite the challenges stated above, original steel windows in the building stock are cherished from a conservation perspective. In Britain, until recently it has been common practice to require the retention of original windows in legally protected historic ‘listed’ buildings. The approach to improving performance to date has therefore long been to retain them and provide secondary glazing behind the original system, unfortunately often to the detriment of the original windows, whose maintenance became difficult. However, the challenge of climate change and net zero goals is beginning to change attitudes among British conservation authorities.

To overcome these conservation boundaries, different alternatives were examined and evaluated based on four main drivers: aesthetics, performance, durability and sustainability. These factors guide the decision-making process in a refurbishment to meet the functional and architectural character needs of each project. Figure 2 describes the alternatives typically proposed in projects; retention of the existing with repairs, addition of secondary glazing, and window replacement with modern interpretations.

Replacement of the windows would be preferred, to establish the best performance, internal comfort and operational carbon. An internal study of modern proprietary systems revealed that most systems are designed for large format glazing apertures, triple glazed packages and have concealed window hardware (locking points, stays etc) which combined result in wider sightlines. These features do not agree with steel windows typical of 1920s-1950s buildings in London / Paris etc. that were smaller, and their 'heritage' style was strongly defined by surface mounted ironmongery (such as ornate handles, stays and connected locking points). As such, replacement of the windows with a modern heritage-appropriate system appeared to be most promising direction.

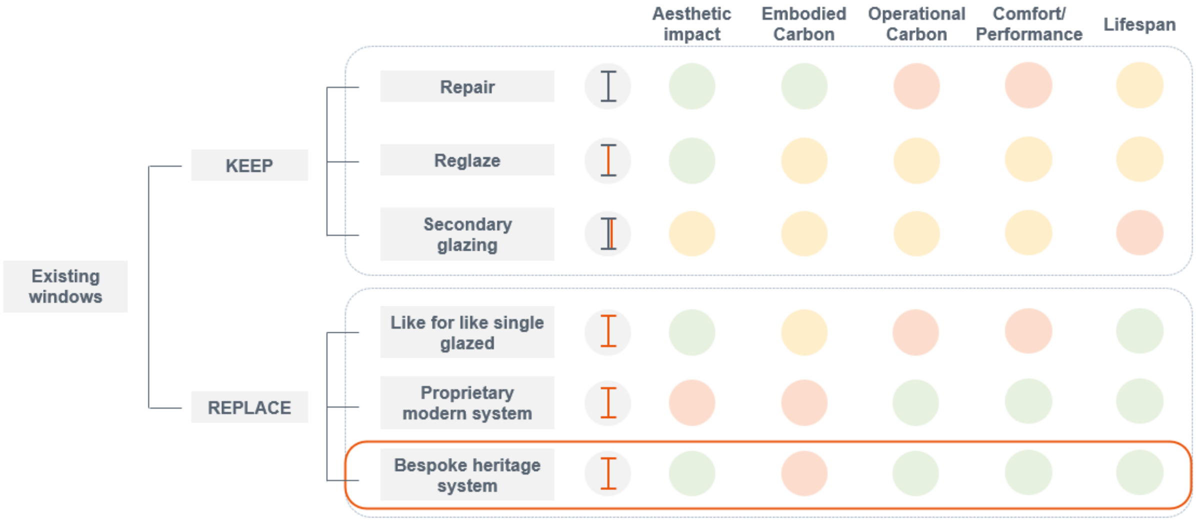

Fig. 2: Comparison of approaches to improving performance of existing steel windows.

Adding to the above benefits of a replacement approach, discussions with our heritage consultants - Donald Insall Associates - revealed that prior to industrialization, windows were typically bespoke elements crafted by skilled artisans. In the UK, “Crittall” represented one of the first 'systemised' approaches to windows after industrialised processes were in place (e.g. Bessemer process to forge and roll steel) and ‘catalogued’ window frame profiles could be mass produced and assembled by licensed fabricators. Today the name of the company is still used to describe most windows from the early-to mid-twentieth century due to the company’s prominence in their design and manufacture, and the consolidation of many systems under their roof during this period. As such the value is less in the material itself but in its aesthetic and place in the wider streetscape. This meant an argument could be made, that whilst the windows carried considerable conservation significance through their aesthetic, the material itself wasn’t as significant.

2.3. Portfolio-wide review of window replacement benefits

To exhibit the benefits of window replacement and identify asset types which would benefit most from a refurbishment, a portfolio study was undertaken. Using TCE asset data, gathered by third-party consultant, and a visual survey of windows in each asset, a high-level energy modelling analysis of 98 TCE assets was completed to model a future window replacement scenario. This methodology involved an evaluation of the windows and masonry for estimated existing and potential future u-values/thermal performance based on year of building construction/refurbishment, glazing type, frame factor and frame material.

Heating load was then evaluated based on TCE asset data on occupancy rate and estimated conduction and infiltration losses based on the building fabric and typical internal air temperature as per CIBSE Guide A. Validation of the current U-value assumptions was conducted through comparison of TCE asset data and estimated heating load during heating months (October to April) (Figure 3). Outcomes from this comparison were used to further examine the change in heating loads and upfront carbon (A1-A5) payback period to quantify the benefits of window replacement in refurbishments (Figure 4).

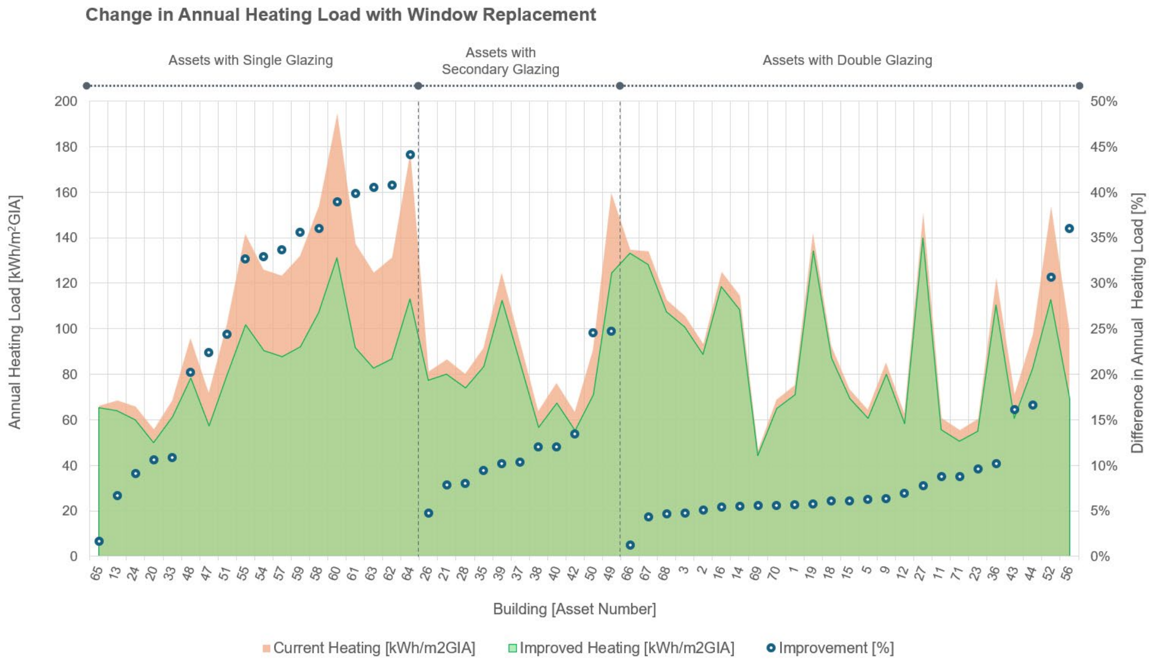

Fig. 3: Heating load assessment on selected assets (redacted) in TCE's central London portfolio.

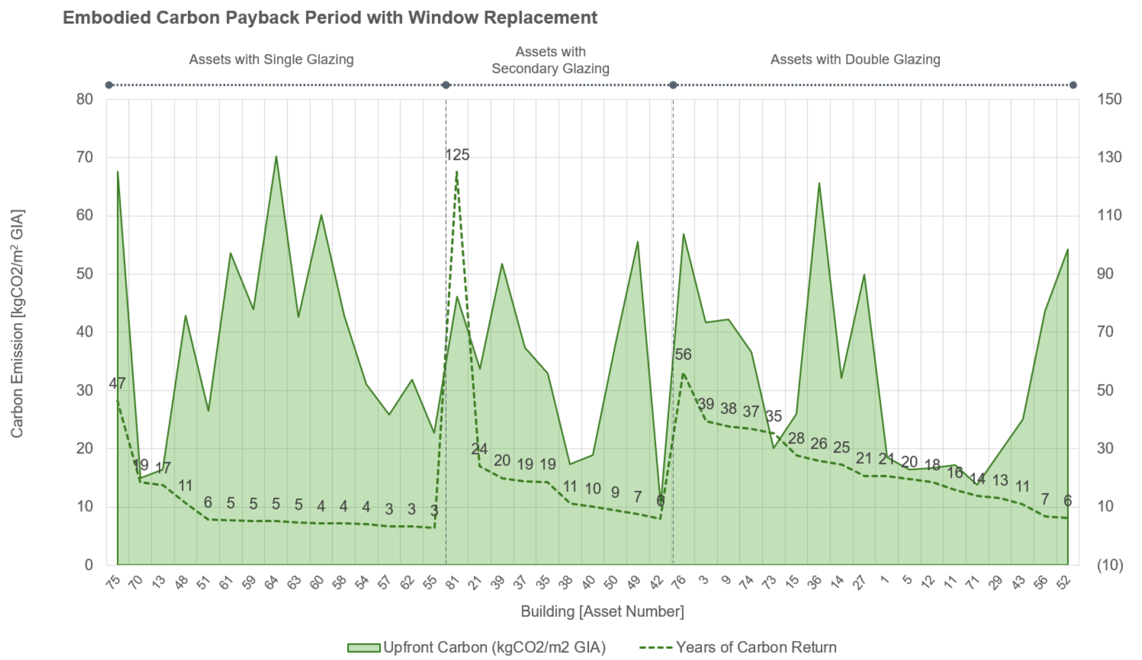

Fig. 4: Embodied carbon payback assessment of window replacement on selected assets (redacted) in TCE's central London portfolio.

The portfolio assessment highlights that buildings with poorly insulated windows (single-glazed) and a large window area see the most significant improvement in thermal performance when upgraded. This is especially true for assets with high upfront carbon emissions (A1-A5), where a high glazing-to-facade ratio with single glazing often results in a shorter payback period. In cases where there is a lower glazing-to-facade ratio will require less upfront carbon investment, however, provides a small percent improvement in annual heating.

2.4. A note on building retrofit strategies

The study above was an academic exercise, and window replacement in isolation needs holistic assessment. The performance of a better performing window system must be considered within the context of a whole-building retrofit strategy rather than as an isolated intervention. For example, window replacement will inevitably reduce uncontrolled air infiltration, making a building more airtight. Without adequate provision for 'replacement' ventilation, this could result in poor indoor air quality, and the failure to remove excess moisture can lead to condensation and mould. In addition, the thermal performance improvements offered by a new window can be undermined at its perimeter if cold bridges at the frame-to-wall interface are not addressed through internal insulation at window reveals. Retrofitting should therefore adopt a holistic, whole-building approach, balancing energy performance with occupant health, durability, and heritage value.

2.5. Circularity

A detailed material recovery methodology was developed to maximize reuse and recycling potential of the existing windows within the portfolio. The methodology consists of three on-site steps: a hazardous and non-hazardous material audit, practical handling and safety measures to minimize risks of contamination of other materials during dismantling, and a dismantling and deglazing strategy and sequencing to optimize efficiency and material recovery.

To validate the methodology, a trial dismantling of a single glazing "Crittall" window was conducted in close collaboration with Saint Gobain for glass recovery and building contractors BAM, Getjar, and Powerday for deconstruction and steel recovery.

A portfolio-wide review revealed that many assets predominantly feature single-glazing, with or without secondary glazing. For this reason, the methodology and trial were focused on single-glazing, specifically validating replicable sequencing and methods for deglazing steel-framed windows.

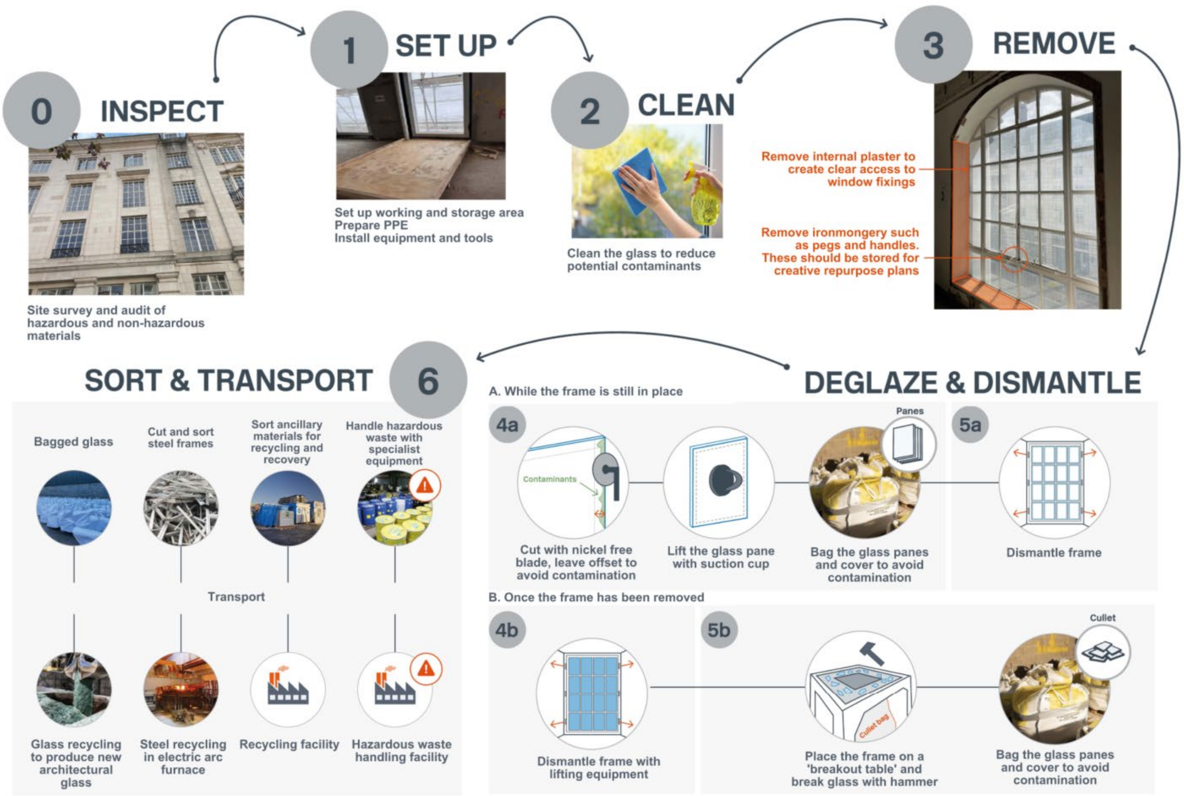

Fig. 5: Proposed dismantling process for windows being removed.

3. Market research

3.1. Existing window configurations

The material properties and sectional profiles of historic Crittall windows were first analysed to inform the development of the proposed new glazing system. Crittall windows are distinguishable by a series of rectangular casement windows with a mix of fixed and openable forms. Historically, the development of windows with transoms, mullions and glazing bars (muntins) originated from limitations in the size of glass available to glaze window apertures (Tutton et al., 2007). Historically, handmade glass panels had to be trimmed and assembled with lead frames or glazing bars and only with the development of machine-made flat glass (drawn glass from around 1920, and float glass from 1959) could sizes be achieved unconstrained by the limitations of mouth-blowing (Louw, 1991). This advancement in glass technology, coupled with the higher strength of steel compared with the historical use of timber and (later) wrought iron, meant that larger glazed areas could be considered with reduced framing.

3.2. Typical profiles, sightlines and detailing

Crittall introduced the “Universal Range” of steel profiles in 1918-1920 which enabled improvements in the manufacturing process compared to previous methods (Figure 6). Typically, muntin widths of ¾-inch (19.1 mm), 1-inch (25.4 mm) and 11/8-inch (34.9 mm) were most popular. Most existing metal muntins in the TCE portfolio were found to be a simple T-profile. Steel profiles were either tenoned and riveted or welded together, with the frames being secured into the wall opening using metal lugs bolted on to the frame and inserted into the mortar joints of the wall, or nails fixed in the bedding mortar.

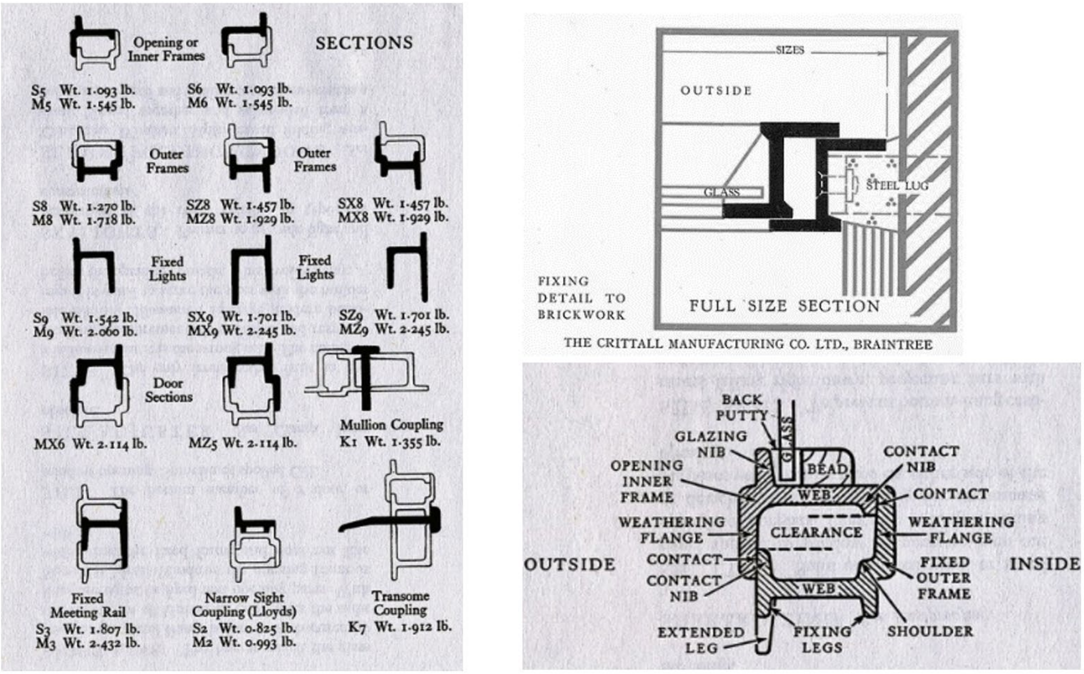

Fig. 6: Universal Range steel windows (the most prolific steel window section) used from 1912 to 1964 (Crittall catalogue, 1928).

3.3. Glass capture and system drainage

Traditionally, steel windows were glazed using single-pane glass set in a solid bed of glazing putty. Later windows adopted beads in metal or timber. Windows were glazed from the exterior or interior, using the fixed frame leg as the backing stop. Moisture resistance relied primarily on the resistance of the glazing seal itself; with little evidence of weep holes used for drainage (Steel Window Institute, n.d).

3.4. Ironmongery

Existing steel windows exhibit a range of bespoke hardware fittings (hinges, pivots, stays, handles, restrictors, manual actuators etc), and operation such as hinged, centre pivot, and offset pivot arrangements. However, all ironmongery shares a common characteristic; they are typically surface mounted and visible, adding to the charm of these heritage windows (Figure 7).

Fig. 7: Example of heritage ironmongery on existing and catalogued steel windows across London (Crittall catalogue, 1928)

3.5. Structural Hierarchy

Vertical and horizontal stiffening profiles were used for windows spanning large dimensions (e.g. double-height spans or multiple casements). To achieve increased stiffness, these profiles had increased sightlines and depths providing a structural and visual hierarchy (Figure 8).

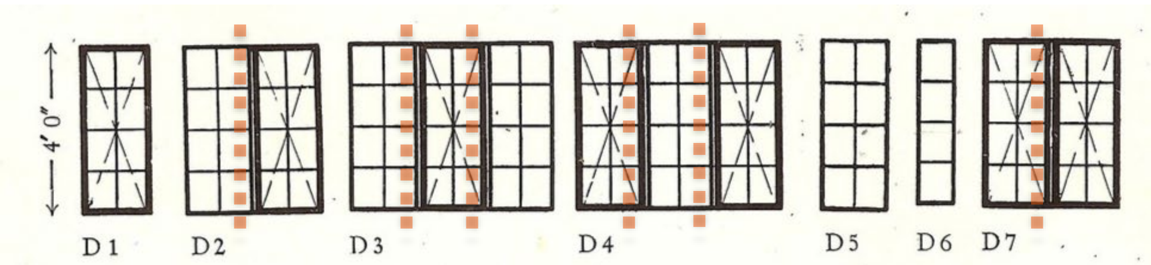

Fig. 8: Highlighted locations of structural mullion positioning in some typical configurations (Crittall catalogue, 1928).

4. System design

4.1. Establishing a baseline design

Given the wide array of steel window profiles and opening configurations in The Crown Estate portfolio, the strategy to more sensitively replace these in a unform manner prioritised to:

- Choose the slimmest sightline heritage profile system, so that any replacement will either match or 'improve' the aesthetic requirements in terms of sightlines
- Choose a flexible approach which limits the number of different profiles being introduced
- Choose an approach which matches the sightlines of fixed and opening lites, such that the operational function of the window can potentially be changed in coordination with the space requirements of the spaces inside in balance with improved performance
- Choose profiles that are prolific and used in the most sensitive TCE assets
- Design for the portfolio and the window sizes / configurations found in these Crittal systems. I.e. don't over constrain the development by assuming modern and large casement sizes, but instead focus on creating the slimmest system possible

The historically commercially available window systems examined and considered included: Crittall Small Universal, Crittall Medium Universal, Crittall Large Universal, Crittall Standard Metal Window, Crittall W20, from which, the Crittall "Small Universal" profile range was chosen as the most appropriate. Information on these systems was gleaned from a combination of old catalogues (housed in the Braintree Museum), dialogue with Crittall themselves, survey and measurements of in-situ windows, and photographs of catalogues found online (various sources).

Table 1: 'Small Universal' profile sightlines.

	Glazing bars	Rails/Jambs	Mullions/transoms	Depth
Sightlines	22mm	39mm	85-110mm	25mm or 32mm

The proposed window system aimed to meet these as closely as possible to maintain the finesse of the heritage systems, with the only more difficult constraint being the system depth, which inevitably has to increase slightly to accommodate some thermal breaks and slightly thicker glass in the proposals.

4.2. Constraining the design approach

As mentioned, modern system design results in a much wider and deeper window profile than the ambition. Nonetheless, the following steps assisted in maintaining the heritage window frame slender aesthetics as well as achieving modern thermal performance needed for the future of London heritage buildings:

- Vacuum insulated glazing (VIG) instead of a typical modern glazing unit (noting that some small additional thickness is allowed to introduce lamination if needed for certain glass criteria such as safety and acoustics)
- Solid steel profiles in lieu of cold rolled thin gauge steel (which is prolific in most modern steel) allowing more customizing of profiles compared to the heavy tooling investment of thin gauge steel sections. It is also in line with the approach taken by early Steel window manufacturers (including the Crittall Universal Suite)
- Design for modest spans, using deliberate hierarchy of stiffer members to frame out openings
- Minimising the size of the thermal breaks without compromising excessively on thermal performance and mitigation of condensation risk
- Use of simulated glazing bars
- Use of wet seals
- Use of face mounted hardware in lieu of concealed hardware (in keeping with the original Crittall approach)

The combination of the above strategies, resulted in a new system that featured a very close depth to that of the ‘Standard metal Window’ and ‘Large Universal’ systems, and more importantly the elevational sightlines of the Crittall “Small Universal” system being targeted.

Furthermore, in the context of modern building design and risk management, the decision to typically opt for an internally beaded system was made, to facilitate glass replacement. Inward opening and side hung vents were also preferred over outward opening and/or pivoting systems found in the original configurations. The solid steel profiles were adapted to mimic the original sightlines and detailing of the windows to avoid distinguishing between fixed lights and opening vents, and between different opening types.

4.3. Adoption of VIG

As a technology developed in the 1990s, Vacuum Insulated Glazing (VIG) is relatively new in the architectural glazing market. A VIG unit offers the potential of a glass unit which maintains visual appearance of single glazing windows and similar or improved thermal performance of a DGU. The slimness of VIG is possible by replacing the air cavity found in a DGU, typically 5-15mm, with a 0.1-0.3 mm vacuum cavity. Thermal performance is improved due to the vacuum cavity, with a U-value ranging 0.5-0.9 W/m^{2}K (Collins & Simko, 1998).

A VIG has small micro-pillars to prevent the glass imploding into the cavity, and some products require a visible evacuation port to extract the air. The pillars were tested visually with key stakeholders to their acceptance, and products without evacuation ports were selected, to avoid the conservation risk associated with this non-original feature.

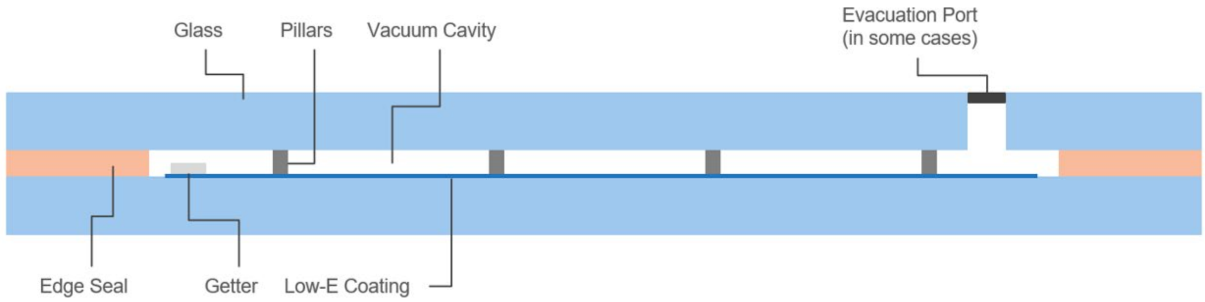

Fig. 9: Typical elements of VIG units.

Despite VIG having much better centre-pane U-values compared to typical double glazing, edge losses are much worse than through a warm edge spacer (Fang et al, 2014). A comparison of the area weighted U-value of a DGU and a VIG highlighted the potential improvements in thermal performance that VIG could provide in different size panels. For small panes the edge losses were found to overcome the centre-pane benefit, as shown graphically in the figure below, a performance challenge that would need to be accounted for in the overall window design.

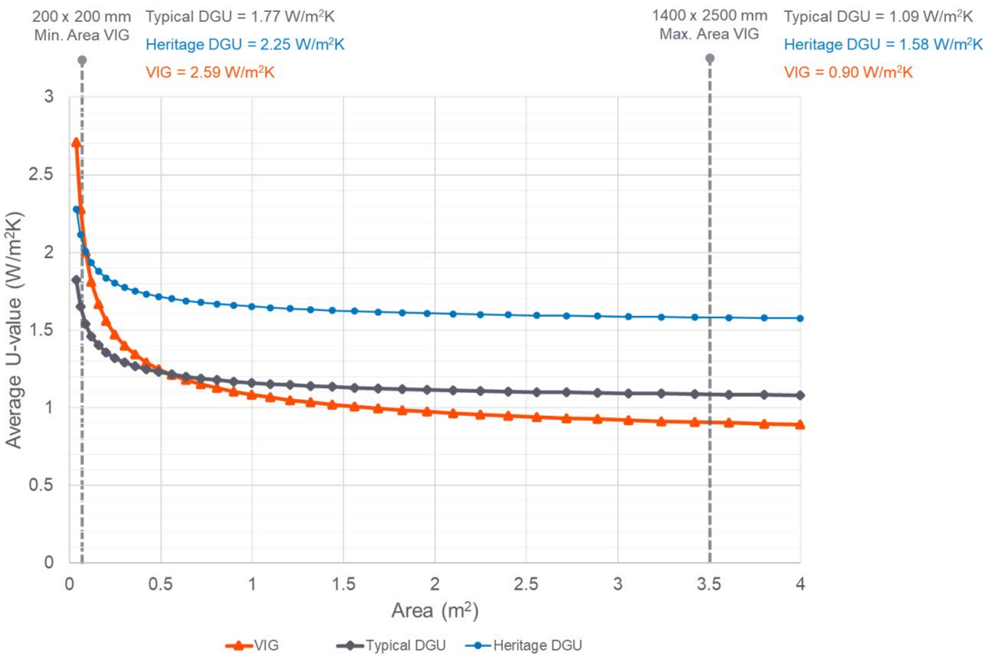

Figure 10: Impact of glass pane area on the effectiveness of VIG vs traditional DGU glazing.

4.4. Steel profile typology

The vast majority of modern steel window systems use thin gauge cold rolled steel profiles, produced via very sophisticated and automated heavy tooling methods to fold thin sheet metal into elaborate profiles. This allows thermal break profiles to be 'rolled in' and creates cavities within the profiles which can be beneficial from a thermal and material use perspective. However, in the case of heritage steel windows, opting for solid steel detailing was preferred for the following reasons;

- Structural stiffness. Given the very minimal section sizes required, solid steel offered the most appropriate way to achieve deflection limits and strength capacity
- Adaptability of profiling (via CNC or additive welding processes) to match the myriad of profile types anticipated without commercially infeasible investment in heavy tooling

4.5. Design for modest spans

Compared to contemporary glazing, heritage windows are typically relatively modest in scale and maintain a clear structural hierarchy in larger apertures between mullions, transoms and typical framing elements. As a result, it was possible to minimize the typical frames, while introducing more depth and width in key structural framing elements.

The adaptability of solid steel also allowed for consideration of different strategies; the principle of structural mullions with inserted casements (left) or the integration of profiles (right). Eventually, integration of profiles was preferred, in order to reduce the number of joints, seals and thermal bridges, but though manufacturing techniques that would maintain the characteristic rhythm of shadow lines on the profiles.

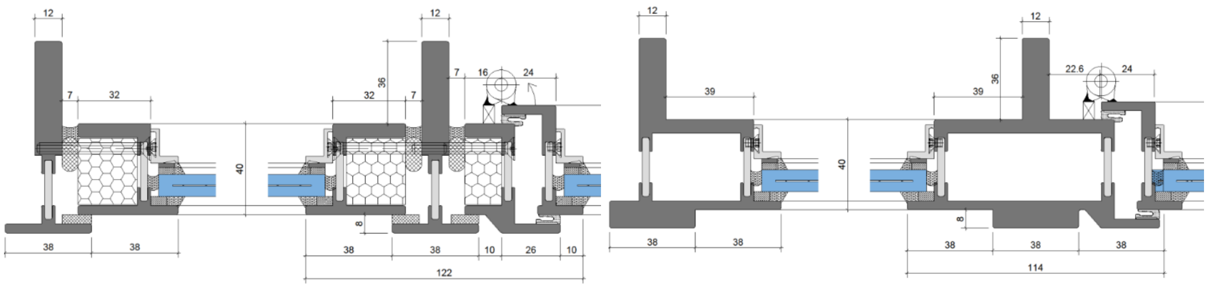

Fig. 11: Optioneering considering whether to use infill units (left) or integrated profiles (right). Drawings by Royal MHB.

4.6. Minimising thermal bridges

The depth of the system was given a lot of consideration, given the critical part it has to play in the ability for the system to hold different glass packages, the thermal performance, the structural capacity of the profiles, and importantly the realistic sightline of the system when viewed obliquely.

The adoption of VIG as the glazing package meant the typical ~55mm glazing zone could be reduced. To ensure the system could accommodate the likely range of glass performance requirements (both structural and safety) a 17mm maximum glazing package was defined. This could allow for a fully laminated VIG unit, or in the instance of needing a curved window, a slimline DGU glass (given VIG cannot be curved), and meant the thermal break zone of the profile could be reduced to 20mm between the warm and cold extents of the frame.

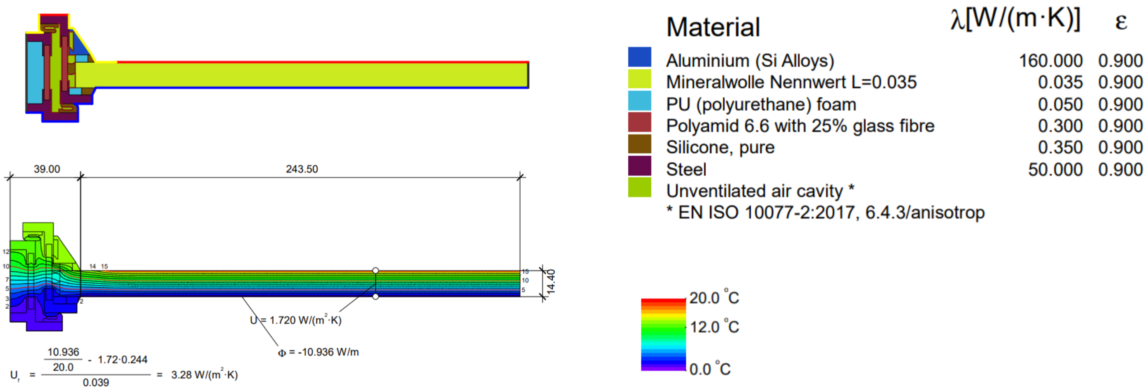

Fig. 12: Extract of thermal assessment of the system to establish U-values and mitigate for condensation.

This system was assessed thermally by EOC using finite element modelling and during manufacturing by Royal MHB, to check that the frame U-values were acceptable and that the condensation risk was mitigated in typical scenarios. The frame depth was minimized to prioritise it's conservation appeal, and a 45mm typical framing depth (including an uninterrupted thermal break length of 20mm) was assessed as having a good balance of visual 'slimness', good thermal performance and mitigated condensation risk, with additional articulation beyond this zone.

4.7. Glazing bar detailing

The impact of the above as well as the additional frame losses associated with traditional glazing bars prompted a study into whether 'true' or 'simulated' divided lites where glazing bars are replicated, should be considered. Although often 'dummy' bars used in IGUs are not favored, as one can see through the spacer, compromising the monolithic appearance, a VIG cavity being very slim does not allow the viewer to 'see through' the VIG. Furthermore, the glazing bar frames on the outside could be fully welded to create a monolithic grillage much like the original detailing, ensuring the confidence of the stakeholders and design team in this approach. This offered many benefits including an original sightline (given a true divided lite needed to be a minimum of 30mm to achieve the thermal break and capture the 2 edge seals of the VIG) and significant thermal improvement (no break in the VIG and therefore no edge losses, as well as no framing loss).

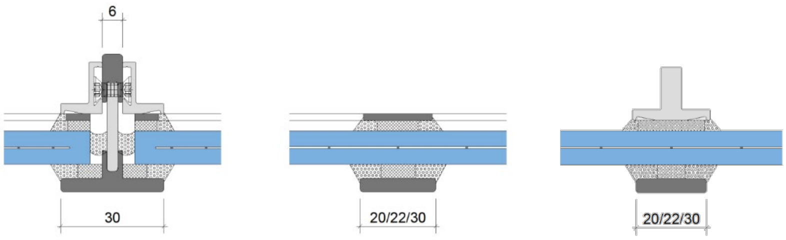

Fig. 13: Glazing bar options studied. Drawings by Royal MHB.

4.8. Sealing strategy

Another key decision in the development of the system was whether to opt for a modern dry-gasket approach, or to use more traditional wet seals. Despite some benefits of a dry gasket approach in (rare) reglazing scenarios, a wet seal was preferred to ensure performance and fit closer with the original aesthetics of the heritage systems. This meant careful consideration of the fixing strategy of the windows at their perimeter, and the associated zones and tolerances, where lugs (highlighted below) were then required to avoid on-site glazing in fixed lites.

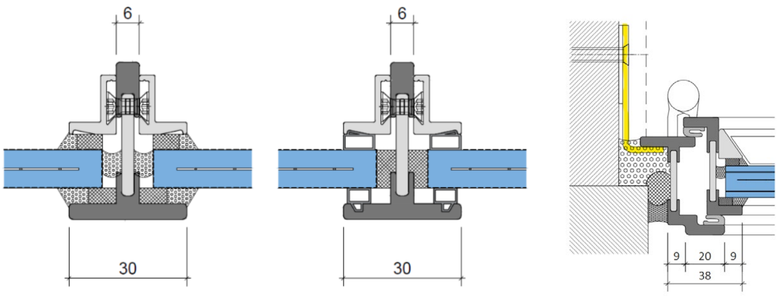

Fig. 14: Wet seal and dry gasketed concepts, and impact on the perimeter fixing detailing to accommodate window lugs without needing to site glaze. Drawings by Royal MHB.

4.9. Surface mounted hardware

A key characteristic of heritage steel glazing systems is that all hardware is typically surface mounted. By embracing this feature, concealed hardware incorporated in the framing elements was overall avoided, with all handles, rods, stays, restrictors, locks etc. being fixed to the face of the profiles for all to see; beneficial for both the profile slenderness, and the aesthetic of the system (Figure 15).

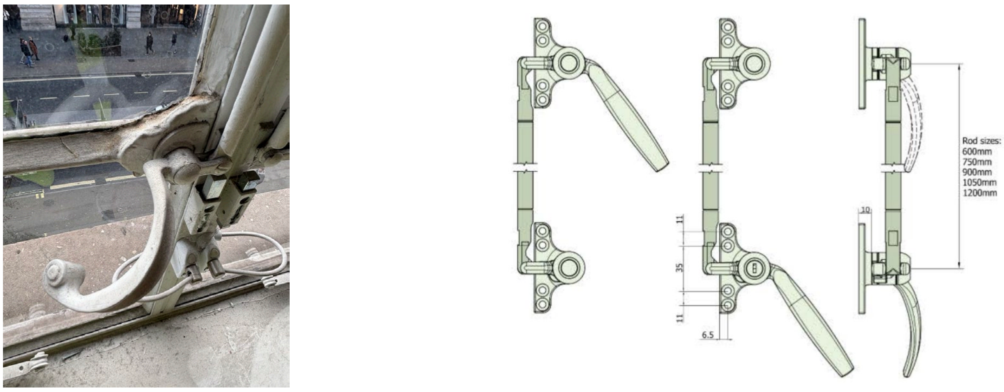

Fig. 15: Example of surface mounted ironmongery on existing windows (left) and an example modern equivalent for use on the proposed window system (right).

4.10. The Design

The final design is a flexible suite of profiles and elements that can be combined to suit the configurations of existing windows being replicated. The ability to include opening lites within the sightline limitations allows for changes to the opening configurations of the original (generally far fewer opening windows are needed as a result of modern air conditioning).

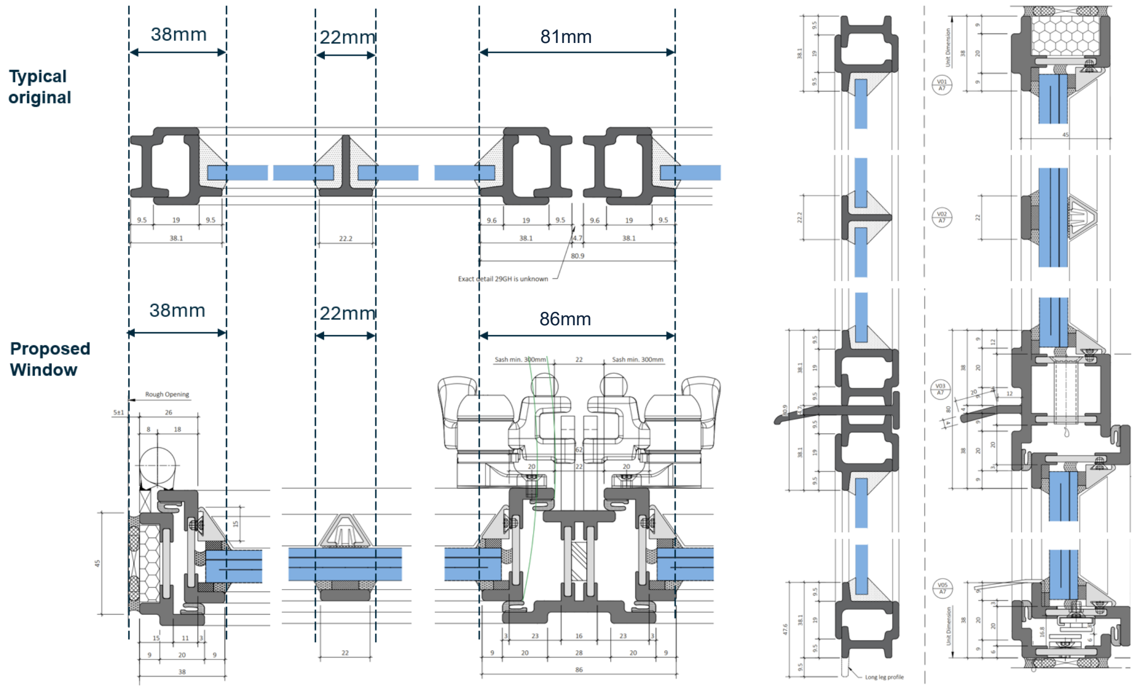

Fig. 16: Example profiles from the new heritage system, compared to the original Crittall 'small universal' suite. Shown here with double laminated VIG glazing (worst case). Drawings by Royal MHB.

5. Manufacturing

5.1. Procurement

Procurement of the system was done relatively early to maximise the benefit of the expertise offered by the incoming window suppliers. Once the decision was made to go for a solid steel window profile, and the baseline design decisions made, this narrowed down the list of potential partners and the system was tendered to a few trusted suppliers. Royal MHB were chosen as they already developed a patented solid steel thermally broken profile system that could be adapted to make this system. Furthermore, the company's extensive knowledge and experience in both development and production of high-performing bespoke steel window systems for other landmark heritage projects in Europe, could be utilized to transform the concept into an actual window.

5.2. Prototyping

Due to the building's prominent location on Regents Street, demonstrating that the new system had the same external appearance as the original system was crucial to the heritage planning argument for the window's replacement. A key milestone was prototyping the MHB-system as proof-of-concept for the conservation stakeholders to review and comment. A series of mock-ups were fabricated, and one was placed in situ on Regent's Street to test the system against adjacent ~90 year old heritage windows. Distinguishing the new MHB-window from the original windows proved quite challenging, thus providing reassurance to the conservation authorities.

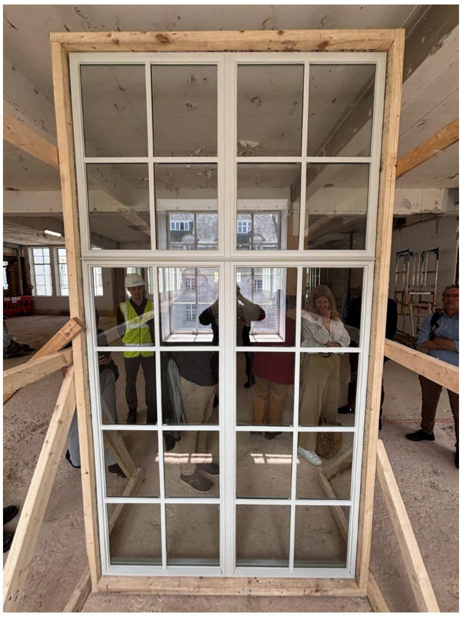

Fig. 17: Typical Regent Street window from the front (Top left) MHB-prototype window in-situ on Regent Street, bottom left window (top right), Details and demonstration of the 'hidden vent' system which allows matching the detailing and sightlines of opening vents and fixed lites, maintaining the heritage shadow lines and articulation of the framing (bottom).

Prior to this; discussion with the conservations stakeholders was arranged around the aesthetic of VIG units in comparison with the original glazing units being replaced. Some key differences were highlighted:

- The original glazing was typically 'poor' (i.e. rarely perfectly flat), whilst VIG units are typically made to a high-level of precision. Debate was had around whether or not a thinner VIG which actually had some visual distortion from the pillars was preferable, and options of laminating 'heritage' glass (with deliberate distortion) were considered.
- The original glass was sub-divided, leading to subtle but perceivable differences in reflection across any one window, whilst the VIG was proposed to be continuous across any one window (with the glazing bars simulated), leading to 'consistent' reflections.
- The VIG pillars are perceivable from very close to the glass (up to 1-2m), compared to single glazing which has no 'dots'.
- VIG is slightly thicker than single glazing, so sampling of the aesthetic of simulated glazing bars was very important.

VIG samples were shared to give comfort to the conservation stakeholders on some of these points (e.g. the presence of VIG pillars) and focus was put on addressing these differences in the prototype. In conclusion to this process, the benefits of the system (i.e. operational carbon savings, internal comfort, safety etc) were felt to broadly outweigh any small aesthetic concerns that remained after these prototypes and the proposals obtained the required permissions.

5.3. Testing

Once the system detailing was finalised and approved in principle through consultation with planners and conservation stakeholders, a suite of product testing was derived from the EN 14351 product standard, CE / UKCA marking requirements and the anticipated employers requirements performance standards for the London portfolio buildings in question. The size, configuration and number of PMUs was optimised and sequenced such that non-destructive tests preceded destructive tests on mock-ups of relevance to cover the anticipated portfolio effort within the allowable range of application of the various test standards. Four different performance mock-ups were fabricated and tested (Figure 18), resulting in a system that meets the anticipated performance.

The tests carried out by MHB include:

- Resistance to wind load - EN 12211
- Watertigthness - EN 12208, EN 1027
- Impact resistance, Soft body Testing - EN 13049
- Impact resistance, Hard body Testing - EN 13049
- Load bearing capacity of safety devices - EN 14609
- Air permeability - EN 12207, EN 1026
- Operating forces - EN 13115, EN 12046-1
- Mechanical strength - EN 13115
- Resistance to repeated opening and closing - EN 12400, EN 1191
- Resistance to vertical load – EN 14608
- Resistance to static torsion – EN 14609

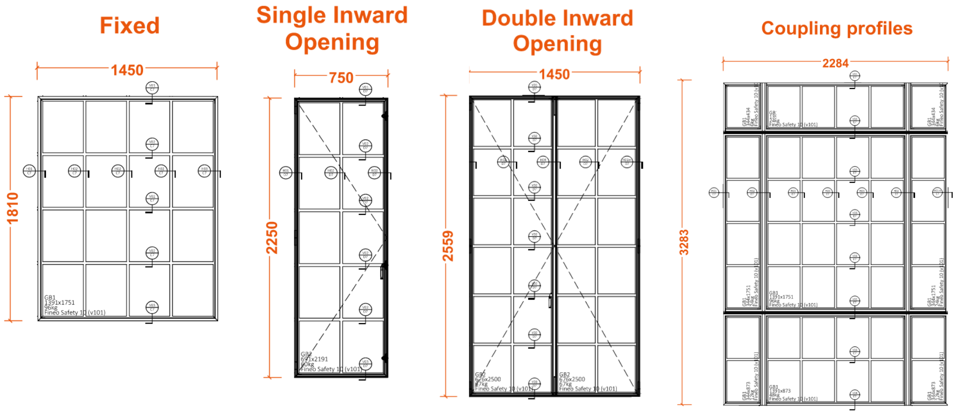

Fig. 18: Four PMU configurations tested (above). Drawings by Royal MHB. Royal MHB in-house testing chamber (below).

5.4. Manufacturing

The development phase involved an iterative cycle of testing various fabrication techniques (e.g. ‘additive’ welding assembly vs. ‘subtractive’ CNC of profiles), culminating in the production of full-scale mock-ups and functional prototypes. The primary challenge lay in developing a production method that could faithfully replicate the complexity of combined steel profiles while simultaneously satisfying rigorous aesthetic, physical, and long-term durability standards. To maintain the authentic, soft radii of historical hot-rolled sections, the manufacturing process opted to utilize precision CNC-machining to shape steel strips prior to their assembly into thermally broken configurations.

6. Conclusions & Limitations

This study has demonstrated that while the existing stock of historic steel windows is widely valued for its refined proportions, slender sightlines, and contribution to the architecture of heritage facades, its technical performance is inadequate by contemporary standards, thus undermining efforts to improve the environmental performance of listed and conservation-sensitive buildings. On the other hand, currently available high-performance window systems fail to replicate the distinctive aesthetic qualities that underpin the heritage significance of these windows.

In response, a new steel glazing system has been developed, demonstrating that structural performance and thermal efficiency need not be sacrificed for architectural elegance. The summary table below outlines the key differentiations between the original windows and the proposed alternative.

Table 2: Comparison of original windows compared to new.

	Original	New
Aesthetics	Very slim frames, heritage detailing	Very slim frames, heritage detailing
U-value	Very poor ~ 6 W/m2K	Good ~ 1.6 W/m2K
Airtightness	Poor	Very good (class 4 to En 12207)
Acoustics	Poor (single glazing)	Good (VIG and thermally broken solid steel)
Watertightness	Poor – leaks common	Very good (typically class 7A to EN 12208)
Condensation risk	High – water damage and mould growth	Low – mitigated through thermal design
Local comfort	Poor – drafts, local hot/cold near windows	Good
Hazardous material	Common – lead paint, asbestos in putty	None
Safety	Difficult to comply with Part K	Compliant and tested
Solar control	Poor – issues due to single glazing (often leading to filming of glass, and often a 'patchwork' of glazing across buildings)	Achievable via subtle coatings in the VIG

By leveraging advanced production technologies and designing for vacuum glazing, the project realized a window system that is as robust as it is exceptionally slender, offering a new path forward for heritage restoration projects. The design process was informed by detailed analysis of historic precedents and during manufacturing a full-scale MHB-mock-up was installed for approval by conservation authorities.

Finally, it shall be noted that the MHB-system is currently designed and tested for applications at upper floors of buildings, where punch windows were most common. The system has not been tested for security performance and is therefore not proposed for ground-floor application, although that might be done at a later stage, depending on specific building requirements.

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- Historic England – consultee and advocate

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