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The Rise of the Metal Window during the Early Industrial Period in Britain, c.1750–1830

H. J. LOUW

By comparison with fields like the textile industry, the building industry's immediate material benefits from the Industrial Revolution were not extensive since relatively few manufacturing processes, machines or materials were developed specifically to solve architectural problems during the eighteenth and early nineteenth centuries. However, like most other activities architecture could not escape the great tide of invention that swept through countries such as Britain and France from about the middle of the eighteenth century. The greatest impact undoubtedly came by the increased availability of metal, especially iron, for engineering, building and decorative purposes. The effect of this development on structural design is well recorded in regard to utilitarian structures such as bridges and industrial buildings, but other aspects of architecture have received little attention [1]. This study aims to investigate the influence of these technological advances on one such area: window design.

The metal window has long been recognised by scholars as a 'leitmotif of industrialised building', and as such it has been accepted as a major factor in the development of the 'Modern Movement' in architecture. Since it is also one of the few elements constituting a modern building whose lineage can be traced back uninterruptedly to the period of the first major technical transformations from which twentieth century architecture emerged, it is indeed surprising that no one has attempted yet to write its history. This paper deals with the early and least known phase of the development—the period before, as Giedion put it, 'mechanisation took command'—leaving the latter part of the story for another occasion. The study is limited to Britain, the birthplace of the Industrial Revolution, and hence the natural starting point for a history of the machine-made metal window.

The Pre-industrial Era

It was in the sixteenth century, when glazed windows with openable sections were adopted on a large scale in northern Europe, that metal first came to be employed as an integral part of window frames. These opening sections or *casements* had wrought iron frames each of which held a lattice of lead with small diamond-shaped glass quarries. This development seems to have been confined largely to England; on the Continent, wood, which was cheaper and allowed much more weathertightness, was the preferred material for windows of that kind. This is not the place to explore the reasons why England should have taken a separate course from the rest of Europe. Suffice it to say that the English persisted in their use of leaded iron casements for the next two centuries despite obvious defects and the criticism of foreign observers [2]. As late as

1660 one of the leading English architects, Sir Roger Pratt (1620–1685), still proclaimed his absolute faith in iron windows when he wrote (probably in connection with Coleshill): "The best material whereof to make great folding casements is that of iron, for there is no sort of timber which can be so well seasoned, but that it will be altered by the weather either as to warping, swelling, cracking, swagging, etc." [3].

Pratt's rather dim view of the suitability of wood for the construction of the opening sections of windows was probably shared by most of his countrymen at the time, but within the next few decades the situation was reversed. The event which caused a change in attitude of the English towards wooden windows was the introduction into English architecture of wooden sliding windows or *shassis* (as they were known at the time) from France during the 1660s. In the hands of the inventive English craftsmen and architects the new window type was soon transformed into what we now know as the *sash-window* [4]. By 1700 sash-windows had already proved their worth in the eyes of a large section of the English population as domestic windows par excellence—their advantages over traditional window forms being hailed as the sign of a modern age of light, comfort and luxury [5].

The growing popularity of sash-windows together with increased importation of foreign timber, especially softwoods, led to a rapid decline in the use of iron casements in all branches of civil architecture during the first half of the eighteenth century. Neither the fact that all-wood sash-windows were considered a potential fire risk (e.g. Building Act 1709) [6] nor the opposition of a small but influential group of aristocrats and *literati* (who associated the demise of leaded iron casements with the breakdown of traditional social values) [7] could stem this advance. The only notable exception was ecclesiastical architecture, where wrought iron frames of relatively simple design replaced the elaborate stone tracery of the past in the new churches built in the classical idiom; but these windows were usually fixed lights and anyway comparatively few churches were built during the period.

If metal windows were to regain anything like their former prominence in English architecture they had to establish a foothold in domestic and public buildings where the standards of taste and excellence were set. To do this the viability of metal as an alternative to wood as the constructional material for windows had to be demonstrated in economic and practical as well as aesthetic terms. This only became feasible when the Industrial Revolution began to provide the technology to overcome the drawbacks of the earlier form of metal window. For example, as a result of technological progress it became possible for complete window frames to be made of metal in rigid profiled sections in a similar fashion to wooden windows, with obvious advantages in terms of weathertightness and durability. Metals also had distinct properties of their own such as incombustibility, superior strength and pliability which gave them important practical and aesthetic advantages over wood, and which could now be exploited to the full.

First Steps towards Industrialisation

Of the various developments which stemmed from the Industrial Revolution three had important consequences for the use of metals in architecture, leading by 1800 to the reappraisal of the structural and decorative potential of such materials in window design. These were, first, the improvement of the quality of known metals such as iron and copper by refinement, and the invention of new ones, especially non-ferrous alloys; secondly, the perfection of the large-scale manufacturing processes which made metals like iron, brass, etc. readily available to the building industry at a reasonable cost; and thirdly, the introduction of new metalworking techniques which allowed the diversification of use of these materials within the industry.

The French seem to have been the first to appreciate fully the enormous potential of the new metallurgical advances for architecture. As early as 1722, in his treatise *L'Art de Convertir de fer forgé en acier et l'art d'adoucir le fer fondu*, the great French scientist René-Antoine Reamur (1683–1757) advocated the mass-production of cheap electroplated decorative iron knobs for doors, knockers, etc. in order to make these elements available to a wider section of the community [8]. About 1750 a Parisian *maître serrurier* by the name of Chopital developed a hot-rolling process for producing profiled iron bar [9]. This water-powered mill, which was the subject of a report by the Académie des Sciences in December 1752 and was illustrated in Diderot's *Encyclopédie* (1765), was apparently the first of its kind developed especially for architectural purposes [10]. It was installed in Chopital's factory at Essonne near Paris and produced sections of no less than eleven different profiles for use as window frames and hand-rails. The bars ranged from 20 to 50 mm in width and were sold in Paris from a certain Bullot's warehouse by 1753. The dealer's catalogue (which must have been one of the first of its kind) also shows a window of about 2 metres high constructed from the iron sections rolled in this mill.

Notwithstanding this early French lead it was in Britain that the industrial base was first developed which made these concepts a commercial reality, and it was here that the most consistent early attempts were made to employ metals for window design. The foundations for the ascendancy of the British iron industry were laid early in the eighteenth century when Abraham Darby I of Coalbrookdale succeeded in substituting coke for charcoal as the fuel for producing iron. Despite this significant innovation the refining sector of the industry appears to have stagnated, which is probably why builders of the period still preferred Swedish iron for better class work [11].

Cast iron was used in England during the first half of the eighteenth century for architectural elements like rails, balusters, etc. but brittleness and poor quality casting rendered it at first unsuitable for use in windows. Wrought iron (which at this stage meant hammered work), was stronger and better standards of finish could be achieved in it, hence the continued use of the material for decorative work, including windows and window grilles (Fig. 1) despite its higher cost. The wrought iron industry was evidently still drawing on the brilliant legacy of combined aesthetic sensibility and technical facility left by the school of Jean Tijou, but throughout much of the century blacksmithery as a craft was in decline. By 1785, when the contents of the Hall of the Worshipful Company of Blacksmiths were sold, the craft was virtually extinct [12]. Henceforth the future of iron in architecture lay with industrial production.

The production of cast-iron is by its very nature an industrial process. Once the casting technique was perfected through the efforts of such manufacturers as the Carron Company (established in 1759 on the River Carron in Scotland), the decorative potential, superior fire resistance and, above all, cheapness of the material pushed cast-iron to the forefront [13] and also led to experiment with it in window design. An unsuccessful attempt was made in 1783 to have some sashes for Inverarary Castle, Argyllshire cast at the Carron Ironworks [14]. In 1790 James Frost, a Norwich carpenter, patented a method for casting bronze and iron sashes "either whole or in parts as may be found necessary, and with mitre joints, compleat both in the mouldings and rabbits intending to hold the glass" [15]. Frost claimed that his method would

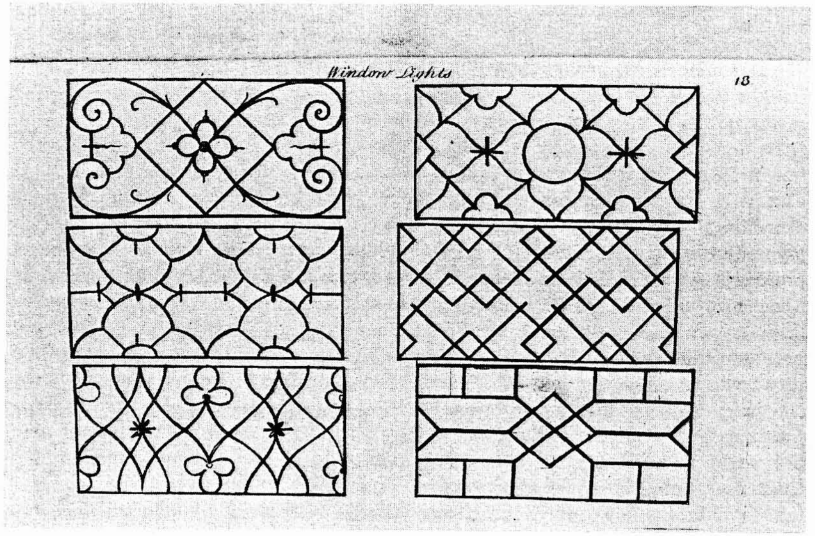

FIG. 1. W. & J. Welldon, Designs for window lights from *The Smith's Right Hand* (1765) (Victoria & Albert Museum).

answer "equally well for large as well as small squares, for gothic or girt windows, hot-house lights, melon or garden frames, fan lights, and for windows of all descriptions".

Alternatives to Cast Iron

However, with some notable exceptions (for example, the cast-iron traceried windows made by the Coalbrookdale Company for St Alkmund's, Shrewsbury in 1795 [16] (Fig. 2)), cast-iron failed to gain a foothold as a suitable constructional material for windows in the eighteenth century other than in relatively restricted categories of use where cost, security and fire resistance were of overriding importance. The prejudice which had built up during the first half of the century against its use for anything other than the simplest utilitarian functions may have been a factor in the delay in applying cast-iron to window design after difficulties with manufacturing processes were resolved. More important, however, was the significant progress made during the latter half of the eighteenth century in the industrial production of wrought iron. This came about mainly as a result of two inventions: the 'potting and stamping' process patented by the Wood brothers in 1761–63, and Henry Cort's 'puddling and rolling' process of 1783, which allowed the large-scale production of wrought iron bar relatively cheaply [17]. Apart from providing the basic-production material neither of these two processes had a direct application in window manufacture, but some of the other patents filed for the working of the metal were aimed specifically at this problem. Only two patents need mentioning here, that for a "machine for making sashes with plate iron" filed by Pegrum Thorpe in November 1763 [18], and William Playfair's patent of May

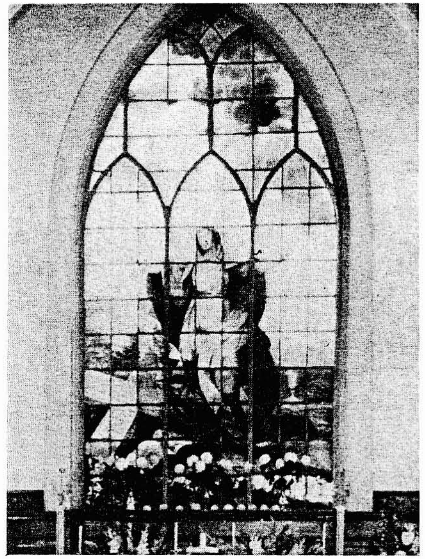

FIG. 2. East window, St Alkmund's, Shrewsbury (1795). The iron frame was cast by the Coalbrookdale Company (Shropshire County Library).

1783 for "making Bars for sash-windows of Copper, Iron or any mixed metal containing Copper", which was based on the cold drawn principle [19] (Fig. 3).

Nothing exactly equivalent to Chopital's hot-rolling mill for window sections appears to have been patented in this country before the nineteenth century (Bailey, 1818). Yet the method was evidently known by the late 1750s and applied to the making of windows, as can be seen from the designs for Gothic windows with profiled iron sections illustrated in William Pain's *The Building Companion and Workman's General Assistant* (1758) (Fig. 4) [20]. Fortunately one such window has survived in a ground floor bedroom at Newhailes House near Musselburgh, Scotland. It is about 2½ metres high and just over 1 metre wide with 16 mm wide ovolo sash bars, and demonstrates both the elegance of design and standards of finish which already could be achieved in mechanised ironwork.

Further evidence that the hot-rolling process was being used in England specifically for the making of metal windows well before 1800, is given by Stebbing Shaw in his *History and Antiquities of Staffordshire* (1798–1801). He quotes an advertisement from a factory, established by the notable industrial chemist James Keir (1735–1820) at Tipton near Birmingham c.1780, which throws much light on this important development:

> Metal sashes for windows—This elegant improvement in architecture, by which the greatest lightness is combined with the greatest strength, is executed here in mouldings made either of a peculiar golden-coloured metal, or wrought iron, which is afterwards to be painted or japanned.... Bars of

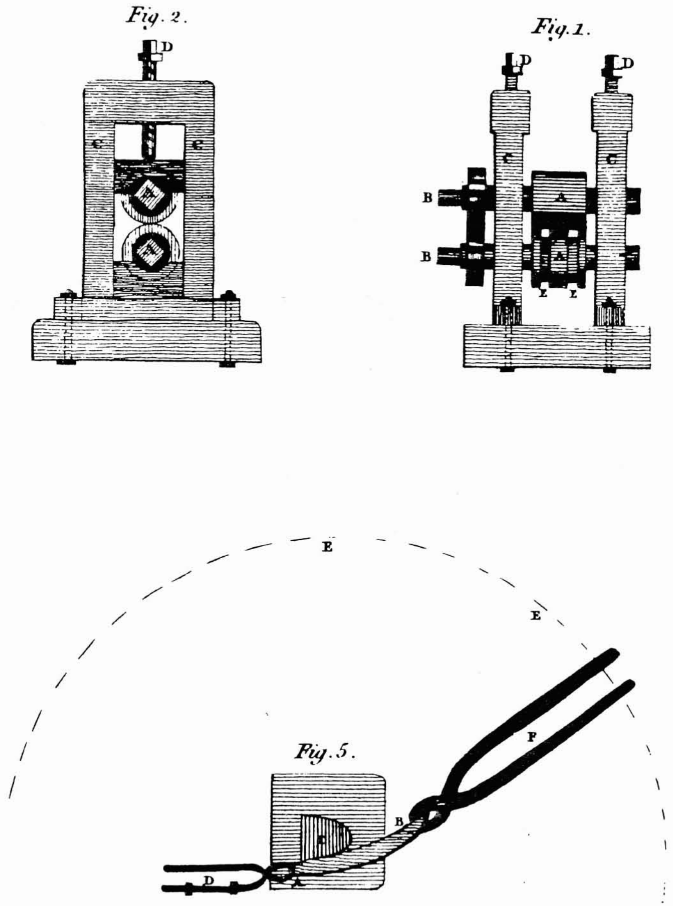

FIG. 3. William Playfair's patent for making bars for sash-windows, etc. (1783) showing the cold drawn process. The rolling mills were used for fender and grate mouldings (Literary and Philosophical Society, Newcastle upon Tyne).

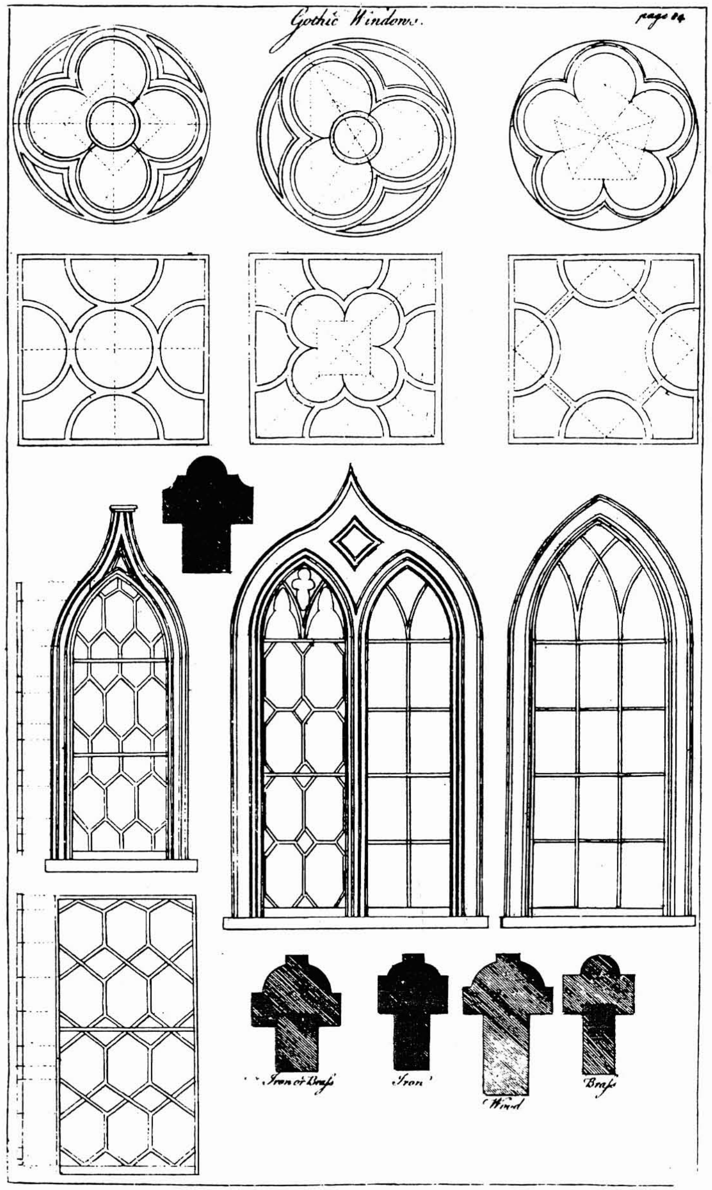

FIG. 4. Designs for Gothic windows in wood, brass and iron from William Pain, *The Building Companion and Workman's General Assistant* (1758) (British Library).

this metal, or of iron, are rolled hot between steel-rollers, in which concavities are so cut and turned, that they give corresponding convex mouldings to the bars as they pass through them.... [21]

The susceptibility of iron (both in its cast and wrought form) to rust has always been a major impediment to its use in windows. Designers therefore readily turned to the higher quality non-ferrous materials such as copper, bronze, and brass when these became more easily available from the 1720s onwards [22]. William Kent had "Brass sashes and frames" installed in the Great Room at 44 Berkeley Square, London, 1742–44. A few years later at Wimborne House, 22 Arlington Street, for the Duke of Newcastle, he again specified "Brass octagon sashes and frames" for some of the first floor windows and "brass sash folding casement and frames" in the attic storey [23]. In the three central windows of the entrance hall at Bank Hall, Warrington (1750), James Gibbs used cupro-iron sash bars in timber frames [24]. The latter windows still exist, but windows of this kind are extremely rare for the period, which is hardly surprising considering their cost. The brass windows installed by Kent at Wimborne House, for instance, cost 6s 6d per square foot at a time when the best quality timber sash-windows came to only 2s 4d [25].

The second half of the eighteenth century saw a much greater diversification in the kinds of metal employed in window frames. The English brass and copper industry, with its centres at Birmingham and London, was expanding rapidly. Increased production brought down the cost of the materials and novel techniques such as stamping, pressing and die-casting opened up new design possibilities [26]. Another factor was advances made in industrial chemistry which led to the refinement of well-known metals and the invention of new ones. Sir William Chambers in 1791 mentions copper being occasionally used for window-sashes [27], but it was the new alloys, or *compound metals* as they were known at the time, which attracted most attention.

In 1774, Francis Underwood, an Ampthill plumber and glazier patented a mixture of tin and lead [28], and a few years later in 1779, James Keir patented his "peculiar golden-coloured metal" (an alloy of copper, zinc, and iron in proportions 100:75:10) [29]. Both materials were employed in the manufacture of windows (see below) and there may have been other variations, for not all inventions were patented at the time. Like iron, these non-ferrous metals at first were worked mainly by the casting and wrought processes. As we have seen, Keir's invention, which was remarkably similar to the well-known Munz metal still in use today, lent itself to being hot-rolled into various shapes. Underwood's patent metal on the other hand, was more suited to being cast and consequently more versatile in its application in window design.

Experiment in the manufacture of metal windows soon progressed beyond the straightforward substitution of new industrial materials for traditional ones. A number of late-eighteenth century patents already provided for a comprehensive system of assembly to exploit the specific properties of the different metals available. The pioneer in this development was Francis Underwood with his invention of 1774. The patent describes the method of assembly as follows.

> The composition of the said frames is block or grain tin, mixed or melted down with lead to any degree of hardness which the work may require; the barrs or mouldings of the angles for the frames are cast solid in moulds of brass or stone, in some of the three following forms, viz: +, T, L, or any other angles the work may require, and the points of the barrs are afterwards burnt together in a reverse mould. The rabitts of the barrs are either of brass, copper, or iron tinned, or in tin plates made in the mouldings before described, and soddered thereto with sodder of the same composition of the mouldings themselves. The points of the mouldings or barrs are let into wood frames, and fastened by the rabbitts with plates and screws or nails, so as not to be seen when glazed and puttied; and the bars for circular, oval, or hemispherical work or figures are cast in angles as afore described, the points curved or afterwards set or bent to the form required. [28]

Underwood's invention signifies an important new departure in the development of the metallic window frame, namely the use of different metals for the various constituent elements of the sash-bar. Unlike Chopital's solid profiled iron bar, all English metal windows of the period consisted of sash-bars composed of two elements, a fillet inserted into a grooved head (see Fig. 4). Up to this time, however, the different components of the frame were always of the same metal. Rapid progress in metal processing technology now opened up new horizons for the production of composite metal bars for windows.

The crucial innovation was the large-scale replacement, from about 1770, of the casting method by cheaper pressing and stamping processes using non-ferrous metals like brass in sheet form [26]. At first cabinet brass foundry (as the industry became known) was restricted to small items for household usage, but the market soon expanded into other areas. Exactly when these new manufacturing processes were first applied to window design is unclear; the earliest surviving examples known to the author are the "composition" windows with flat wrought-iron frames and pressed-metal mouldings of either brass or copper employed by David Stephenson in the Chancel of All Saints' Church, Newcastle-upon-Tyne (1786–89). John Nash used windows with similar frames at Southgate Grove, Middlesex, in 1797 [30]. Compared with the composite sash-bars already in use at the time, John Gregory Hancock's patent of 1795 [31] seems unnecessarily complicated but it provides useful evidence of the freedom given to the metal window designer by the progress of the metal manufacturing industry in the previous 50 years. The refined composite bar system for metal windows had obvious advantages in terms of production costs and flexibility of use and it remained a popular form of construction in the early-nineteenth century despite the problems caused by excessive corrosion [32].

The End of the Century

The increase in the number of patents filed for metal windows during the last quarter of the eighteenth century in England suggests that a market had been created for the commodity. This is confirmed by the sudden appearance in the 1790s of a large number of patterns for fanlights, skylights, and other types of window in metal after almost 30 years of silence. The difference between mid-eighteenth century pattern books like John Jore's *A New Book of Iron Work* (1756) or W. & J. Welldon's *The Smith's Right Hand* (1765) (Fig. 1), and the patterns produced by people like J. Bottomley and I. & J. Taylor during the 1790s (Figs. 5 and 6) is not only one of quality. It is also an indication of the significant shift which had occurred within the metal working trades during the intervening years as a result of what G. M. Trevelyan has called the "new forces of machinery and capitalised industry". Whereas the early pattern books were still following a tradition going back to the sixteenth and seventeenth centuries (i.e. of providing designs for the use of individual craftsmen), those of the late-eighteenth century were, as W. A. Young observed, "prepared by or for manufacturing firms and their object was to promote the sale of the goods illustrated therein" [33]. Within a few years the individually produced designs of Bottomley and the Carters in their turn made way for the fully-fledged published trade catalogue which was to become such an important part of the nineteenth century building industry.

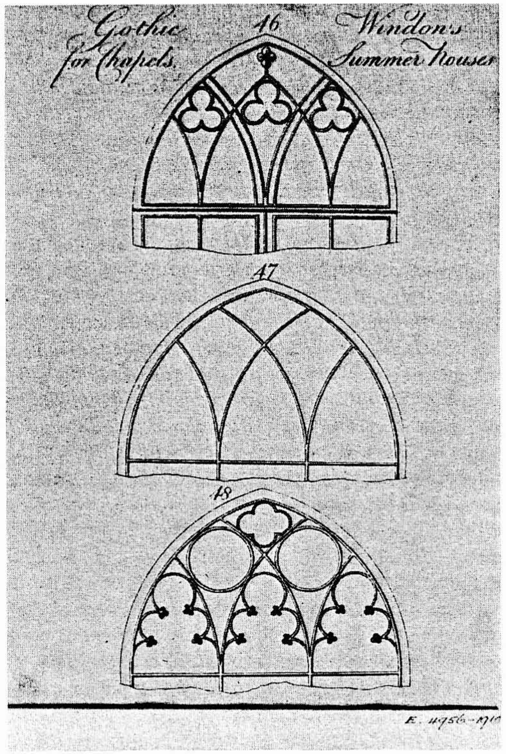

FIG. 5. Gothic windows for chapels and summerhouses from Joseph Bottomley, *A Book of Designs* (1793).

Although the designs of only a small number of the late-eighteenth century metal window manufacturers have come down to us, there were several firms active in this capacity at the time. London was the principal centre for this kind of work and the quality of its products had already impressed Sir William Chambers sufficiently by 1791 to merit a special mention in his treatise on architecture [27]. The Carters were not manufacturers of windows, but a London publishing firm producing designs for others; whereas Joseph Bottomley was a producer as well as seller of metal windows. J. Andrews' *New London Directory* of 1789 lists Bottomley as being in partnership with Francis Underwood; a few years later he had his own 'manufactory' at 42 Wood Street, Cheapside [34]. According to *Holden's Triennial Directory* (2nd edn, 1799) the firm

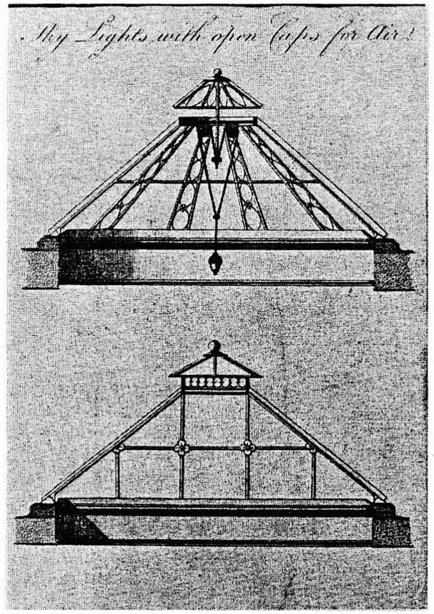

FIG. 6. A wrought iron skylight from Joseph Bottomley, *A Book of Designs* (1793).

was still operating from that address by the end of the century. It is recorded that the architect Robert Mylne had dealings with Francis Underwood in London in 1781–82 in connection with metal sashes for Inveraray Castle [14]. In 1784 the latter's address was given as "No. 38 Poultry, and Paddington" in *Bailey's British Directory or Merchants' and Traders' Companion*. During his brief partnership with Bottomley the firm moved to High Holborn where it remained until the nineteenth century, when it was known as Underwood, Doyle & Underwood.

Outside London the major concern of this nature was that of James Keir, established near Birmingham *c.*1780. By the late 1780s Keir had also opened a warehouse at 18 Gerrard Street, Soho [35]. The 'advertisement' of this company partly quoted above stated that their metal windows had been installed at Windsor Castle, Carlton House and "in many principal houses in the Kingdom" [21]. Sir John Soane's Bill books confirm that this was no idle boast. Between November 1791 and November 1795 James Keir & Co. provided 'Eldorado sashes' for no less than eight of Soane's commissions, all except one in London. The name Eldorado was apparently given to the metal which Keir invented, on account of its golden colour, and although it brought its inventor no commercial success [36], it was taken up by other manufacturers as well; notably James Cruikshank, who *c.*1800 appears to have taken over Keir's business in Gerrard Street, selling "Eldorado metal and wrought iron sashes by patent" [37].

Cruikshank's catalogue in the Soane Museum, dating from about that time, contains about 50 designs. Half of these are for fanlights which are very similar to those of Bottomley and the Carters, which would seem to indicate that the market for this type of window was beginning to stabilise. The collection of patterns in the catalogue (and the slightly later one produced by the Underwoods), however, includes numerous unspecified designs equally suitable for glazed doors or fenestration depending on demand (Figs. 7 and 8). This might suggest that the demand for metal windows at the turn of the century was diversifying as well as growing. Catalogues like these certainly demonstrate the wide range of 'off-the-peg' metal windows that had become available to architects by the end of the eighteenth century. They are also a reminder that it was not only the craftsman whose creative role was being curtailed in the process. An architect like Robert Adam in the 1770s, as a matter of course, would provide his own designs for even the most complicated metal window to be executed by the craftsmen of his choice [38]. His late-eighteenth century counterpart Sir John Soane, however, regularly bought these ready-made from one of a number of wholesaler/manufacturers dealing in the commodity [39].

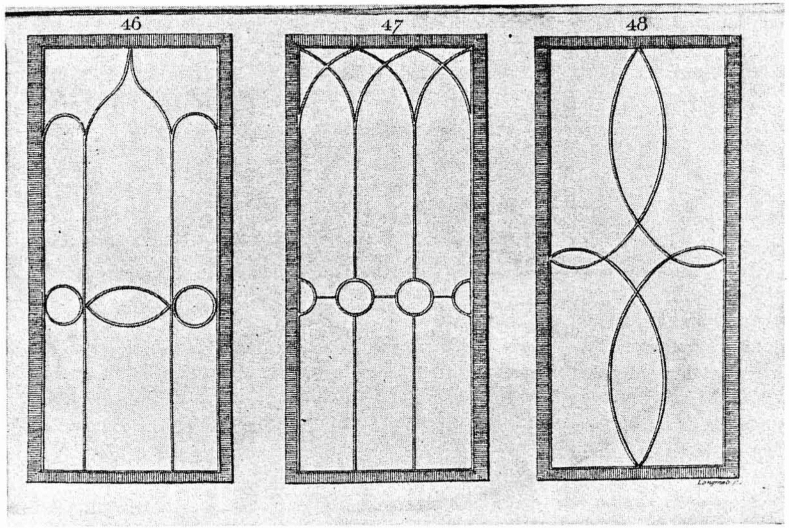

FIG. 7. Designs for metal windows and/or doors by James Cruikshank, *c.*1800 (Soane Museum).

The loss of individual creative freedom brought about by the progressive intrusion of industrial technology and labour practices into the building world was a price which many people at the time were willing to pay in exchange for greater convenience and economy. As one of the principal beneficiaries of the new order, Joseph Bottomley's is hardly an impartial voice in this respect, but the case he made in 1793 for the superiority of the new metal windows over their traditional wooden counterparts is probably a reasonable representation of contemporary thought on the subject:

> The modern improvements in Architecture are so replete with conveniences, elegance, and taste that whoever surveys the edifices, erected a little more

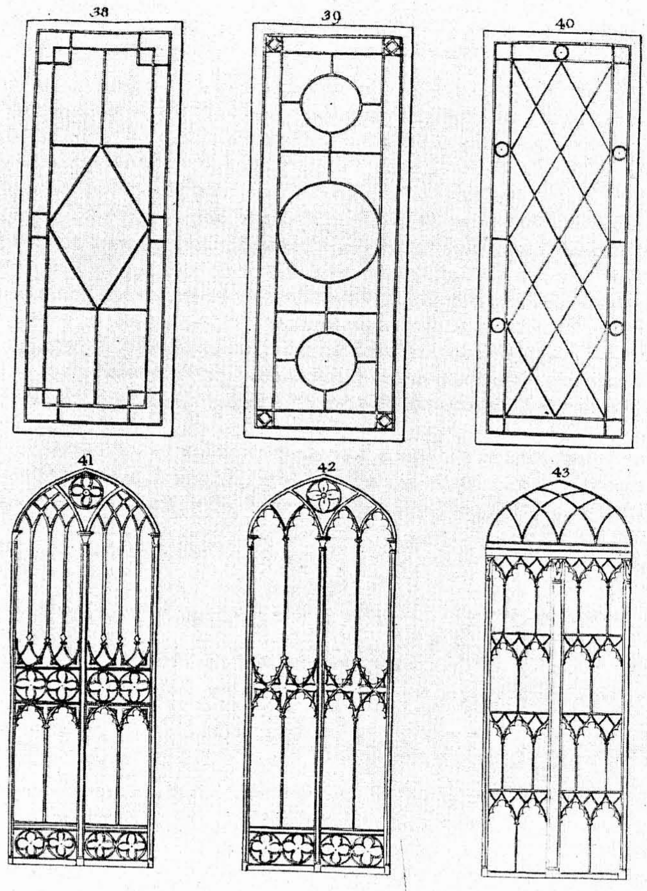

FIG. 8. Designs for metal windows and doors by Underwood, Doyle & Underwood (*c.*1810) (Soane Museum).

> than half a century back, and compares them with those of the present time, must be astonished at the improvements in this science; amongst the advantages those of admitting light, are not the least conspicious[;] the windows, skylights, and fanlights, of the date before mentioned, are so crowded with wood, as to require a space of near double the size of that of the present, to admit the same quantity of light and air. The change now taking place in the materials for sashes, skylights, fanlights, staircases etc from Wood to Metal, has besides the elegance of appearance, the advantages

of strength and extensive durability. The difference of expence in the former and latter is so inconsiderable, as not to be worthy of notice; nay, in many cases, such as curve-lineal and Gothic work, the expense is less in Metal than in wood. [34]

With contemporary accounts such as this supporting the evidence of the considerable number of metal window designs which survived from the period, it is tempting to conclude that metal windows had become a prominent feature of public and domestic architecture by the end of the eighteenth century. However, this was the case only for specific items such as fanlights and skylights. Although metal windows of the kind that manufacturers like Bottomley traded in increasingly came to figure in the works of some of the leading architects like Soane, Nash, and Holland, the vast bulk of windows employed in civil architecture at the time still were wooden sash-windows. The principal reason for this was probably economic. Despite Bottomley's claim that metal windows were no more expensive than their equivalent in wood he was obviously comparing them with the costliest wooden windows available. Furthermore, he neglected to mention that in most cases metal windows still required a wooden frame. For example, the "2 reeded mahogany sashes & frames double hung" (the very top of the range in sash-windows) installed for Soane at Sydney Lodge, Hamble, Hants. in 1789, came to only 2s 10d per square foot complete, while the "Eldorado sashes with circular tops to pattern" which he used at Messrs. Morland & Hammersley at Pall Mall in 1791 were 2s 10d per foot for the metalwork alone, excluding the cased frames and $2\frac{1}{4}$ inch mahogany sashes that added another 2s 0d per foot. It is true that by then the price for metal windows was coming down while the trend for wooden windows was upwards, but in November 1793 Soane was still paying 3s 4d for good quality Eldorado sashes complete with mahogany sliding frames, which is considerably dearer than anything then available in wood. Iron frames of a simple design, on the other hand, could be had for 1s 8d including wooden frames in February 1794; but even this price was only reached three years later by common softwood double-hung sash-windows [40].

There were, however, other reasons why metal windows did not replace wooden sash-windows in the spheres of domestic and public building during the eighteenth century. The increasing emphasis in the latter half of the century on elegance in design, as well as the growing importance of 'light and prospect' in architectural thinking, made the fact that the framework of a window could be manufactured in considerably thinner sections in metal than were possible in timber, a significant selling point in favour of metal. We have already seen how Kent and Gibbs began experimenting with brass windows when they were still exorbitantly expensive. Isaac Ware was also certainly not alone amongst the architects of the 1750s and 1760s to have thought metal windows "a very elegant improvement in the article of windows".

In view of the early recognition of the aesthetic qualities of metal windows amongst the arbiters of taste in architecture, and considering the speed with which th industrial base was built up for large-scale production, the general adoption of metal a a constructional material for windows may well have followed despite its higher initial cost had it not been for another factor. This was the positive way in which the makers of wooden windows responded to the challenge of the burgeoning metal window industry. The sash-window was one of the pillars of the Renaissance of English joinery from the late-seventeenth century, and by the mid-eighteenth century the craft was buoyant, skilful, progressive, and well able to defend itself, as the following quote from Isaac Ware's, *A Complete Body of Architecture* (1756) testifies:

We have of late also fallen into the method of retrenching the wood-work in our frames of sashes, in a very happy manner. Those thick bars we used to employ hurt the eye, and obstructed a great deal of light; they made a large window resemble a number of little ones: the intent is, that as much glass should be seen, and as nearly in a continued body as possible; this broke in upon it.

Our present use of brass, for frames of sashes instead of wood, is a very elegant improvement in the article of windows; but these frames are expensive, and our people, taking the hint from them, have found the way to make them of wood now, with great strength, though no apparent thickness. [41]

A number of factors enabled English joiners to contain the advance of industrialisation with respect to the windows of domestic and prestigious public buildings, principally the greater availability of a variety of good hardwoods and softwoods from abroad, improved woodworking techniques and the popular preference for wood rather than metal as a building material [42]. But in the new sorts of building generated by the industrialising economy—the so-called functional tradition—the joiner had no traditional role, and the conditions for the adoption of metal windows were more favourable.

New Building Types

Fear of fire even more than economic considerations was the reason for the increased use of iron in industrial buildings during the eighteenth century. Just how much the former aspect still was in the forefront of people's minds is shown by the various building acts of the period: from the 1709 Act of Building to that of 1774 the motive power was the need for greater protection from fire. Each act sought to restrict the use of combustible material in buildings to the minimum and limit its use to very specific conditions [43]. These acts did not achieve very much in themselves. In the words of the Associated Architects' report on the causes of fire in buildings (1793), they were "well known to be inefficient, unintelligible and the source of perpetual contention" [44]. Nor did they specifically encourage the use of iron over and above that of non-combustible materials. But they did create an atmosphere conducive to the use of iron—the only really practical non-combustible alternative to timber—the moment when the cost of iron was reduced and it became available in sufficiently large quantities.

Since windows and doors occupy an important position in fire prevention, mainly because they are the principal routes by which fire spreads in and between buildings, it was almost inevitable that sooner or later attempts would be made to replace timber frames with non-combustible iron ones, especially in high fire-risk buildings such as factories, warehouses, arsenals, etc. which had turned to wooden sash-windows in the course of the eighteenth century. Already in 1772, William Cauty in his *Natura Philosophia*, recommended that all timberwork in buildings of the kind in London, be replaced by iron as a safeguard against fire [45]. It is known that by the early 1780s some foundries were casting iron fire-doors and frames [46], but it was only after such spectacular failures as Samuel Wyatt's Albion Mill (built 1783–86 on the banks of the Thames with an internal timber-framed construction, timber doors, and windows, and totally gutted in March 1791 [47]) that more serious attention was paid to proposals like these. During the 1790s several warehouses and mills in London and the midlands were constructed with a high proportion of iron as a structural material, including cast-iron windows, some of which still survive [48]. One of the pioneers in the introduction of iron as a structural material into buildings of the kind was William Strutt of Derby (1756–1836). In 1792–95 he not only introduced iron window frames in his mill at Belper and warehouse at Milford, but also cast in his own foundry all the hardware for the workers' houses accompanying these two buildings, including iron casements with 150 × 100 mm pane sizes (49].

Another type of building which, on the face of it, stood to benefit much from the use of iron instead of timber windows was the greenhouse or conservatory, given that the minimum obstruction to daylight was important in order to achieve the correct internal environment for the cultivation of exotic plants. Despite growing opposition from horticulturalists however these until the end of the eighteenth century remained essentially 'architectural conservatories', adhering to formal architectural ideas (timber sash-windows, stone pilasters or columns, cornices, friezes, etc.) rather than adopting the latest technological knowledge in order to achieve the maximum degree of transparency [50].

France led the way in forging the synthesis between social idealism and rational architectural planning in the eighteenth century, and offered the first evidence of a functional approach to window design in institutional buildings. It took the form of the promotion, by a committee appointed by the Academie des Sciences in 1786, of the use of iron window-frames for future hospital building projects [51]. In England hospitals retained wooden windows until the nineteenth century. The one area in which this country did experience a parallel development to the French one was the architecture of confinement (mental institutions and prisons), where pressure from the humanitarian movement led in some cases to the introduction of glass windows instead of open iron grilles [52]. The attention paid by Samuel Tuke, a Yorkshire Quaker, to the psychological as well as physical well-being of the mental patients in the design of his Retreat at York (inaugurated 1796) was nonetheless exceptional: for reasons of security the building was fitted with cast-iron windows, but these were disguised to suggest a domestic environment. This is how Tuke described the windows in 1813:

> There are two windows in the room [i.e. dayroom], which afford an agreeable view of the country. They are three feet and a half wide by six feet high each containing 48 panes of glass, or 24 in each sash. The frames of the sashes are of cast iron, about one inch and a half square; the glass-bars are about five-eights of an inch thick, and each pane of glass is about six inches and a half by seven and a half. Air is admitted through the windows, by placing the upper cast iron sash, not glazed, immediately over the lower one, and hanging a glazed wooden sash, precisely of the same dimensions, on the outside of the iron frame. In this manner the double sash windows, in general, especially in the patients' apartments, are all effectually secured, without an appearance of any thing more than common sashes with small squares. [53]

Samuel Tuke's use of industrial products for humanitarian ends was a good example of how in the eighteenth century some people were determined to apply the fruits of industrial technology to the greatest social benefit. The movement found its most imaginative, but also its most extreme, expression in Britain in Jeremy Bentham's Panopticon projects of 1788–1816, none of which were built [54]. In these imaginary schemes, developed with the help of his brother Samuel and others, iron windows figured prominently and in some cases, for example the Industry House or Poor-plan Manufactory of 1797, with its continuous bands of horizontal fenestration fully integrated with the structural system, they were prophetic of developments to follow much later.

Early-nineteenth Century: a market established

The Benthams' Industry House was an early product of what J. C. Loudon was later to call the 'School of Reason': those who, like engineers, designed on the basis of "fundamental principles instead of antiquated rules and precedents" [55]. It was not representative of architectural thought or practice at this time. When the later stages of the Napoleonic Wars (1793–1815) led to serious timber shortages, it was in categories of building where architects had least influence, namely industrial and horticultural structures, that metal was adopted on a large scale for window frames [56].

Outside these two classes of building relatively few serious attempts were made during the first quarter of the nineteenth century to extend the use of metal in window design. If Soane's practice is any guide the market for metal windows in the domestic field did not expand as much after 1800, despite the acute shortage of timber caused by the war. Likewise patents for metal windows filed at the time, mostly concern hot-houses, conservatories, shop-windows, etc. [57], although any of the growing number of metal window manufacturers catering for demands in these growth areas would also have been able to make better quality domestic windows to order. One of the firms established during this period, Henry Hope Ltd. (founded by Thomas Clark in Birmingham in 1818), still operates today as Crittall Construction Ltd, the manufacturer of metal windows [58]. Like the others this firm specialised at first in metallic horticultural buildings, but an order for "22 Gothic Head windows with iron rim and flat copper bars" for Lord Arundel at Wardour Park in 1819 shows their willingness also to cater for the luxury domestic market when the opportunity arose [59.).

It is possible that metal glazing bars were used in shop fronts as early as the 1770s [60], but it was only during the 1820s that designers and manufacturers began to pay serious attention to the possibilities which the metal frame offered for display windows. No doubt this development came about as the result of improvements in both the metal window and glassmaking industries. Some of the larger metal window manufacturers like Richard & Jones of Birmingham began to specialise in copper sashes for shop windows [61], and a new generation of designers (e.g. G. Basevi, J. B. Papworth, J. Young) emerged who regularly employed the wide range of metals available on the market to this purpose. By the time that the latter, John Young (*c.*1798–1877) published *A Series of Designs for Shop Fronts, Porticoes and Entrances to Buildings Public and Private* (1828), in which metal windows figured prominently, metal frames had already been established as a permanent part of shop fronts. This development was to receive a further boost during the next decade with the large-scale introduction of plate glass shop fronts [62].

Cast iron was the industrial material which benefited most from the Napoleonic Wars and the new emphasis placed on non-combustible structure. Cast iron also offered the greatest possibilities for widespread application in window design, because it was equally suitable for cheap mass-produced utilitarian work and for fashionable ornamental design. In his *Observations on the Theory and Practice of Landscape Gardening* (1803) Humphrey Repton laid down principles for the use of cast-iron in architecture [63], and leading architects soon began to experiment with it in their buildings. Despite Edward Smirke's claim in 1867 that "no architect employed cast-iron largely as a building material" until it had been introduced by his brother Sir

Robert Smirke [64], the most celebrated uses of the material date from the period before Smirke received his major commissions, with William Porden's Eaton Hall, Cheshire (1804–12), and John Nash's Royal Pavilion, Brighton (1815–20). The former building in particular was renowned for its elaborate Gothic cast-iron traceried windows with bronze sliding sashes. A contemporary tourist guide to the building describes one of these windows as follows.

> . . . the mullions terminate below, at the commencement of the lower sash, intersecting each other in a tasteful manner—they are all of cast iron, which, for minuteness, beats the chisel, and for durability, stone itself—the sashes being formed of bronzed copper, the divisions of the glass are contracted to the advantage of light and prospect. [65]

From Porden's correspondence with the Earl of Grosvenor we know that casting of the iron frames for the windows commenced in 1805. Porden complained bitterly that the designs were being copied by Lord Radnor and warned the Earl not to allow the founder to use the moulds to make "the beauties of Eaton common before it is finished" [66]. The bronze frames for the sashes together with the stained glass were provided between 1807 and 1810 by J. S. Jordan & Co., a Birmingham firm which also, in 1808, supplied the cast-iron traceried windows for nearby Eccleston Church, built after Porden's designs *c.*1806–09 [67]. A later age which thought Porden's cast-ironwork at Eaton Hall "unworthy of Gothic" destroyed these windows. Fortunately the Buckler watercolours of the Eaton Hall interiors, and two of Porden's own designs for the windows survived (Fig. 9) to give some idea of the qualities of the metalwork which was so much admired by contemporaries and emulated at a few more important houses of the period, for example, Alton Towers, Staffs. (*c.*1820).

In view of the early application of the material in church window tracery it is only to be expected that cast-iron would be used again for the purpose when it came into common usage early in the nineteenth century. Porden's Eccleston Church is an early example of this, but the great opportunity for the material to establish itself in the area came with the great building campaign after the Church Building Act of 1818. Economy was a prime consideration and cast-iron was ideal in this respect as was recognised by Sir John Soane who, in his report to the Church Commissioners, April 1818, recommended that "windows should be principally of iron, glazed in small squares in metal" [68]. However, despite this advice neither Soane himself, nor the majority of architects who designed churches during the so-called 'Million Era' used the material for this purpose. Only Thomas Rickman (1776–1841), who had already designed several churches with cast-iron traceried windows for a rich iron-master by the name of John Gragg in 1813–16, employed cast-iron extensively in those churches that he and H. Hutchinson designed for the Commissioners from 1819 onwards [69]. In some cases they even used the same moulds for a succession of buildings in order to keep the costs down (Fig. 10).

Despite these pioneering efforts to exploit the decorative qualities of cast-iron in window design, and notwithstanding the fact that the material was rapidly becoming popular for a whole range of architectural elements (as L. N. Cottingham's *The Smith and Founder's Directory* of 1823–24 testifies) the public remained sceptical of its use for windows other than in utilitarian buildings. However, in situations where economy was the principal factor, the simple cast-iron casement or fixed light, which in particular the Birmingham foundries started to produce in large numbers from the late 1820s onwards, remained the only viable alternative to the ubiquitous wooden sash-

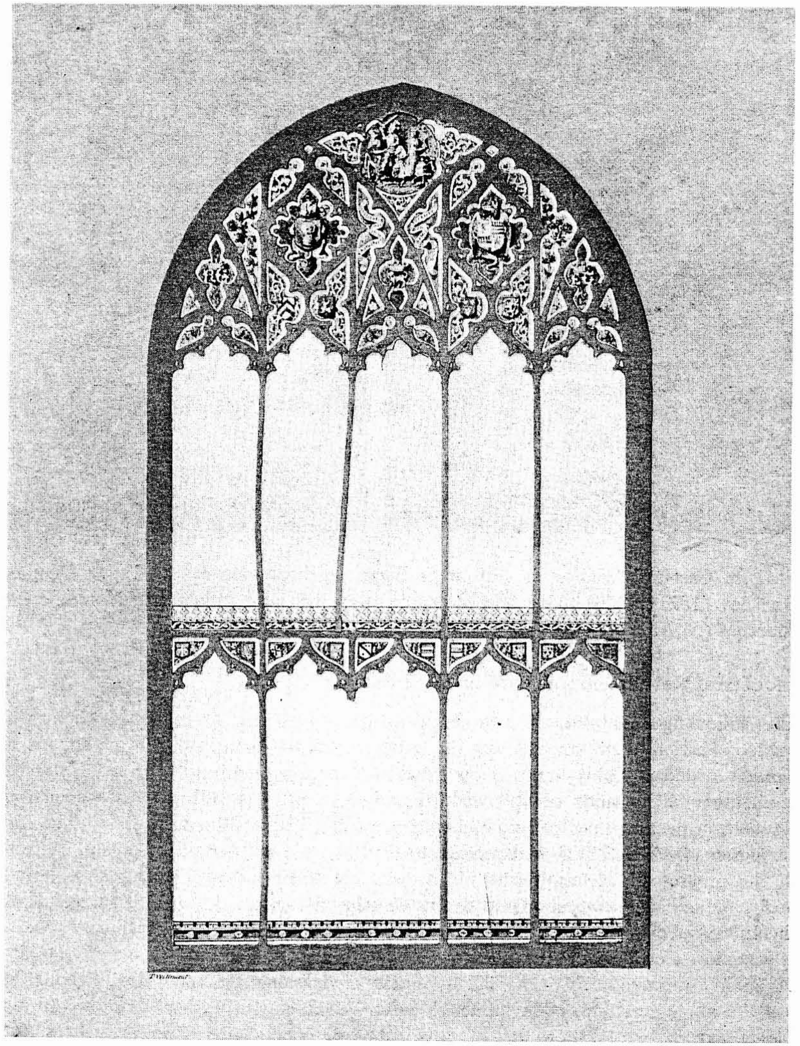

FIG. 9. A paper cut-out pattern for one of the cast-iron and bronze windows in the Library, Eaton Hall (Eaton Hall Archive).

window. It is as much due to these mundane objects of nineteenth century everyday usage as to the more spectacular products of what James Fergusson so aptly called "ferro-vitreous art" that the technology existed a century later when different conditions, and a different climate of opinion, heralded the metal window as the harbinger of the modern style in architecture.

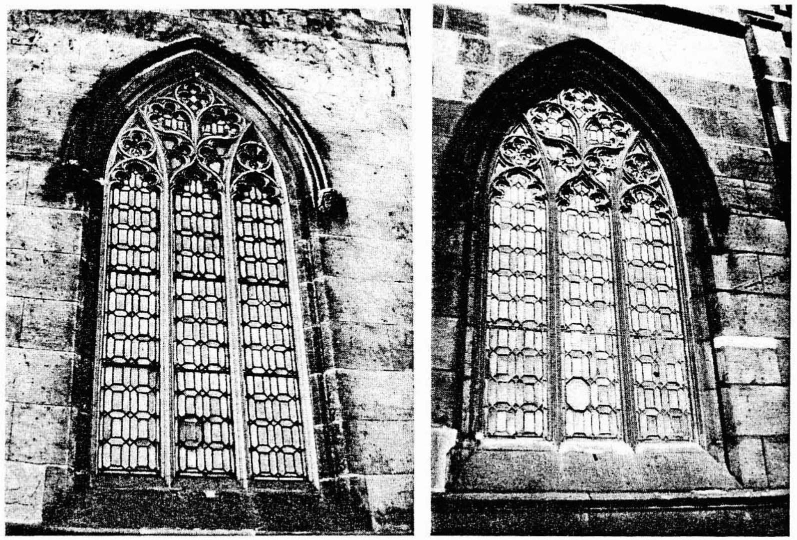

FIG. 10. Cast-iron window tracery at St Barnabas, Erdington (1822–23) St George, Barnsley (1821–22), showing how Rickman used the same moulds for a number of churches (M. H. Port).

Industrial Revolution and Window Production

The following conclusions can now be drawn. First, it is clear that without the industrialisation of the trade during the latter part of the eighteenth century the metal window would probably not have survived into the nineteenth century, such was the momentum of advance of the wooden sash-window. Instead with the Industrial Revolution, we see metal windows firmly established by 1830 within certain specific categories of use in British architecture. Secondly, it is possible to distinguish a pattern in the progressive mechanisation of the metal window industry during this period which by and large corresponds with that in other industries. As with most aspects of the Industrial Revolution in Britain this was neither a systematic nor a linear process. It was more a catalogue of entrepreneurial opportunism riding on the wave of a rapidly expanding industrial economy. Thirdly, our investigations also show that, although it was the single most important influence on the development of metal windows during the period, industralisation was not the only influence. Some other influences, for example, the shortages of timber during the Napoleonic Wars, the campaign for non-combustible construction and the emergent functionalist doctrine, worked in its favour. Other influences like the continuing high cost of quality metalwork, and competition from joiners who had popular and tested products, sash-windows, at their disposal and were determined to protect their livelihood, presented formidable obstacles to the advance of metal windows.

In the final analysis the eighteenth and early-nineteenth century history of metal windows therefore presents a complex picture of the changeover process, within one particular aspect of building technology, from an individualistic craft-based system of

production and distribution to an essentially factory-based one. As the only major building component to which this happened within the compass of the Industrial Revolution, metal windows offers the student of industrialisation and its impact on architecture a unique opportunity to observe this phenomenon at its very origin.

Correspondence: H. J. Louw, School of Architecture, University of Newcastle-upon-Tyne, Newcastle-upon-Tyne NE1 7RU, Great Britain.

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Innovation in Structural Theory in the Nineteenth Century*

T. M. CHARLTON

At the beginning of the nineteenth century the state of knowledge was such that theory of structures was ripe for rapid development. This was due, for example, to the work of the Bernoullis, Euler and Coulomb. Thus elementary statics was being applied to masonry arches and timberwork and the elastic theory of bending of beams (still in common use) had been determined. The principle of virtual velocities (nowadays termed virtual work), of ancient origin, was available as a powerful aid in the application of statics. Construction for which statics was insufficient, in that supplementary conditions relating to elastic deflexions had to be introduced for precise analysis, though not uncommon was not understood. For this reason calculations were approximate. Included in this category were the *encastré* timber beam and the beam supported at intermediate points as well as at each end (the continuous beam). The former was acknowledged, notably by Robison before 1800, to be twice as strong as the same beam simply supported at its ends; the latter was probably regarded as a succession of *encastré* spans for estimating its strength. Timber framework was used at that time for bridge and roof trusses using design principles established by practice over the years [1].

Rapid development of theory of structures in the nineteenth century was undoubtedly stimulated by the emergence of the railway era and metal construction. However, some major advances were premature and probably due to the keenness of individuals. In this respect the Frenchman C. L. M. Navier (1785–1837) affords an outstanding example [2]. Thus the value of his general method of finding the forces in the bars of loaded frameworks, including those with bars or elements supernumary to the needs of statics, was not widely recognised for more than a century. But his theory of *encastré* and continuous beams was soon accepted. It was used to great advantage in Britain, notably by Brunel and Robert Stephenson through their assistants, Bell and Wild respectively, who were made aware of it by Moseley [3]. That theory was, perhaps, the principal advance in relation to engineering practice before 1850 and was refined subsequently. It is an example of the theory of statically-indeterminate structures based on the assumption of elasticity (the elastic theory) with which much innovation in the nineteenth century was concerned.

The nature of structural forms over the years had been dictated by the available materials of construction and their properties. The arch and pillar which utilise the

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