TECHNOLOGICAL ASPECTS OF EARLY ENGLISH IRON ARCHITECTURE

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From 1780 to mid 1840's the textile mill played a key role in stimulating the structural use of iron, the seminal building material of the 19th century. Whilst other fields contributed by progressively more adventurous use of the new material no where else was iron as generally applied or as systematically investigated. After the third decade of the century the railway made a greater impact, at first relying heavily on the accumulated experience of the textile mill builders but growingly responsible for independant advances. By the 1860's textile mill design was still evolving but the scale of the challenge it presented was less than that of the railway from which it increasingly received technology.
The development of the first generation of textile mills with iron framed interiors has been adequately covered by previous writers(1). For this reason I will summarise only briefly the period up to 1805. The most important influence upon the structural character of the textile mill was the risk of fire. That no manufacturing process was immune from this hazard had been amply demonstrated in 1791 when the Albion Corn Mill was destroyed, but that section of the textile industry based upon plant fibres was particularly vulnerable. As the scale and capitalisation of factory building increased so accordingly did the losses suffered. Against this background the first steps were taken to introduce less combustible materials into factory construction.

The initial innovations were those of Wm.Strutt and were incorporated into a factory and a warehouse of 1792 and 1793 at Milford and Derby in Derbyshire. The use of timber was retained for the principal floor beams but bridging joists and floorboards were replaced by segmental brick arches springing from skewbacks mounted on the lower edges of the beams. The skewbacks were encased in sheet iron and the exposed undersides of the beams were plastered to render them flame resistant. The spandrels of the arches were filled with sand upon which the floor surface of brick tiles was laid. The beams were intermediately supported by two rows of cruciform section cast iron columns.
A more radical departure from traditional textile mill construction took place in 1796 with the erection of the Castle Foregate Flax Mill, Shewsbury, for the Leeds based flax spinning partnership of Marshall and Benyon. Marshall's interests were primarily centered upon Leeds but the Benyon brothers had an existing woollen business in Shewsbury. This and the local tradition of linen manufacture prompted the construction of the new mill. The design for the building was undertaken by Charles Bage who was also included in the partnership. Benyon's desire for a building which would be relatively resistant to fire almost certainly resulted from the loss of the Leeds B Mill which was destroyed in February, 1796. Surviving correspondence indicates that Bage's efforts to achieve this object were in part inspired by Strutt's work but the central idea to use cast iron beams was Bage's alone, although he may have been influenced by the highly innovatory local iron industry. The mill was complete by 1797. It is fully described in Skempton and Johnson's article in the 'Architectural Revue' for March 1962, so more than a brief outline of its form is not necessary. The main body of the mill measures externally 177' 3" by 39'6". Internally the width is 36' whilst the length is divided with one or two exceptions into bays of 10'6" by brick arches springing from cast iron beams. The cross sectional

profile of the beams reflects Strutt's work. At mid span they comprise a seven inch web tapering in thickness from one and one eighth at the upper edge to 1 1/2" at the point where it is supplanted by a triangular prism which expands the section width to 5" at the base. Its form is clearly derived from the beams used by Strutt at Belper. The beams were cast in two lengths and bolted together on the centre line of the building. The section varies in depth from 7" at the walls through 11" at mid span to 10" at the point over the columns, where negative bending moments are incurred by the continuous nature of the beam. To obviate the use of timber in the roof a similar system of brick arches springing from cast iron beams was employed. Upon these were set the roof slates giving the roof a saw tooth outline.
The Castle Foregate Mill was followed in 1799 by the construction of the Salford Twist Mill by George Lee. This mill Wm. Fairbairn mistakenly (2) assumed to be the first fire proof mill and it is he who was responsible for attributing the authorship to Boulton and Watt. A.J. Pacey in an article in the 'Architectural Journal' (3) argues that this was not the case and that Fairbairn's opinion had been wrongly formed around drawings in the Boulton and Watt collection, which related only to Boulton and Watts contribution to the new mill, that is to say the steam engine and the gas plant. These Pacey maintains were prepared from sketches by Lee who was in fact personally responsible for the design of the fabric of the mill. Further confusion arises over the form of the beams. Skempton and Johnson proposed that here for the first time the inverted T cross section was used. The first plan considered was for beams with a span of 12' 10" and a cross sectional profile derived from that which Bage had used at Shewsbury. This view they based upon a drawing in the Boulton and Watt collection of 1799.
A later drawing by Creighton, Boulton and Watt's draughtsman shows the building in 1801 nearing completion, with the iron work in place awaiting the brick arches. Done at Lee's request this is a perspective view taken from a previously measured cross section of the mill. The cross section shows the beams to span 14', implying a revision of the plans during the intervening period. The maximum depth of the beams had also altered from 11" to 13" and Skempton and Johnson assumed that this alteration also embraced the new cross section. The Boulton and Watt drawings unfortunately do not show the cross section and the authors have to accept Fairbairns version of this.

Pacey disagrees and suggests that Fairbairn mistook what was in fact the section originally proposed for a developed inverted T section of the type to which he would have become accustomed through his own work. In Pacey's view the design of the beams was unconnected with Boulton and Watt and was instead based upon Lee's contacts with Bage and upon Bage's mill. The design evolved by Lee following these consultations differed from the originals only in the addition of a small lip added to the base to assist the skewbacks in supporting the arches, the design which Skempton and Johnson suggested was rejected in favour of the inverted T section. Pacey sees Fairbairn's misapprehension arising from a visual inspection which failed to reveal that the arches concealed skewbacks. Fairbairn's contribution is shadowed by further doubts. The cross section of the mill whilst evidently based upon the revised width of 42' shows three beams each spanning 14'. Creighton's drawing on the other hand indicates only two beams joined, as was the case at Shrewsbury along the centre line of the mill.

Whatever the case may be regarding the beams the columns represent a definite innovation. The cruciform cross section which had previously been utilised, both in the fire proof mills descussed above, and elsewhere, was replaced by hollow cylindrical columns (4). It seems that at least part of the motivation for this change was related to the desire to heat the mill by passing steam through them, to which end flanged connections for a steam main were incorporated into the ground floor castings.
The eventual fate of this mill is also subject to conflicting accounts. Skempton and Johnson believed that it had been destroyed by war-time bombing but Turpin Bannister refers to an account in the 'Builder' of 1845 (5) which implied that it was demolished following the failure of the cast iron roof in that year. It might be added that if this were the case Fairbairn could not have examined the building at the time "Application of the use of Wrought and Cast Iron to Building Purposes" was written (1854), and nor could he make the claim,as he does,that the building was "eminently successful". It is possible therefore that Fairbairn in all innocence had examined the wrong building.
For the third of this pioneer group of mills we return to Marshall and Benyon's partnership. Between 1802 and 1804 the partners decided to separate and to achieve this Marshall purchased from Benyon his share of the concern. With capital derived from this transaction Benyon erected a mill of his own in nearby Meadow Lane, Leeds. Bage was again the designer. In this building the form of the beams that the fire-proof mill was to embody for the next thirty years was fully established. They were simply supported at the walls and over the column tops, and coupled by wrought iron shrink rings embracing horizontal spigots cast onto the side of the beam ends. Thus the negative bending moments, to which the design of the beam was totally unsuited and which occured with the earlier forms of beam, was avoided. The cross sectional profile ceased to embody the skewbacks and relied solely upon the bottom flange to support the arches. The web which was 11" deep had a thickness of 1", and the bottom flange was 4" wide by 1" deep. Each beam seems to have spanned 12' and intermediate support consisted of three rows of pillars of cruciform cross section. The brick arches divided the length into 10' bays. It is likely that this mill had a cast iron roof for Bage was known to have been experimenting previously with a 38' span truss. If this was so the Meadow Lane Mill was the first to resort to this device.

Built concurrently with Meadow Lane Mill was a further mill for Benyons at Shrewsbury. Little is known of this building apart from the external dimensions, for it was demolished at the end of the 19th century. It seems to have been fire proof and it is reasonable to suppose that it shared characteristics with the Meadow Lane Mill for once more Bage was the designer. He is also thought to have colluded with Strutt in the reconstruction of the Belper North Mill after the fire of 1803 had destroyed the 1786 building. This mill is widely known from the illustration in 'Rees Cyclopedia' which was taken from a drawing by John Farey Jnr. Strutt does not appear to have played any further role in structural innovation after his initial contributions, although his frequent correspondence with Bage make it probable that he was influential in stimulating Bage's developing idea's.
Bage's association with the design of the mills hitherto described is well attested. The identity of subsequent mill builders is more obscure. In discussing the Salford Twist Mill it was pointed out that here for the first time a fresh influence outside the Strutt Bage circle appeared. It was also noted that this mill had at least one and possible two novel features in its structural engineering.

Of the two mills which will now be discussed Armley Mills at Leeds was without doubt heavily influenced by Lee's work and it may equally be the case with the Houldsworth Mill, Glasgow. The two were built virtually simultaneously.
In 1970 the condition of the Glasgow Mill was such as to necessitate demolition. Scottish Ancient Monuments took the opportunity to survey the building over the period that it was dismantled and the results of this work were published in "Post Mediaeval Archaeology" four years later (6).The following details are taken from that survey.
The now usual arched floor was supported by T section cast iron beams spanning the 38' 9" internal width with three castings. Intermediate support consisted of two rows of cylindrical cast iron columns. The beam ends at the junctions embraced the columns and were united by a split ring on the upper surface of the beams rather than at the sides. In this it followed the practice established at Meadow Lane, rather than Belper North (7). The beam section at mid span had a total depth of 15 1/2" which was reduced to 9" at the points of support. The web had a thickness of 1" and the flange which was chamfered on the under edge had a width of 4" and a depth of 1 1/2" over the central 2" diminishing to 1/2 inch at the edges. Tie bars were installed between the beams to counter the residual stresses from the arches. They were less effectively positioned than those at Meadow Lane. The attempt to conceal them within the brick arch although intended as a protective measure raised them above the point of maximum advantage.

The roof trusses which were of cast iron were thought to have been a later addition but in fact they have much in common with other examples of the period and were I suspect original.
Armley Mill near Leeds is in terms of its structural content one of the most remarkable buildings in the country (8). Its development was such that by 1830 it contained with the exception of the Tredgold beam section, every type of general form of beam and column hitherto employed in the textile mill. It was as far as is known the first mill in the wool textile industry tu utilise fire proof construction, and with the demolition of the Houldsworth Mill is now the oldest standing mill building with hollow cylindrical cast iron columns.
The early history of the mill cannot be dwelt upon here, but by 1788 it was the largest fulling mill in the country and possessed one of the most advantageous water power sites in the area. These factors attracted Benjamin Gott who had pioneered the factory woollen industry at his Bean Ing Mill near the centre of Leeds. He had begun the transaction to purchase Armley Mill in 1804 but before it was complete a fire destroyed the main building. The attractions of the site were such that he had no hesitation in rebuilding. He was a close friend of Lee and the new mill was heavily indebted to the Salford Twist Mill. The cylindrical columns were modelled upon Lee's and had identical facilities for the provision of steam heating in addition to their structural role.

Because of conflicting views of the beams in the Salford Twist Mill it is not possible to say whether the Armley beams were a development of them. The continuous form of the beams at the Salford Twist Mill which Creighton depicted were certainly not followed. The beams at Armley were simply supported over the columns and the longitudinal profile reflects this fact. The junction over the columns is achieved by side mounted shrink rings and in this the progenitor may have been the nearby Meadow Lane Mill of which Gott was doubtless aware. Again because of the confusion of the cross sectional form of the beams at the Salford Twist Mill the derivation of the Armley beams is unclear. If at Salford they were of the inverted T section then both the form and the dimensions correspond. For the Salford Twist Mill, Fairbairn gives the web as having a depth of 12" and a uniform thickness of 1 1/4" whilst the bottom flange measures 3 1/4" x 1 1/4". The Armley beams are almost identical. The bottom flange varies between 3 1/4" and 3" wide with a depth of between 1" and 3/4". The web which is 9" deep at the point of support is 12" deep at mid span having a 3/4" thickness at its upper edge increasing to 1 1/8" at the junction with the flange. The three spans vary to accomodate the mule gate. two are of 11' and one of 8'. Cast into the flange are bolting faced to carry the drive shafting to the machines. These are obviously inspired by the practice of attaching the line shafting by coach bolts to the underside of the timber beams in non fire proof mills (9).

The three lower floors are supported by two rows of hollow cylindrical cast iron columns with a mean diameter of 6 5/8" on the ground floor where the free standing height is 11' 3" and a diameter of 5 1/4" to 5 1/2" on the upper two floors where the free standing height is 9' 6". The metal thickness is 1/2" in all cases. The roof is of timber queen post trusses. Detailed coverage of Armley Mill between 1805 and 1825 for reasons of brevity will not be undertaken. Even so two particular features of the structure warrant inclusion in this account. In about 1810 the corn mill which had occupied one wing of the building was dismantled and the floors, in order that the building should be reusable for the woollen trade, had to be replaced. The ground floor which would have necessitated the most urgent treatment seems to have been rebuilt immediately. Whilst cast iron beams of a T section were employed, the floor was of stone flags rather than brick arches. To support the flags the beams were installed flange uppermost. The columns are also curiously atavistic compared with those employed in the main mill. In the corn mill the older cruciform section was adopted. The beams couple over the columns but by intervening lead packing between the bolting faces to accommodate movement.

Before leaving the subject of Armley Mill the roof of the drying house is worth comment. This seems to have been erected between 1809 and 1810. A sinuous cast iron structure it is typical of the iron roofs of the period before the cast iron arch established itself as the most acceptable form. The activities of Gott and Benyon seemed to have acted as a stimulus to Leeds factory builders to adopt fire construction. This and the location of most of the Leeds textile mills away from the areas of later urban development has left Leeds with a higher concentration of pioneer structural iron work than probably anywhere else in the country.

In 1808 Marshall (10) now unassociated with Benyon began to extend his premises by the construction of a warehouse and a flax drying shed. The warehouse was structurally similar to the Meadow Lane Mill. The drying house was more original. Solid cylindrical columns supported a cast iron plate which ran down the centre of the building. This plate was of uniform depth and thickness, 9" x 1 1/8" respectively and was entirely devoid of a bottom flange (11). To this was bolted T section cast iron beams with their flanges uppermost. This frame supported a cast iron chequer plate floor, by which means heat from steam pipes in the ground floor could pass upwards through the building.

This range of buildings was extended in 1817 by the addition of a mechanics shop. The solid cylindrical columns are repeated but the beams which support a brick arched floor although of the usual inverted T section have a web of uniform depth and thus appear to pay no regard to the development of the bending moment over the span.

The roof is fire proof and is one of the earliest examples that I have encountered of the use of wrought iron tension cords to resist the tendency to outward displacement that occurs at the foot of the cast iron principle rafters.

The mechanics shop was followed in the same year by a further and much larger building. Inexplicably Marshall reverts to cruciform cast iron columns (12) and equally anachronistic the drive shafting, like that at Armley Mills was bolted to the cast iron beams. It may be that only the accidents of survival give the impression that this mill was somewhat conservation in its design. In nearby Otley Mill built about 1815 cruciform columns were also applied to support timber floor beams. Even so the line shafting is suspended from bolting faces on the column itself, a position which was to be conventional subsequently. Twenty years later Hollins Mill in Bradford was constructed with columns which made concessions to both forms. The solid cylindrical core is braced by four ribs which have a pronounced entasis. In 1827 identical columns were installed at Providence Mill, Brighouse.

Between 1827 and 1830 Marshall continued to extend his mills. The structural system he employed was unexceptional for the period but the cast iron roof is noteworthy. It dates from 1830 and covered the mill of that year and an earlier one of 1837 which ran at right angles to it. Each truss is composed of three principal castings which are bolted together. The strength of the frame is mainly derived from the near arch form of the lower booms.

The cast iron arch form of roof enjoyed some popularity until the 1840's. Baines in his 'History of the Cotton Manufacture of Gt. Britain' published, in 1835, illustrates such a roof and clearly shows its peculiar advantage for mule spinning. An identical roof to that illustrated survives in Halifax at the Mill built for James Akroyd in 1828. So great is the similarity between the two that I suspect they emanate from the same builder. An earlier variant of this form survives in Manchester at Bee Hive Mill in Ancoats. The load bearing function is preformed by cast iron arch but the principal rafters are of wood held in place by brackets cast into the arch and supported by a vertical cast iron predestal at the ridge. In all three cases the outward thrust of the arch at the spring line appears to be restrained by the cast iron floor beams which would entail, amongst other things, a direct tensile stress upon the beams unless there are concealed wrought iron tie rods.

The cast iron roof at Carr Mills, Leeds of about 1825 performs no attic role but simply bridges the top floor. Here the ties are visible and consist of rectangular section wrought iron bars suspended at the centre from the ridge casting by a vertical wrought iron bolt.

Generally speaking the design of the fire proof textile mill had stabilised by the 1830's but this is not to say that the cast iron T section beam and the brick arch held sway absolutely. In some instances flagged floors were preferred supported by cast iron beams and cast iron bridging joists. This type of floor was used as early as 1816 in a section of the Forge building at Woolwich Dockyard designed by John Rennie Jnr. Two examples survived until recently in Yorkshire but now only one remains. Pildacre Mill near Ossett was surveyed by John Goodchild prior to its demolition and is sufficiently close in structural character to Carr Mills, the other example, to warrant the assumption that the same engineer was responsible. The roof of Carr Mill described above was identical to that of Pildacre Mill. The floor structure differed only in that at Pildacre its width necessitated the inter-position of columns whilst at Carr Mill the beams are of single span. The parabolic profile of the web in both cases necessitated projecting lugs to receive the cast iron bridging joists upon which the flag stones of the floor rested. A uniform surface for the reception of a flagged floor was attained in a different way at Bee Hive Mills where the web was inverted in a manner which resembles that alluded to earlier in connection with Armley Mills.

This example and those quoted earlier in connection with the 1808 and 1817 Marshall Mills serves to illustrate the fact that the design of cast iron was not always in accord with the tasks it was called upon to peform. The extent to which the application of cast iron was supported by a scientific understanding of its nature devolves into the related question of how far had theoretical investigations kept pace with practice, and assuming the availability of theory how readily was it transmitted to the engineers and architects working in the field. Skempton (13) has shown that Charles Bage had experimented with both columns and beams and was conversant with similar work on cast iron carried out at Ketley. Two problems faced him at Shrewsbury. He was dealing with a new material and had only general theories for the most part derived from work on timber and stone to draw upon. Secondly he needed to be able to predict theoretically the behaviour of a non rectangular section unlike anything that had been investigated before.

Resorting, as had traditionally been done in England, to the Galilean Notion of the location of the neutral axis at the concave surface of a beam deflected by a load, he adopted the form $M=k.1/2BD^2$. This assumed that in a brittle material only tensile stresses exist and that they are uniformly distributed over the full cross section as would be the case in a figure subjected to a purely tensile load. K is a constant related to the tensile strength of the material. The case of the inverted T section was then considered. He assumed that the tensile force was mobilised only in the flange, but generated a moment about the top of the web, and produced the form $M = k.A.\bar{y}$, where A was the area of the flange and $\bar{y}$ the distance of its centre of gravity from the top of the web. With data acquired from experiments on rectangular cast iron beams he derived the relationship: -

$$W = 14.5. \frac{bd^2}{l} \quad \text{for a rectangular beam}$$

$$W = 29. \frac{A.\bar{y}}{l} \quad \text{for a flanged beam.}$$

The constant k was equal to 7.2 tons per sq.inch. He subsequently tested to destruction beams intended for use and found the results closely aligned with those he had predicted. His theory does not appear to have gained general currency and never achieved a status of publication.

Bage was not the first to investigate the behaviour of cast iron under load, for as Skempton points out in discussing Bage's theory, Banks had previously considered the question of cast iron engine beams and deduced rules accordingly. The growing dissemination of cast iron in building construction and elsewhere drew the attention of several subsequent investigators amongst whom were Peter Barlow and Thomas Tredgold. Tredgolds "Practical Essay on the Strength of Cast Iron" appeared in 1822, and was the outcome of a series of experiments which he had carried out on the new material. As a result of these he proposed a revised cross section symmetrical about its y axis with top and bottom flanges of equal shape and area. In so doing he failed to appreciate that unlike timber with which he had considerable previous experience, the properties of cast iron

differ in response to compressional and tensile stresses. Although his publication was widely known there is little evidence that the section he proposed was adopted on any scale.

Until the 1830's the form of beam most generally adopted remained substantially that discussed earlier. How much it owed to theory and how much to purely evolutionary development after Bage's contribution it is difficult to say. In contrast the next major advance in the theoretical understanding of cast iron was ultimately to have a profound effect upon beam design and indeed upon all areas where cast iron was in use.

In 1830 the Manchester Literary and Philosophical Society published Eaton Hodgkinson's "Theoretical and Experimental Researches to Ascertain the Strength and Best Forms of Iron Beams". This was to be the fundamental basis of all subsequent 19th century cast iron design and contained relevant comments upon wrought iron. Eight years before he had published a paper, on "The Transverse Strength of Material", which resulted from investigations carried out at the suggestion of his tutor, John Dalton. Partly it was a review of existing published work and reflected the opportunity which his association with Dalton had provided to familiarise himself with continental work on the strength of materials. In it he noted and corrected Peter Barlow's earlier misinterpretations of the moments of tensile and compressive stresses. By experiment he concluded that tensile and compressive strains were equal only for equal stresses. Barlow following the work of Duleau had erroneously assumed that the moments of these forces about the neutral axis were equal. Concomitantly Hodgkinson also recognised the correct position of the neutral axis and its coincidence with the centroid of the section.

Subsequent to the publication of this paper in 1824 his attention turned increasingly to cast iron. His early experiments carried out at Hatton foundry near his Salford home centred upon the extensive and compressional forces generated in a cast iron specimen and their relationship to fracture. A cast iron plate with a single rib on one side was cantilevered out from a support and alternately loaded with the rib uppermost and then reversed. From the behaviour of this specimen he observed that equal forces led to equal extensions and compressions, a conclusion that had previously been reached by Tredgold but without experimental verification. It was this that had persuaded Tredgold to propose the ideal beam section as having equal flanges and, a neutral axis as a consequence located half way up the section. Tredgold had failed to realise that this embodied a further assumption that cast iron behaved equally as a response to compressional and tensile stresses. By his experiments Hodgkinson was aware that this was not the case. Hodgkinson's work had been closely followed by the eminent Manchester engineer, Peter Ewart, and realising the importance of it he induced the firm of Fairbairn and Lillie to accomodate and avail their testing facilities to him.

Euqipped with the best available resources and freed of financial constraints he began the series of experiments which led in 1830 to his second submission to the Manchester Literary and Philosophical Society, the paper mentioned above. It constitutes a clearly defined turning point in the history of cast iron. He begins by discussing the general case of a loaded cantilever. With a clear but unstated recognition of Hookes Law he defines the neutral axis and gives formula as both for its determination and for assessing the strength of such a beam. The bulk of the paper concerns the experiments conducted at Fairbairn and Lillie's works with the lever testing machine which Fairbairn had devised for proofing his own beams. With a pattern of eliptical elevation and Tredgold's cross section, a trial beam was cast and tested to destruction. A series of castings followed from the same basic pattern in each of which the distribution of metal was altered in favour of the bottom flange until the final specimen underwent failure by the ejection of a wedge shaped piece of the web. At this point the ratio of the bottom flange to the top flange was 6 to 1. The new section represented a 25 % saving in metal for the same strength and hence reduced both the self weight and the cost. To compute the strength of a beam of this form he discarded the elastic criteria with which he had prefaced the paper and relied instead upon a formula based upon ultimate strength and closely akin to that which Bage used. The strength of the beam was assumed to vary directly with the area of the bottom flange (a) and as of the total depth at mid span (d) $W = \frac{cad}{l}$

In such a case the whole of the tensile force was assumed to be mobilised in the bottom flange and the compressionable forces entirely above that point. Hence the neutral axis would be located as closely as practicable to the bottom flange. The co-efficient c was derived from his experimental results or rather two co-efficients were presented, one based upon the failure of beams cast on their sides, 514 cwt, the other for beams cast erect with the bottom flange uppermost, 536 cwt. In tons c is thus 25 or 26 depending upon the particular case. Later comments concern the longitudinal profile of the web and flanges. He distinguishes between the application of the eliptical and parabolic functions and decides that for beams of his particular cross section uniformly distributed loads require a profile somewhere between the two. For a point load the profile will be triangular. In conclusion he drew attention to the beams hitherto adopted by Fairbairn and Lillie and points out that they although of the conventional section offered greater resistance to fracture than those proposed by Tredgold as an improvement upon them.
The successful application of Hodgkinsons work on beams owed much to the close relationship with Wm. Fairbairn whose reputation as a mill builder was already well established by the mid. 1820's. Fairbairns career warrants a much more critical examination than it has hitherto received. His achievements as a mechanical and civil engineer are well known not least as a result of his own literary efforts. Most accounts of his life have been taken from the partially autobiographical "Life of Sir.Wm.Fairbairn" which was completed by Wm.Pole after Fairbairns death in 1877. Fairbairns book "Mills and Millwork" first published in 1861 has also been extensively used as a source. Understandably neither of these is wholely objective. Both advanced claims which are difficult to substantiate and both are equally guilty of the sin of omission.

After a false start working on a bridge near his home town of Kelso his engineering career began at the Percy Main Colliery in Co.Durham where in 1804 he was apprenticed as a pitwright. In 1811, his indentures complete, he moved to Newcastle and subsequently to Bedlington but his stay was brief for at the end of that year he was in London. Here he remained for two years and at sometime over that period was employed by Penn the marine engineer. In 1814 he was in Dublin working at the Phoenix foundry from whence later that year he returned to England and Manchester. Here he was employed by T.C. Hewes as a draughtsman and this I suspect was one of the formative influences upon his subsequent career, although he himself seems to have been relunctant to admit to this. Hewes was one of a group of four or five Manchester engineering businesses which dominated the millwrighting trade in Britain. Other firms outside Manchester had considerable reputations but nowhere was there a similar

concentration of engineering expertise. Howes was at the forefront of this group and may possibly have been the most distinguished. Despite this, little is known of his work and it has proved difficult to evaluate how much Fairbairns ideas developed from those of Hewes. Hewes had started as a textile machine manufacturer but by the time Fairbairn joined the firm had widened his interests to include the construction of fire proof textile mills. Unfortunately references to this side of his work are too general to be of any value. Smith (14) in his thesis on Hewes attempted to pin down a number of his mills but with little success. The only fire proof mill he could suggest might be by Hewes, were Gordon's Mills near Aberdeen but the evidence was tenuous.
From the point of view of his influence of Fairbairns idea's, even if confirmed as a Hewes mill, this would be of little value for by that time Fairbairn was already building mills on his own account. Fairbairn can have been with Hewes for less than twelve months for by November 1817 he had started his famous partnership with James Lillie. Their first major work involved them in the renewal of the transmission system at Murray's Mill in Ancoats. This was followed on Murray's recommendation by a contract for work upon M.Connell Kennedy's new fireproof Sedgewick Mill. It has been suggested that Fairbairn and Lillie played a part in the design and construction of the fabric of this mill but this cannot be substantiated.
"The Life of Wm.Fairbairn" gives the impression that the construction of the mill had not begun prior to Fairbairns association with it, but the Kennedy papers reveal that it was already well advanced by mid 1818 and that the Manchester firm of J & P. Sherratt were responsible for casting the iron work. Fairbairn and Lillie's role seems to have been confined to the mill work and it is improbable that Kennedy would have been prepared to entrust the construction of his first fire proof mill to the relatively inexperienced Fairbairn.

The important question of Fairbairns first essay into mill building is unresolved. He gives no indication and neither does his great contemporary propagandist, Dr. Ure. It is however obvious that between 1817 and 1824 his reputation had grown sufficiently to justify his employment by some of the leading textile manufacturers in the country. Benjamin Gott's, Armley Mill has been referred to above but it is to his other factory at Beam Ings that we must now turn our attention. The Napoleonic War had been responsible for continuing expansion at Bean Ing but the level of structural innovation had been limited. Despite a disasterous fire in 1799 the later buildings, unlike Armley Mill, were of conventional non fire proof construction. In 1823 Gott began a new series of extensions the focus of which was to be a four storey fire proof mill. The contract was let to Wm. Fairbairn. With outside dimensions of 105' by 35' the structural system consisted of three brick arched floors supported by T section cast iron beams. A preliminary sketch of the transverse section of this mill exists (15). The clear span of the beams is shown to vary between 16' 4 1/2" on the ground floor and 17' 2 1/2" on the second floor, the difference being accounted for by a diminished wall thickness. A marginal sketch shows that the intended beams had an overall length of 18' with a parabolic web profile giving a total depth including the thickness of the bottom flange of 10 1/2" at the ends and 1'5" in the centre. Accommodation for three tie rods is indicated one to be set into the wall the other two at one third and two third intervals of the span. All are located at the top edge of the web. The junction between the beams which takes place around the top of the columns was to be accomplished by side mounted shrink rings.

A further letter of October 1824,written while the mill was still under construction,relates to the failure of one of the cast iron beams, but under what circumstances is not made clear. It contains a sketch of the offending beam the dimensions of which do not correspond to those given on the drawing previously referred to. Here the beam is shown with a clear span of twenty feet and a total length of 20'9". The mid span section has a total depth of 1'4 1/2" whilst the end section is 11" deep. Thus the section depth was maintained to within 1/2" but the span is 2' greater than anything shown on the earlier drawing. As this later sketch was based upon beams which were actually being incorporated into the building we must inevitably conclude that the design had been altered.
This letter also gives a cross section for the beam shown. The web depth as previously stated was 16 1/2", less the depth of the bottom flange which is not specified and diminishes in thickness from 3/4" at the top to 1 1/4" at the junction with the bottom flange. The bottom flange has an overall width of 4 1/2" but whether it was truly rectangular or chamfered to conform with profile of the Jack arches is ambiguous. The failure of the beam was caused by a blemish in the casting located at mid-span in the upper part of the web. The beams were apparently cast locally in Leeds, for Fairbairn in another letter speaks of dispatching the models (patterns) to that place or alternatively having the castings made in Manchester but notably not at his own foundry. Similarly the patterns for the columns were sent to Leeds, and two evidently went astray according to a letter of the 9th of October.

In his book, "On the Application of Cast and Wrought Iron to Building Purposes" Fairbairn documents a test on a beam which he carried out in 1824 in connection with the Leeds contract. He was persuaded to test the beams because as he says "He entertained doubts as to the security of the (use of) cast iron beams". This may indicate that he had not previously used cast iron beams in mill construction.The beam illustrated differs substantially from those detailed above. In this case the span for the purposes of the test was 14', the beam having a mid span depth of 15" which diminished to 9 1/2" at the points of support. The web tapered from one inch at the base to 5/8" at the top whilst the bottom flange was 1" thick and 5" wide. With a ten ton load concentrated at the centre the beam deflected 0.48" and the web began to buckle. At 12 1/2 tons the deflection had decreased to 0.665" and the web was buckling badly.
Returning to the new mill itself the form of the roof raises further questions. The section fails to show in detail the roof trusses. In ink, a rectangular central frame is shown beneath the rafters which might be taken to portray either a wooden queen post truss or some form of iron roof. Over this is superimposed a vague pencil outline which might equally indicate a cast iron arch. The correspondence envisages an iron roof for Fairbairn promises to dispatch a "plan of the iron roof", but a subsequent letter of 1825 shows that an iron roof was intended to cover the boiler house. To this is appended a sketch of a trussed iron roof, the nascent version of a design which Fairbairn was to widely employ later.

It is an unfortunate fact that although this mill was demolished only recently (1970) no authority took the trouble to ensure that it was recorded and it is only because of John Goodchild's foresight that I have been enabled to show you the slides which you have seen.
A close contemporary of Gotts mill is that which Fairbairn began in 1825 for John Wood of Bradford. Again Fairbairn had been called in by one of the leading textile manufacturers in Britain. The Wood and Walker Mill complex in Wakefield Road, Bradford was by 1822 the largest in the town. Unlike Leeds the factory textile industry here was of

more recent origin and the scale of building less radical. It seems that before Fairbairn's new mill for Wood fire proof structures were unknown in Bradford, where the predominance of wool rather than the more inflammable flax made them less relevant.
This mill was demolished in 1879 and the information about its structural form is fragmented. The 1850 five foot plan of Bradford shows the buildings to cover the site irregularly, the result of a disordered pattern of growth. Fairbairns contribution measures 40' by 80'. It was powered by an 80 h.p. Boulton and Watt engine. Once again Fairbairn tested the beams to destruction prior to their application to the building and these tests are included in the book above referred to. The test beam has a clear span of 20' 9" and a mid span section 18" deep and 11 1/2" at the supports. The web diminishes from 1 1/2" thick at the base to 1" at the top edge with a flange 6" by 1 1/2". No web buckling appears to have accompanied the test loading of the beam which failed at 19 tons. It is likely that this beam was identical to those used in the construction of the mill, but as we observed above, the beams tested in connection with Gotts mill differed markedly from those used in practice.
It cannot have been long after the completion of these mills that Fairbairn and Lillie began their association with Hodgkinson. How many more mills Fairbairn was responsible for between that time and the next known example of his work is not clear. Bailey's mill at Stalybridge he put up in the late 1820's but this, demolished in the 1920's, is now known only through the illustration of the steam engine contained in "Mills and Millwork". Where he first applied the new beam section is nowhere evident from his written work. The first bridge to utilise the form was that carrying the Liverpool and Manchester Railway across Water Street in Manchester. This was constructed by George Stephenson and Fairbairn was possibly responsible for the iron work. Hodgkinson in his paper says that John Kennedy had announced his intentions to employ them in a projected extension of his premises but I have not yet been able to distinguish which mill this was or indeed whether it was ever built.

In 1975 Orrells Mill in Stockport was demolished and this prior to construction of Saltaire Mill in 1851 was generally felt to be Wm. Fairbairn's most notable work.
Over the period of its demolition it was fully recorded (16) and this is the earliest Fairbairn Mill on which definite statements can be made regarding its structure. Ralph Orrell had enjoyed a meteoric rise to prosperity in the cotton thread spinning trade. In part this no doubt was due to the generally favourable environment which characterised so many of these careers but a sufficient comment upon his entrepreneural talents is the following culled from a friendly biographer "It is well known that Mr. Ralph was a very passionate man and beat some of the children rather unmercifully, but he had many redeeming qualities which rendered him much beloved".
He practised these redeeming qualities in a series of small mills in Stockport and was occupying premises in Heaton Lane, close to where his Travis Brook mill was built in 1834. The new mill was conceived as a fully intergrated structure carrying out the full range of manufacturing processes to the finished fabric. Power loom weaving, in the development of which Stockport had played a prominent role, was to be undertaken in a weaving shed at the rear of the main building. It is not known when construction began but rates were being paid on the premises in December 1834, although it did not attain its full rateable value until two years later. Andrew Ure describes the mill in his "Philosophy of Manufactures" of 1835 and also in "His Science of Cotton Spinning" of 1836. From these descriptions it is evident that the full compliment of machinery had not been attained

at that time. The core of the site was a six storey block with projecting wings at either end. The main body had an exterior length of 280' and a width of 53' whilst the wings were 68' long and 42' wide. Within the south end of the main block were two 80 N.H.P. steam engines supplied with steam from an adjacent boiler house. Cellars were confined to the areas beneath the wings but an attic storey ran through the whole of the roof. Wall construction throughout was of brick. The floors were of the conventional brick arch with a span of 9' 6" between beam centres and a rise of 1' 1" representing 1 tenth the length of the cord, which compares exactly with the figure recommended in Fairbairn's "Application of Wrought Iron". The ground floor beams of the main block had a clear span of 23' 10". The mid span section consisted of a 3/4" thick web connected to the bottom flange by a triangular prism 3" deep and 3" wide at the junction of the bottom flange. The latter was 10" wide and 1 1/2" thick. The top flange was 3 3/4" wide and 1/2" deep. The total overall depth of the mid span section was 1' 7 1/2". Both top and bottom flanges were parabolic in plan and the web was parabolic in elevation. At the points of support the section depth was reduced to 1' 2 1/2" and the width of the top and bottom flanges to 2 1/2" and 5 1/2" respectively. Tie bars were located in the web 1' above the upper surface of the bottom flange.

In the wings the floor beams had a clear span of 18' and a mid span section of 1' 4 1/2" total depth. The web was 3/4" thick but the triangular prism of the base although 3" wide at its maximum was only two inches deep. The bottom flange was 8 3/4" wide and 1 1/4" thick and the top flange 3 1/4" by 3/4". The plan and elevation of these beams were similar to those in the main block.
The general feature of these beams conformed to the principles formulated by Hodgkinson and reiterated by Fairbairn in his books. Compared to their predecessors, the addition of a top flange and the parabolic profile of both flanges with the re-location of the tie bars lower down the web were all progressive steps (17). The proportional relationship between the flanges is less easy to assess. Hodgkinson it will be recalled had recommended that the ratio of the area of the top flange to that of the bottom flange should ideally be one to six. The uncertain qualities of cast iron had caused this figure to be revised subsequently to between 1.3 and 1.4. Another problem with the Orrell's Mill beam is the variability of the sectional profile which results from a probable tolerance in the dimensions of the final casting of about $\pm$ 1/4". This is particularly the case with the main buildings where the thickness varies between a 1/2" and 3/4". With the former figure the ratio comes out at 1.8 whilst with the latter a more realistic 1:5.3 emerges. Taking 3/4" as the probable intended dimension for the depth of the top flange the ratio of the beams of the wings is 1:4.87. It remains to suggest the load which was envisaged for these beams. Applying the formula $W = \frac{cad}{l}$

to the main mill beams $W = \frac{26 \times 15 \times 19.5}{286} = 26.59$ tons

and for the beams in the wings $W = \frac{26 \times 10.93 \times 16.5}{216} = 21.72$ tons.

If Fairbairn had used an iron roof in Gott's Mill he was not inclined to repeat the eyperience at Stockport. In 1975 when the mill was surveyed the roof trusses of one wing only remained.
The roof over the main body of the mill had been destroyed by fire in 1971. The missing section from photographic evidence and from Ure's account was, like that which remained in the wings, built of timber and was designed to give working attic space.

From the point of view of this paper the other buildings on the site need only be touched upon. To the rear of the main block and extending to the river was a large weaving shed with a saw tooth profile roof constructed of timber. This was flanked by various single and multi storey units which accommodated ancillary processes. The mechanical sizing shed contained a water wheel. Separate from the main group of buildings was a gas house which accommodated the retorts on the ground floor and the purifiers on a fire proof upper floor.
The only other remaining mill from this period which can be attributed to Fairbairn with any certainty is in Carlisle. It was completed in 1836 and hence is a close contemporary of Orrell's mill. In the construction of Shaddon Mill, Fairbairn is known to have been assisted by a local architect, Richard Tattersall. He had trained in Manchester under Wm. Haley and whilst considered by some to have been primarily a gothicist he was equally conversant with the classical style, which he had employed at the County Infirmary. "The Dictionary of Architecture" states that he was responsible for several cotton mills but how many involved Fairbairn and indeed how often he worked with a consulting engineer is an interesting question.

Shaddon mill was built for Peter Dixon who like Orrell had enjoyed a rapid rise to prosperity. Today the mill with its now truncated chimney dominates that part of Carlisle and before the development of the area in the 1860's its impact must have been greater. Whilst the architectural treatment of Orrell's mill was relatively austere Shaddon mill built of the local pink sandstone incorporated strong elements of the regional vernacular. If the exterior stands in contrast to Orrell's mill the interior is virtually identical as was the arrangement of the boiler and engine houses. The engine was housed in the North end of the mill and the boilers in a two storey extension alongside it. The mill building has an exterior length of 224' and a width of 58'. There are seven floor levels and a total external height of 83'. The structural ironwork, only examined in a cursory way as yet, consists of cylindrical cast iron columns of about 8 1/2" diameter supporting cast iron beams of a section and profile identical to those of Orrell's mill. The timber roof trusses have a central valley supported by cast iron columns and are glazed on the interior slope to illuminate the top floor. A detailed survey of this building will be carried out over the next twelve months.

By the mid 1830's Fairbairn was undoubtedly the best known mill builder in the country and for the reasons which have been outlined above, his work must have been amongst the most advanced. How closely other builders followed his example and the rate at which the new ideas were disseminated will only be known after much more research has been carried out. For this reason I advance the following cases tentatively as evidence of the changing structure of mill cast iron work.
In Leeds a brief examination of two fire proof mills constructed in the 1830's showed that the older type of beam persisted for a further decade. The 1824 mill of Hive's and Atkinson was extended in 1833 by a six storey building 163' long. At that time the largest flax mill in the town it is to be anticipated that it would embody the most advanced technology available. The interior was completely fire proofed to the extent of having an iron roof, unlike those constructed by Fairbairn. The floors are of the usual Jack arch construction supported by cast iron beams and columns. The beams retain the inverted T section.

Although Buckram House Mill, later Water Lane Mill, cannot be dated as exactly as the last example it appears in its present form on

Fowler's map of 1844. Other information relating to this mill makes it reasonable to conclude that it was built in the second half of the 1830's. Now a car showroom, the first floor is utilised for storage to which end a hoist has been installed. This penetrates an arch and in consequence two floor beams have been exposed. The supporting columns are eight inches in diameter with a free standing height of 10'8". They are positioned two feet off centre and the beam spans as a result are 16' 8" and 18' 10". At mid span the vertical web is 2" thick and 14" deep connected by 1 1/2" fillets to a bottom flange 6 1/2" wide and 1 1/2 inches deep. The arches span eight foot. Water Lane Mill may have been amongst the last fire-proof mills in the area to use the older beam form. Hunslet Mill built in 1838 has the new cross section and the parabolic web and flanges. To regard this mill as the onset of a new tradition may be an incautious generalisation for it is possible that it was built by Fairbairn. When offered for sale in 1869 the original engine running the main mill is stated to have been built by Wm. Fairbairn from which it might possibly be inferred that the mill was also by him.

Ten years later the new form had gained virtually universal acceptance and Fairbairn was approaching the end of the more innovatory phase of his career. It is from this period that his last known work dates. In 1851 he began the construction of Saltaire Mills for the Yorkshire textile millionaire Sir Titus Salt. Vast in scale and architecturally magnificent it included all Fairbairns previous experience. Both Salt and Fairbairn regarded this mill as their crowning achievement. The architectural treatment was entrusted to the local firm of Lockwood and Mawson and most of the ironwork was cast in nearby Bradford by Messrs Cliffe and Company. The beams perpetuate the design which Fairbairn had done so much to popularise. In two respects however,the mill differs from the other known works of Fairbairn. The floors although arched are of hollow brick construction to reduce weight,an idea used by Strutt in his 1792 mill and again in the 1830's by Telford at St.Catherine's Dock. The roof is a mature version of his early ideas. The cast iron roofs current up to the 1830's were as Fairbairn himself pointed out quite as expensive as an additional storey. They had been superseded by wrought iron roofs the development of which probably owed as much to the railway station train shed as it did to the textile mill. By using wrought iron angle for the compression members and rods for the tensile components light structures of great span could be achieved. The Stephensons had made use of this roof for their early railway stations. Fairbairn claims to have invented this type of truss in 1827 but the idea was already employed in at least one surviving building. Bee Hive Mills in Ancoats, Manchester, built in 1824. The roof at Saltaire deviates from the accepted practice in that the principal rafters are built up of wood flitched with wrought iron plates rather than the more usual angle iron rafters. It is instructive to compare the Saltaire mill roof with that built at the same time by Wren and Bennett, successors to Hewes and Wren the former partner of whom has already been discussed in connection with Fairbairns early career. In 1851 they completed the first half of a mill for Jonathan Akroyd in Halifax. The roof is dissimilar to the Saltaire roof only in that the principal rafters were of the normal angle iron.

Finally the form of the beams at this mill serve to make the point that although the cross sectional profile of cast iron beams was in the majority of cases that of Fairbairn and Hodgkinson there was still room for the aberrant form. In the boiler house of this mill the Jack arches are dispensed with to be replaced by cast iron bridging joists. The top flange of the beam is visible. Instead of

the more usual rectangular section it is of a square section.Beams of this form, and probably again by Wren and Bennett were also used in John Shaw's G & F mill built at the same time and demolished in 1977.

Notes

1) S.B.Hamilton - The Use of Cast Iron in Building. Trans.Newcomen Soc. 1942. T. Bannister - The First Iron Framed Buildings - Arch.Review.Vol. 107.(1950) Prof.A.W.Skempton and H.R.Johnson - The First Iron Frames - Arch.Review March 1962. Prof.A.W.Skempton - The Origin of Iron Beams. Actes. DU. Congres International D'Histoire Des Sciences 1956. H.R.Johnson and Prof.A.W.Skempton "William Strutts Cotton Mills" 1793-1812 Transac.of Newcomen Soc. Vol.XXX 1955-56 and 1956-57.
2) Wm. Fairbairn "The Application of Cast and Wrought Iron to Building Purposes" 1854.
3) A.J.Pacey "Earliest Cast Iron Beams" Arch.Journal 1968.
4) This development may have occured previously in non fire proof mills. Both solid and hollow cylindrical columns are known to have been used with timber beams by 1802/3.
5) "The Builder" Vol. 3. 1845.
6) "Post Mediaeval Archaeology" Vol. 8. 1974.
7) Professor Skempton suggests that this was a more convenient method but in fact side and top mounted rings enjoyed about equal popularity throughout the 19th c. Fairbairn always used side mounted rings.
8) Research is continuing into the histroy of this building. It has been definitively dated in its present form by drawings in the Boulton and Watt collection.
9) In Yorkshire this inconvenient arrangement was superseded by bolting faces cast into the upper end of the columns. Stonebridge Mill, Leeds built in 1805 has such facilities.
10) These mills have been dated from an annotated estate plan of 1889 in Leeds City Libraries.
11) The designer seems to have assumed that the absence of the brick arch floor made this feature unecessary but in fact in a cast iron beam the bottom flange performs a role in relation to tensile stresses occasioned by the load.
12) This may have been because the ceiling height was greater and Marshall's engineer did not trust the form used earlier in this context.
13) Prof.A.W.Skempton - "The Origin of Iron Beams" Op.cit.
14) S.P.Smith - T.C.Hewes University of Manchester, Inst.of Science & Tech.MSC Thesis 1968.
15) University of Leeds, Brotherton Manuscripts. Gott Collection.
16) National Monuments Record Survey 1976.
17) The tie bars although placed lower down the web were still above the ideal position. Fairbairn's desire to locate them within the arch raised them above a point of maximum effect.