Early Applications of Prestressed Concrete in the United Kingdom

by C. Burgoyne

Synopsis: The initial impetus to the application of prestressed concrete in the United Kingdom was heavily driven by the conditions imposed by the Second World War. Refugees from Germany, particularly Mautner and Abeles, brought skills and knowledge of tests carried out in France and Germany. The need to provide emergency structures, both for military purposes and to meet civilian needs, together with shortages of many materials, especially steel, led to the construction of beams on a scale, and at a speed, which would not have taken place in more normal times. The paper covers developments in the UK from the outbreak of the war in 1939 up to the early 1950s, when more normal times returned. This period of development is still not properly documented because security conditions prevented the publication of full details of the applications.

Keywords: history; prestressed concrete; United Kingdom

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INTRODUCTION

Prestressed Concrete was not developed in Britain, but several early applications took place there. The Second World War had a major effect since it significantly affected both the need for structural elements and the supply of materials.

Freyssinet's used jacking at the crown of arches at Rairéals-sur-Besbre (1911), Veurdre (1912) and Boutiron (1913 – Figure 1) to overcome the effects of concrete shrinkage and creep[1], and he conducted laboratory experiments which eventually led to his influential patent in 1928[2]. Glanville's more theoretical work on creep at the Building Research Station in England was taking place at the same time[3], but it was undoubtedly Freyssinet's work that led directly to prestressed concrete. He recognised that high-strength concrete and high steel pre-strains were needed to leave some prestress after creep had taken place.

The first publication drawing the attention of British engineers to prestressed concrete was a paper by Gueritte in 1936, read before the Institution of Structural Engineers; this was a translation of a paper by Freyssinet, who attended the meeting[4]. Gueritte had, as early as 1931, read a paper before the British Section of the Société des Ingénieurs Civils de France, describing the views of Freyssinet[5]; this was only one year after Freyssinet had extended his patent for the use of prestressed concrete. The 1931 paper was, however, more concerned with the bridge at Plougastel, near Brest, and the novel centring system used there. It refers to the properties of concrete lying somewhere between those of a solid and a liquid (an implicit reference to viscoelasticity), but gives few details. It also talks of the benefits of providing confining reinforcement to enhance the strength of the section.

The company of L. G. Mouchel and Partners, who had built up a pre-eminent role in reinforced concrete as holders of the U.K. licences, set up the Prestressed Concrete Company as early as 1937. The company does not appear to have become fully active until the arrival in the UK of Dr. Karl Mautner in the summer of 1939. Mautner had been a director of Wayss & Freitag in the 1930s, and was also a professor at Aachen. He was of Jewish descent, but despite holding the Iron Cross as a result of his distinguished service in WWI, he was rounded up with other Jewish professionals and placed in Buchenwald concentration camp in 1938. At that time, however, it was possible to buy oneself out of the camps and with the help of the Mouchel Company in England, and probably also of the British Secret Services, he came to England. He brought with him details of Freyssinet's work, with which, as licensee, Wayss and Freitag had been actively involved[6].

Gueritte published two further papers in the early 1940s. The first[7], in July 1940, describes the mass-production of precast, pretensioned beams; it also describes the design of emergency bridge beams and the design of a 3-span post-tensioned river bridge with a main span of 48 m, the central 15 m of which were formed of a simply-supported span. There was also a technical appendix written by Mautner. The second paper, published in 1941[8], gave extensive details of a test carried out at Southall on a beam 8.8 m long (Figure 2), and also described the test carried out about 5 years before, in Germany, on a longer beam designed by Freyssinet and tested by Mautner. The various developments sprang from this work.

In this paper locations are given using the Ordnance Survey Grid Coordinate system[9], which consists of two letters and 6 numbers, sufficient to define any location to within 100m. These coordinates, when entered into UK-based web mapping systems[10], will produce detailed maps of each location, at a variety of scales.

WAR-TIME CONSTRUCTION

Monkton Farleigh Mine. The limestone mines at Monkton Farleigh in Wiltshire (ST799656) had been worked in the 18th and 19th centuries to extract a seam of high quality freestone that was used to construct the city of Bath. The seam was about 5 m thick and typically 25 – 30 m below the surface. It had been excavated using the pillar and stall method, leaving quite sizable columns of stone to support the overlying lower-quality limestone that was not extracted (Figure 3). This mine, and others in the vicinity, were used as bomb-proof bunkers to store ammunition and other ordnance before it was required[11]. They covered some 80 hectares and were capable of storing about 350,000 tonnes of bombs. Monkton Farleigh mine was connected to the main Great Western Railway by means of a narrow-gauge railway tunnel and also by an aerial ropeway.

The original pillars left by the miners were irregular, and not suited to mechanical handling, so it was decided to replace the pillars by regularly-spaced walls, 5 m apart, and to use prestressed concrete beams at 1.5 m centres. Mr Allan of the Ministry of Public Buildings and Works, and Lt-Col Withers of the Royal Engineers, decided in 1939 to investigate the use of prestressed concrete for these beams, which were designed in consultation with Mautner and successfully tested[12]. They were designed for a central point load of 81.5 kN applied at the centre of the span, and were clearly intended to restrain loose blocks of stone falling from the roof rather than supporting the whole of the overburden, so they do not appear to have been loaded initially. Access to the mine was by inclined adits. Figure 4, which was not taken specifically to include the beams, shows two such girders. They were supported at their ends by steel rods hanging from brackets let into the walls; in the photograph these have been sprayed with concrete, presumably as corrosion or fire protection.

The scheme went ahead, with the intention that every third wall would be built, after which the intervening pillars would be removed and the intermediate walls completed. However, the demolition of the pillars took place much more quickly than the building of the walls, with the result that large areas of the ceiling were left unsupported and some of the walls that had been completed were overloaded[13]. A collapse occurred and the whole rebuilding scheme was cancelled, with the result that only a limited number of prestressed beams were installed. Nevertheless, this appears to be the first use of prestressed concrete in the UK.

The beams are described in Gueritte's paper in 1940[7]; although he does not mention the mine by name it is clear that these are the beams to which he refers. The paper also gives details of the anchorage blocks used in the stressing beds (Figure 5). With plans to fabricate such a large number of beams in a very short period of time, long-line fabrication was adopted. Nine parallel prestressing beds were made, 151 m long, in each of which 28 beams could be produced at the same time. The beams were complex in shape; the drawings show them with rectangular cross-section at the ends but I-beam section in the middle, with a web whose thickness varied along the length. 282 such forms would have been required if all beds were in use simultaneously. Shear links were provided and individual link spacings were specified, which today would be regarded as impractical, although it shows the over-riding importance attached to the optimisation of the steel. The tendons were stressed to about 1140 MPa so extensions of nearly a metre had to be accommodated at the jacking point. This was done by stressing pairs of wires using a yoke, with packing being installed once the desired extension had been reached. Once the concrete had cured sufficiently, the jacks were reinstalled, the packing removed, and the prestress released. If all 3000 beams had been built, each mould would have been used 12 times, and allowing for transfer of prestress at an age of seven days, with another week in between for setting up the reinforcement and concreting, it would have taken some 6 months of flat-out operation to complete the order.

There was relatively little to see on the surface, with a view to avoiding the attentions of the Luftwaffe, but the site was bombed in August 1940; it is thought that the bombers mistook the stressing bed for the (much longer) runway on a nearby airfield which was their intended target. Figure 6 was taken by the RAF to check the site camouflage; it was deemed to be unsatisfactory.

The mine is no longer used to store ammunition, but some parts have been taken over for commercial secure storage of documents and computer media. As a result, large parts are inaccessible and none is open to the public. Some of the beams are still in place, although their present condition is unknown. Grote gives a sketch of the present layout of the beams[6].

Railway Ties (Sleepers in UK parlance). Prestressed concrete railway sleepers were introduced in 1942[14]. There had previously been experiments with reinforced concrete sleepers, as early as 1917 in Ireland, with others on the LNER main line in 1928, but these were generally unsatisfactory as the reinforced concrete crumbled when subject to frequent heavy loads[15]. Wartime difficulties in obtaining suitable hardwood for the traditional timber sleepers led to further experiments in 1941 with reinforced concrete[16], and some were put onto a branch line near Derby. The tests were inconclusive, so the next year 100 of the sleepers were placed on the main LMS line near Watford; they survived for 10 days. At the same time, development work was under way on prestressed concrete sleepers, designed by Mautner for production on an experimental long-line stressing bed at the Royal Signals Research Establishment (RSRE) at Malvern. The first of these sleepers was used in a trial in 1942 and they were so successful that all work ceased on reinforced concrete apart from occasional use in sidings. A purpose-built factory was constructed by Dowsett at Tallington in 1943 and continues in production to this day (Figure 7)[17]. It has been estimated that after 50 years of production there were some 35 million prestressed, pretensioned, monoblock sleepers in use in the UK alone[14].

The sleepers are designed for point loads applied by the rail, to be resisted by upward pressures from the ballast (Figure 8). If the ballast is in good condition, support is concentrated under the rails, but after settlement the ground support can be much more uniformly distributed. The sleepers are normally in hogging bending between the rails, and sagging bending under the rails; the top profile is altered so that the tendons remain straight but are in the appropriate position to resist the different moments. No other reinforcement is provided in the sleepers apart from a fixing to attach the rails[14].

Emergency Bridge Beams. During the early part of WWII there was a considerable need for bridge beams for emergency repair. Many of these beams were made of steel, but it is known that a number of prestressed concrete beams were also made. It is not known how many beams were made nor, to a large extent, is it known where they were used. Gueritte[7] describes standard beams designed for spans of 4.6 m, 6.1 m, 9.1 m, 12.2 m and 15.2 m. The beams were to be used side-by-side, with timber decking. In some cases, the beams were to be tied together transversely by prestressed rods, which also served to attach the handrails (Figure 9). It is clear that savings in the amount of steel required were one of the primary advantages seen for these beams; it is also clear that these bridges were expected to be temporary and were seen as a means of restoring communication in the event of bomb damage. One surprising aspect is the preponderance of box beams in the smaller sizes; although they are more likely to be stable when placed, without any need for a transverse tie, the internal shutter must have been difficult to form and wasteful of resources.

In the discussion to a later paper[8], Chettoe describes the construction method, which is very similar to that used for the Monkton Farleigh beams. He mentions three fabrication yards, using beds between 180 m and 250 m long, each with three or four parallel lines, but he does not give named locations. Presumably these did not include the facility at Monkton Farleigh itself, but it is very likely that they were situated at other Government research establishments, such as RSRE where the sleepers were made. It is clear that a very large number of these beams were probably built, but there is no central record of where most of them were used. A paper published in the Institution of Civil Engineers in 1943[18] refers to two bridges built with these beams; these were clearly intended as permanent installations. Mention is also made of another that was planned.

Bridge over the LMS in Lancashire. This bridge was one of those described in the 1943 paper[18] (Figure 10). It has now been removed, but was located at OS Grid reference SJ595948, where the A49 road crosses the West Coast Main Line in Newton-le-Willows. The bridge was unofficially known as the Bloodystone Bridge since nearby was a monument to the murder by a returning crusader of his wife's lover. The bridge was unusual in that the beams were skew to both the road and railway; the girders available from the emergency bridge stock had to fit onto the existing bridge abutments and were not the correct length for the skew span (Figure 11). The bridge was assessed in the early 1990s and a 7 tonne weight limit applied; the original cast-iron parapet beam and the reinforced concrete slab at the side were replaced in 1993. The prestressed girders were replaced in 1997; one of the principal reasons for its removal was the lack of shear reinforcement linking the beams to the top slab.

Bridge in North Yorkshire. The other bridge referred to in the 1943 paper is at Sinderby, where the Great North Road, now the A1, crossed the Ripon to Northallerton Railway[18] (Figure 12). It is at OS Grid Reference SE335811. The road was dualled in the 1950s by adding two further carriageways to the west of the existing road; the old road over the bridge now forms a little-used private access and is not part of the public highway. The railway line has closed, and the void beneath both bridges has been filled-in with earth and concrete, but the bridge deck, including the prestressed beams, remains in position (Figure 13). The degree of support provided by the in-filling must be doubtful, and it certainly prevents both ventilation and inspection. According to Thomas[19], this bridge may have succeeded the LMS bridge above since it is said to have incorporated ties to stop the beams spreading, which had occurred on the other bridge. Despite having similar spans and prestress to the bridge at Newton-le-Willows, and also having no steel linking the beams to the slab, this bridge has never had a weight limit imposed. The long-term future of the bridge is uncertain since the road is soon to be upgraded to motorway standard and the bridge will cease to have any use.

POST-WAR CONSTRUCTION

After the end of World War II, Britain's economy was in a very poor state, with serious shortages of materials. Indeed, food rationing became worse after the end of hostilities, and as much production as possible was diverted for export to earn foreign currency. The back-log of maintenance that had built up meant that there was a heavy demand for steel; one of the principal drivers for the adoption of prestressed concrete was thus the recognition that prestressed concrete structures typically needed only about 25% of the amount of steel for the flexural reinforcement and a slightly reduced need for shear reinforcement because of the axial prestress that was induced.

The stock of emergency beams was used to rebuild bridges. It is claimed that they were so cheap that new construction was unable to compete. No central record exists of where these beams were used, but four locations were mentioned in 1949 in a brief note "An Exhibition of Prestressed Concrete"[20]; Linford (Hampshire), Bury St Edmunds (Suffolk), Tilemill (Berkshire) and Newport Fronbridge (Pembrokeshire). However, it is probable that a very large number of these beams existed and they would have been too valuable an asset simply to throw away. Detailed locations of these bridges, and any others made with the same beam stock, together with photos and condition reports, are still sought.

Adam Viaduct (1946) near Wigan carries the LMS railway from Wigan to the South West, over the River Douglas, at SD571051[21]. It has four spans of about 8.8 m each, with sixteen I-beams in each span[22] (Figures 14 and 15). It was prestressed with the Freyssinet system. The advantages were claimed to be the speed of erection and the fact that ballasted track could be used; the heavier beams meant that the bridge was also less susceptible to vibration. This bridge is still in use and has recently (1999) been listed by English Heritage, a process that recognises its architectural or historical significance, and gives some degree of protection.

Nunn's Bridge, at Fishtoft near Boston in Lincolnshire, was the first application of post-tensioning in the UK, in 1948[23]. The bridge has five beams 21.3m long, 1.1m deep below an integral top slab (Figure 16). Each beam has twelve Freyssinet 12-wire draped tendons. The bridge replaced a three-span brick arch built by Rennie which was temporarily retained to support the falsework. The bridge is still in use and shows no sign of rust staining or deterioration of the concrete; the only maintenance undertaken appears to be attention to the handrails. The bridge is located at TF367415.

Masonry Repair (1948). The first application of the Magnel system in the UK was to the strengthening of a church tower at Silverdale near Newcastle-under-Lyme in Staffordshire[24] (Figures 17 and 18). The tower was suffering seriously from subsidence caused by coal mining. The badly-cracked masonry was injected with grout to consolidate the brickwork to form “beams” of appropriate shape. A channel was cut into these beams to receive the tendons which were stressed against steel anchorage plates. Subsequently, the chase was filled with concrete to protect the tendons. The intention was that, if any further subsidence occurred, the internal beams would behave as if simply supported and prevent any further cracking of the masonry.

Airport Taxiway (1949). A prestressed concrete taxiway was built at the London Airport at Heathrow[25, 26]. This was similar to a complete runway slab built by Freyssinet at Orly; the slab was only prestressed transversely, but was made up of a series of 45° triangles (Figure 19). Vertical rollers were inserted in the joints, so as the slab contracted transversely it pushed against end abutments, thus inducing a longitudinal prestress as well. This system neatly overcomes the friction that would arise if direct application of the longitudinal prestress were attempted. The slab was 120' wide by 355' long. At about the same time a prestressed concrete road was constructed at Crawley, but this was prestressed longitudinally, which must have caused significant friction to develop between the slab and the ground[27].

Prestressed concrete in buildings (1949). Two notable applications of prestressing to buildings took place in 1949. The first was the fabrication of roof beams for the new Heathcote Factory at Tiverton in Devon[28], while the second was a much larger application to a new storage and distribution facility for H.M. Stationery Office at Sighthill in Edinburgh. This was the forerunner of precast, prestressed building construction[29, 30]. The secondary roof beams were pretensioned in a factory, while the main beams and the secondary beams for the floor were precast on site and post-tensioned before lifting them into position. These beams used the Magnel system, and some of the tendons were curved up at the ends. This building is regarded as significant since it took the ideas of precasting and prestressing from the bridge community to the building community.

Partially Prestressed Concrete. Paul Abeles was another refugee who came to England just before WW2. He was a believer in what is now called partially prestressed concrete, where additional untensioned reinforcement was included in the beam. The idea was to increase the ultimate moment capacity in the beam, with the primary effect of the prestressing being to reduce the crack widths but not to prevent their formation. He published a paper[31] espousing his views in 1940, which was severely criticised by Mautner in the subsequent discussion. The first major application of his techniques is believed to be the reconstruction of railway bridges for the electrification of the LNER railway out of Liverpool Street Station in London. The bridges had to be raised to allow clearance for the overhead wires, without needing to raise the road. These beams were discussed in a paper in 1952[32]. His systems were openly criticised - there were many who said that rather than combining the advantages of reinforced and prestressed concrete it combined their disadvantages instead. That debate continues to this day!

Conflicting systems. In the years after WWII there were many conflicting prestressing systems. The Freyssinet system, under the guidance of Mautner and later Alan Harris, were already established in the UK and held valid patents, but immediately after the war Prof Magnel of Ghent University was actively publicising his system, and Abeles was proposing the use of partially prestressed concrete. Many other systems were developed; some to avoid the patents held by the early protagonists, but others with genuine improvements[33]. It was during this period that today's standard systems were developed using 7-wire strands held by 3-piece wedges.

The history after 1950 is well-documented - *Concrete*, *The Structural Engineer* and the *Proceedings of the Inst. Civil Engineers* all carry many papers relating to innovations or landmark prestressed concrete structures, and there have been a number of papers and reviews giving details of prestressed concrete over the next 50 years[34,35,36,37,38,39].

CONCLUSIONS

While it is clear that prestressed concrete would probably have become a successful material anyway, the special circumstances that came together in the United Kingdom between 1938 and 1950 led to the more rapid introduction of the technique. Refugees from Germany brought skills and knowledge with them; pressures to produce a large number of beams very quickly for wartime purposes, combined with shortages of materials, especially steel which was needed for many other purposes, all contributed to the rise of prestressed concrete. Only after the war did questions about patents and commercial exploitation arise.

It is probably unsurprising that wartime security concerns meant that details of the use of prestressed concrete were not published more widely, and other technical achievements in the war, such as Radar, the Spitfire, codebreaking and more visible civil engineering achievements, such as the Mulberry Harbours, have captured public attention. But the more effective use of concrete by prestressing also played its small part.

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Figure 1 – Boutiron Bridge

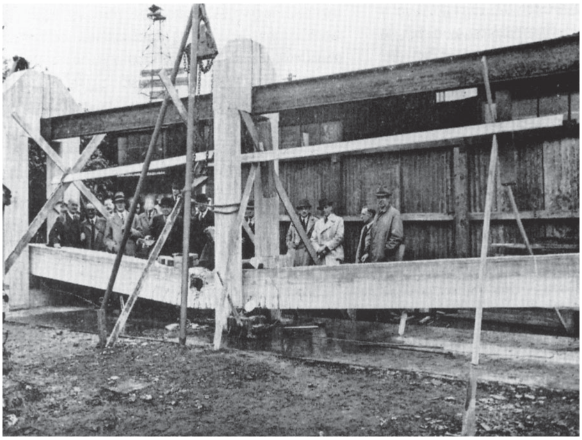

Figure 2 - Southall beam test[6]

Figure 3 - Pillar and stall mining at Monkton Farleigh

Figure 4 – Two beams in place at Monkton Farleigh

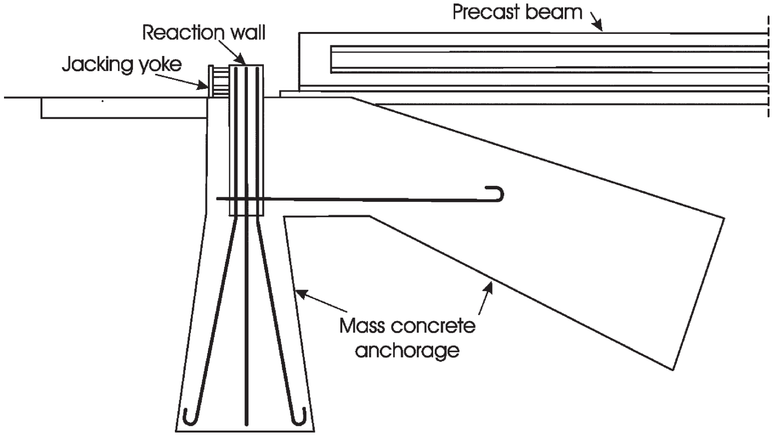

Figure 5 - Anchorage block at Monkton Farleigh stressing bed[5]

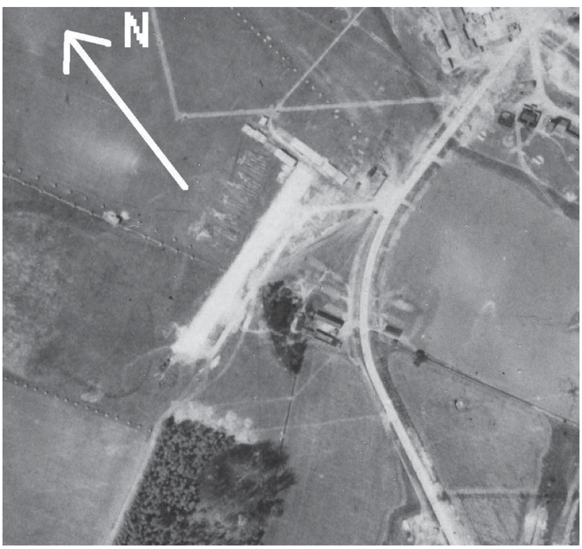

Figure 6 - Aerial view of the prestressing bed at Monkton Farleigh (ST797658)

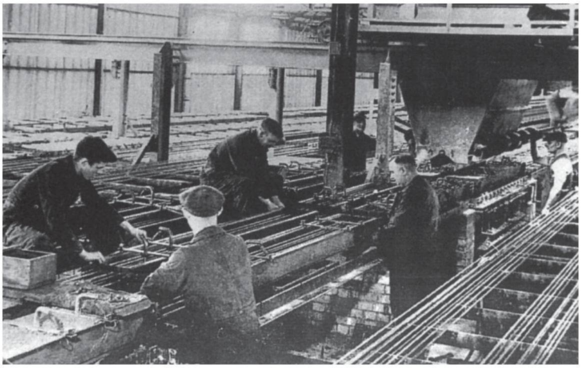

Figure 7 - Original long-line prestressing beds for railway sleepers[13].

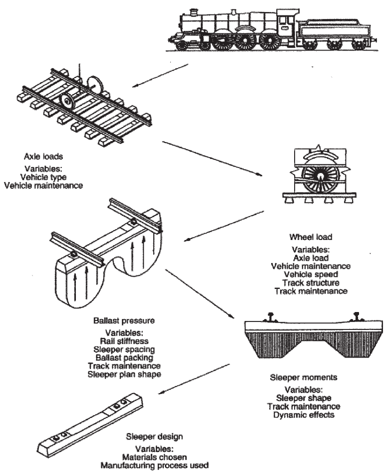

Figure 8 - Sleeper design process[13]

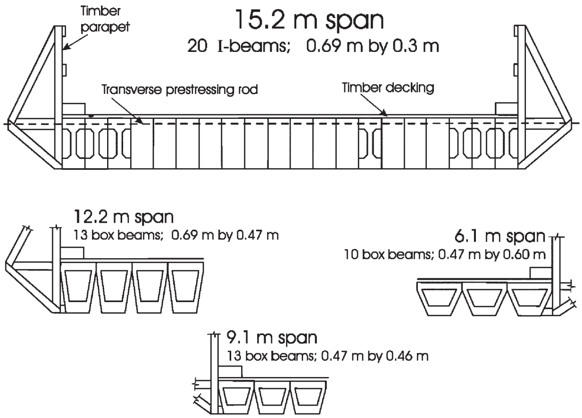

Figure 9 - Emergency bridge cross sections (Redrawn from Reference 7)

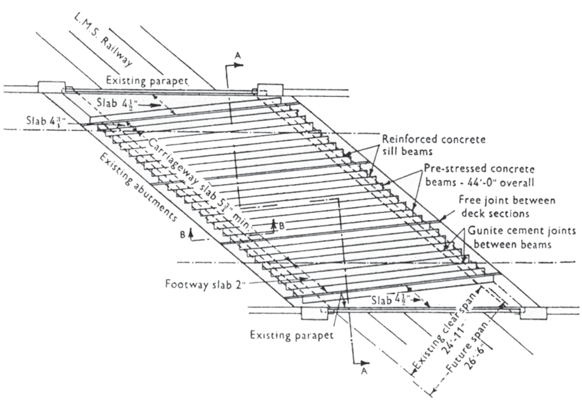

Figure 10 - Plan of Bloodystone Bridge[17]

Figure 11 - Underside of Bloodystone Bridge showing cast-iron edge beam and tapering reinforced concrete side slab.

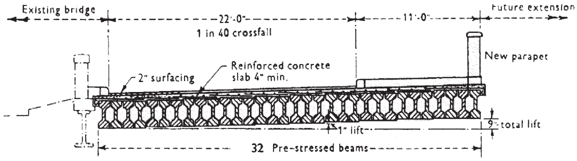

Figure 12 - Cross section of Sinderby Bridge[17]

Figure 13 - The only exposed part of the prestressed beams at Sinderby (below parapet)

Figure 14 - Adam Viaduct, Wigan

Figure 15 - Underside of girders at Adam Viaduct

Figure 16 - Nunn's Bridge, Fishtoft

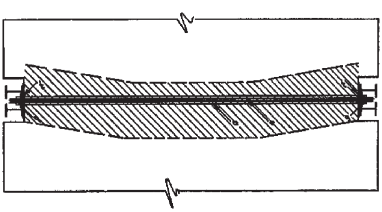

Figure 17 - Long section through church wall[24]

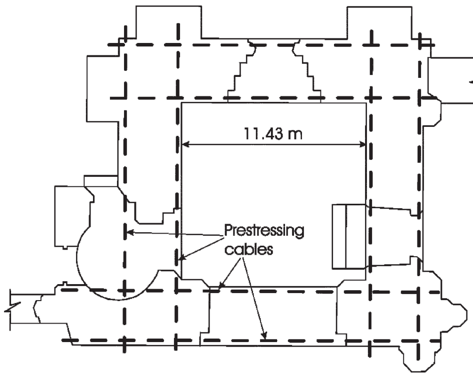

Figure 18 - Plan of Silverdale church tower showing strengthened areas (Redrawn from Reference 24)

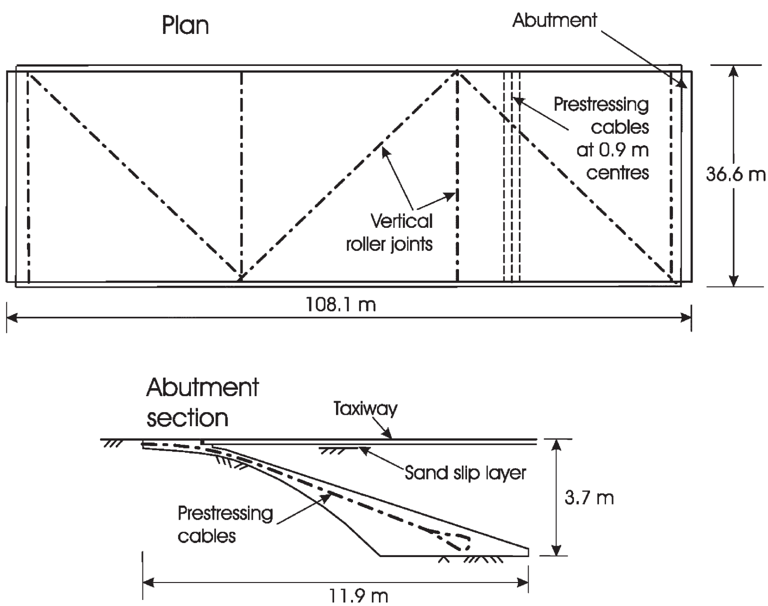

Figure 19 - Heathrow Airport Taxiway (Redrawn from Reference 28)