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The Creation of the Roof to the Waterloo International Terminal

Conception de la toiture de la gare internationale de Waterloo

Projektierung des Daches des Internationalen Waterloo-Bahnhofs

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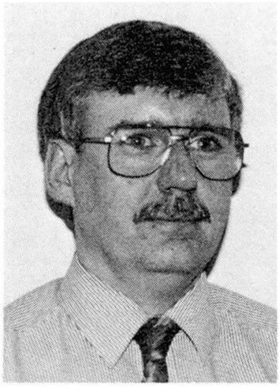

Alan C. Jones, born 1955, received his Civil Engineering degree from Portsmouth Polytechnic, England. He has worked for Anthony Hunt since graduation and has been responsible for the structural design of many notable steel buildings including the Inmos Factory Gwent and the Schlumberger Research Centre Cambridge.

SUMMARY

The train shed roof at Waterloo is a lightweight steel frame spanning up to 48 m and clad in stainless steel with large glazed areas including the whole of the west elevation. The shed is approximately 400 m long and is curved and tapered on plan. This paper describes the design criteria for the roof structure and outlines the analysis, fabrication and erection methods employed in its creation.

RÉSUMÉ

La toiture en sheds de la gare ferroviaire de Waterloo est une charpente métallique légère d'une portée de 48 mètres, revêtue d'un habillage en acier inoxydable et pourvue de grandes surfaces vitrées, y compris la totalité de la façade ouest. La couverture en sheds a une longueur d'environ 400 mètres, est de forme courbe en plan et de largeur variable. L'auteur expose les critères de l'étude structurale de la toiture et fournit les points essentiels des calculs statiques, de la fabrication et des méthodes de montage prévues pour cette réalisation.

ZUSAMMENFASSUNG

Das Shed-Dach über den Zügen im Waterloo-Bahnhof ist ein leichter Stahlrahmen mit bis zu 48 m Spannweite. Die Verkleidung besteht aus Edelstahl mit grossflächiger Verglasung, die auch die Westfront umfasst. Das Shed ist ungefähr 400 m lang, im Grundriss gekrümmt und von veränderlicher Breite. Der Beitrag beschreibt die Bemessungskriterien, die Berechnung, das Fertigungs- und Montageverfahren, die beim Bau verwendet wurden.

1. INTRODUCTION AND BRIEF

1.1 Introduction

This paper sets out to describe the background to the design and construction of the new train shed for Waterloo International, London's gateway to Europe via the Channel Tunnel and the first clear span terminus to be built in the capital since St Pancras in 1868. Trains will run from Waterloo to Paris and Brussels. Each train is 400m long, carries 800 passengers and will travel non-stop from London to Paris in three hours.
Peak passenger flow is 6000 per hour with an anticipated maximum of 15 million passengers per year. There are five dedicated platforms, four for general use and one as a 'stand-by'.

The train shed is, of course, only the tip of the iceberg with, below it, three layers housing departures, arrivals, immigration, car parking and servicing, all designed to airport rather than railway station standards.

This paper deals only with the train shed roof and supports for which we were responsible as consulting engineers.

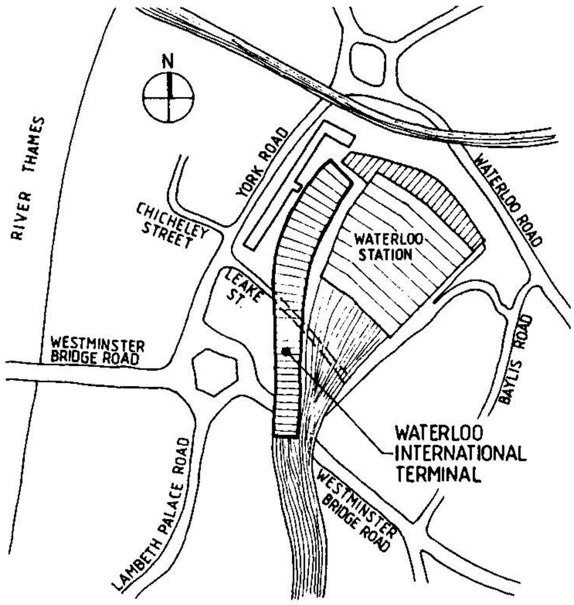

FIG 1. LOCATION PLAN.

1.2 The brief from British Rail

In March 1988 YRM Anthony Hunt Associates were commissioned by British Rail to work with architects Nicholas Grimshaw & Partners on the train shed structure for the new channel tunnel terminal at Waterloo. Sir Alexander Gibb & Partners, who were already acting as transport consultants, were appointed for all the substructure works and Cass Hayward as consultants for the track structure.

The final brief from British Rail was simple in outline although of course quite complicated in detail:
- a clear span structure of approximately 400 metres length unheated and uninsulated. Due to the constricted nature of the site which dictated rather narrow platforms, intermediate columns were considered to be undesirable
- level separation of departures/arrivals with customs hall/immigration areas.
- basement car parking
- alongside vehicle access
- a new link to London Underground
- new high level pedestrian walkways.

Waterloo International is a transport building for the late 20th century linking Britain to Europe. It is a dramatic combination of engineering and architecture using current technology to follow the traditions of the great 19th century British engineers, Brunel at Paddington and Barlow at St Pancras.

2. DESIGN CRITERIA

2.1 Environmental loads

Snow loads were evaluated taking into account the possibility of drifting in the valleys. Uniformly distributed maintenance loads were considered to be within the allowances made for snow but specific point loads were determined at various locations to cater for personal access equipment including a safety harness system on the roof and support for a temporary maintenance cradle below the primary trusses.

Wind loads were assessed using a scale model in the wind tunnel at the University of Bristol and the tests incorporated various stages of development of the surrounding area, including the proposals to redevelop York Road and Elizabeth House.

The structure is in an external location and is therefore exposed to extremes of temperature. The structure was divided into seven independent units each in the region of 50m long with free expansion joints located in the valley sections.

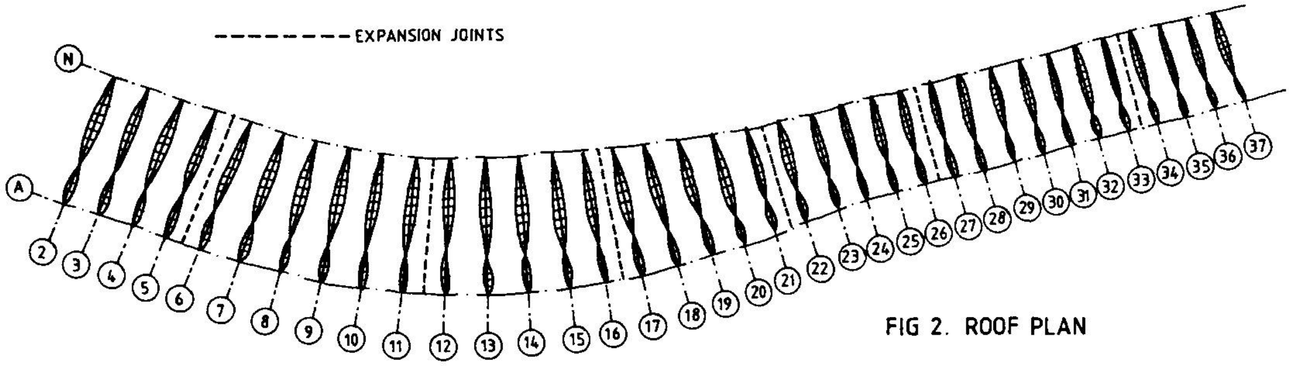

FIG 2. ROOF PLAN

2.2 Foundation Movements

Over its length, the roof structure is supported on many different foundation systems ranging from the new raft foundation system for the main terminal building to the well established mass concrete foundations of the existing brick arch structures of the old station. Consequently, large differential vertical movements occur at several locations. Wherever possible, thermal expansion joints have been located over areas of maximum predicted vertical movements so that both movements can be accommodated at the same time. The roof is also subjected to short term vertical movements created by the passing of trains over the track support structure. This is a more localised effect and is absorbed by the inherent flexibility of the steel frame and cladding.

2.3 Hazard Loads

The movement of trains in close proximity to structure required careful consideration and this was a prime concern at Waterloo. The roof was designed for various extreme loads deemed to simulate an impact from an incoming train. This included the total removal of a single truss support.

3. GEOMETRY

3.1 Plan layout

The plan shape of the building is dictated by the available land around Waterloo. The train shed, which covers the five new platforms and the associated tracks, is 400m long. The 36 roof trusses twist and curve on plan and reduce in width from 48.5m at the northern (town) end to 32.7m at the southern (country) end, to follow the site and limit of the platform widths as passenger flow reduces away from the entrance.

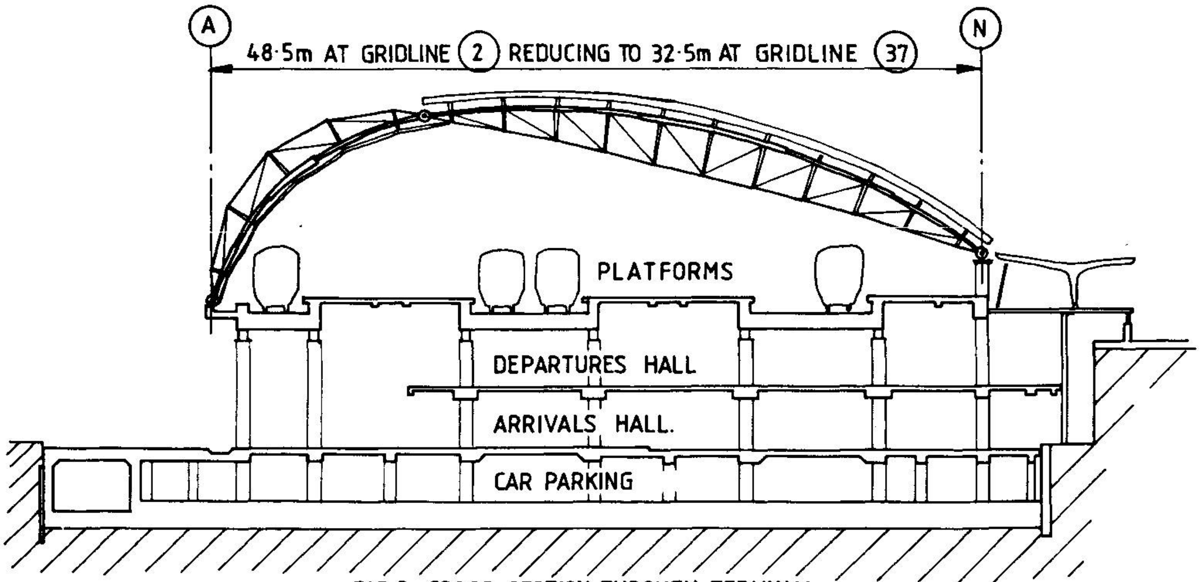

FIG 3. CROSS SECTION THROUGH TERMINAL

3.2 Section

The proximity of the original structure alongside the new roof, and the closeness of Elizabeth House and the access road to the west, set the external building envelope quite tightly. This, combined with an asymmetric platform arrangement, necessitated an external structure with sharply rising cladding above the first railway track. This in turn largely determined the asymmetric arch shape. As a result of this asymmetry, pairs of bowstring trusses are joined off-centre to form a flattened three-pinned arch. The smaller external element is referred to as the minor truss; the longer internal element as the major truss. The bowstring trusses are necessary to accommodate the bending moments created by uneven loading conditions and the building shape. The form has thus developed into a unique structural arrangement that reflects the bending moment diagram and arching forces in response to the natural laws of physics. The result is an efficient and therefore lightweight steel structure which makes good use of the underlying track support structure by utilizing it as a tie between supports.

4. STRUCTURE

4.1 Primary Trusses

The bowstring trusses are joined at the interface between the glazing and decking with a cast steel knuckle and stainless steel pin. A similar connection is provided at the bases, where they sit on the platform structure. The internal truss comprises two telescoping compression booms up to 356mm in diameter with a single 75 dia tension rod. The booms are interspaced with tapered tubes varying from 219mm dia down to 60 dia at the tie rod. Due to the asymmetric arch profile, the external truss is inverted, with a single compression boom 356mm maximum diameter and twin 75 dia outer tie rods.

4.2 Secondary Structure

Single circular hollow section tubes form the secondary structure between trusses. The valley shaped roof can experience considerable out of tolerance loading between bays causing the main prismatic trusses to twist. This is prevented by continuity of the secondary structure provided by tie rods taken from the truss booms to the centre of the longitudinal tubes. On the major trusses tie rods are located both above and below the tubes giving a movement capacity in either direction. However, on the minor trusses only external ties could be incorporated. In this case moments causing the ties to go into compression are resisted by moment connections between the tubes in adjacent bays. The three-dimensional shape of the structure also provides a degree of arch action which helps limit deflections due to imposed loads.

5. ANALYSIS

5.1 Stress and Deflection

The steel frame was analysed using a full three dimensional model consisting of a typical 5 bay roof section. This model was subjected to a comprehensive combination of loads (see section 2) and detailed information on stress levels and deflections was obtained. Stress was checked in accordance with BS 5950: Part 1: 1985 and the deflection results were incorporated into a performance specification which provided the basis of the design for the cladding system.

5.2 Aesthetics

The visual relationship between the structure and cladding and also between individual structural elements was given a high priority among the other design criteria. Computer aided draughting techniques were used to create solid three dimensional models of a typical bay of structure, together with the cladding and all primary connections. This enabled the structural elements to be blended together in the most acceptable way. For instance, the posts in the major truss which pass from the large diameter compression boom to the small diameter tension boom must effect this transition in the most elegant way. It was decided that the most suitable method was to taper the post. This was modelled on the CAD and then alternative sections were investigated, including tapered tubes, box sections and cruciform sections. Examination of the alternatives as they would be viewed from the platform showed the circular section to be the most acceptable.

6. FABRICATION

6.1 Repetition of Detail

Whilst the budget for the roof was set to reflect the prestigious appearance required by the client, careful control of the details was necessary to prevent the cost becoming prohibitive. The setting out of the trusses ensured as many details as possible repeated at each gridline - despite the varying spans. The largest truss was set out to suit its span and height and then each successive truss was reduced according to a scaling factor relating to the span. In this way the geometry at most of the connections remained constant for all trusses. This was important because the principal connections incorporated cast steel nodes which required a new pattern every time the geometry changed. The various truss configurations were rationalised into four different structural types with only two variations on the external diameter of the main boom members. Hence, only two different patterns were required for each main connection

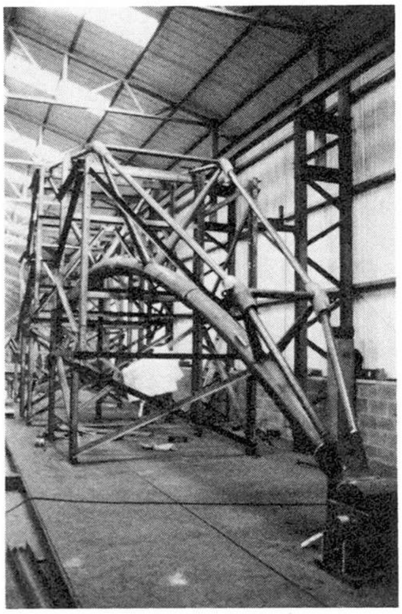

Photo 1. Minor Truss in the fabrication jig.

6.2 Assembly

The primary trusses were assembled in the workshops of Westbury Tubular Structures Ltd, using specially constructed jigs. Comprehensive checks were undertaken of all dimensions using electronic distance measuring equipment and a full regime of non-destructive testing was initiated.

The prismatic form of the trusses made transportation difficult due to the large volume occupied by each unit. It was possible to fabricate and transport the minor trusses as a single piece, however, the major trusses were split into three with site bolted splice connections between them. Each truss was trial assembled in the workshop and surveyed as a complete unit prior to shipping to the paint shop and on to site.

7. ERECTION

7.1 Pre Site Trial Erection

At a very early stage it was decided in conjunction with the construction managers, Bovis Construction Ltd, to incorporate a full scale trial erection of a single bay into the contract and the area between grids 15 and 16 was selected as being representative of the average complexity of the whole structure. The purpose of the trial was to test the erection procedures within the trade contracts and hone on site activities to give as much overlap as possible. The steel fabricator erected a full bay of steelwork including two primary trusses and associated secondary elements, adjacent to their workshops. This was then clad by Briggs Amasco Ltd who provided the decking and glazing systems. Several minor, but very significant, modifications to the connection design and erection method statements arose from the experiences gained .

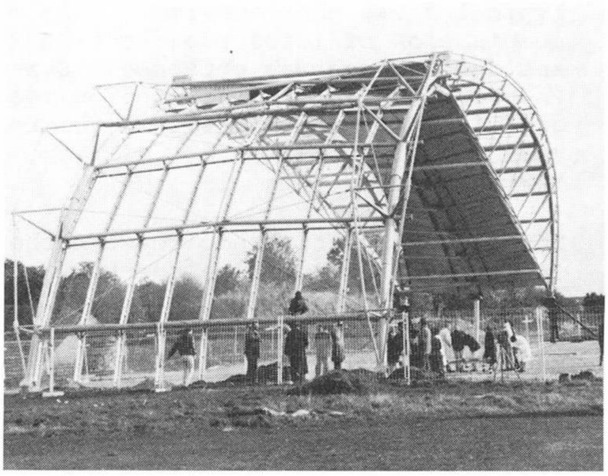

Photo 2. Trial Erection at Wetherby

7.2 On Site

Erection on site commenced on two fronts, at the north end of the station and half-way down the shed by Leake Street. Each section began with one complete braced bay of steelwork and progressed southward one bay at a time.

The first operation was to position the two base castings onto the track support structure according to the actual dimensions of each truss obtained from the shop surveys. The major truss was then brought to site in three sections and assembled horizontally on cradles resting on the track structure. The main pin connection was made to the base on gridline N and the other end of the truss lifted up into position on the temporary trestles at the central pin. The trestles provided lateral restraint to the truss to prevent any horizontal lateral movement which may have overstressed the base connection. The minor truss was then lifted onto the base casting on gridline A and the pinned connection made. The final operation was to support the internal end of each truss with individual mobile cranes and lower them down together until the forked connection intermeshed and the centre pin could be installed. The temporary trestles continued to provide lateral restraint whilst the next truss was erected and the secondary structure inbetween was assembled.

8. COMPLETION

The roof structure and cladding was completed along with the remainder of the terminal in May 1993, on time and within budget and is due to receive trains from Paris and Brussels in the summer of 1994.

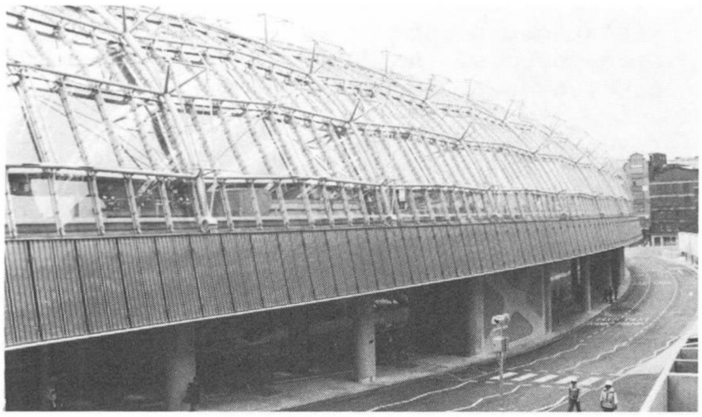

Photo 3. West Elevation of the complete roof