Concrete Bridge Design and Construction in the United Kingdom

By the ASCE Committee on Construction Equipment and Techniques

Abstract: Bridging has been the key element in the development of road systems. The scope and range of solutions has depended on the effective exploitation of the most economical materials available. The growth of span and load-carrying capacity is reflected in the moves leading to the use of concrete. The design and construction of concrete bridges has altered rapidly during recent decades. This has been brought about by better analytical methods, better planning, and increased mechanization in the construction of the works. However, these steps have also brought in their wake new problems for the engineer, contractor, and supervisor. This paper shows the different approaches on a number of factors. The first part shows the design of bridges in classes for span and type with reference to the pertinent factor for that design. The second part looks at the contractor's approach to construction and illustrates the need for flexibility in the construction method in order to meet contract deadlines. The third part considers the role of the supervising engieer, who achieves a balance between the designer's intentions and the contractor's proposals.

Part I. Selection of Deck Type for Multispan Bridges

Introduction

At any moment, and in any particular location, the types of bridge construction that are genuinely economical are relatively few. These economical bridge types are being continually refined and added to by specialist firms that have recognized their shortcomings. The situation is however confused by relatively inexperienced companies that design "irrational" bridges, giving the impression of greater diversity than exists objectively.

The types of bridge that should be built in any site depend on the state of development of the country, the local rates for materials and labor, as well as on the availability of skills.

This paper will attempt to identify the main criteria that govern the selection of bridge types in the relatively developed economies of Europe, the United States, the Middle East, and Far East.

The choice of bridge type cannot be discussed separately from the selection of the method of construction. In the present paper, the classification of bridge types has been made following their construction technique.

Steel or Concrete

Plate-girder steel bridges lend themselves to rationalization of their design, guided by clearly identifiable industrial costs and detailed codes of practice. Concrete bridges are far more difficult to optimize, with a wide diversity of opinions being held on design factors. An example is the acceptable minimum thickness of members. As a result, medium-span steel bridges tend to be well designed, while there are all too many examples of poorly designed

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concrete bridges. Steel bridges are well adapted to the modern practice of subcontracting large parts of civil-engineering projects, while concrete ones usually demand more input from the main contractor.

Steel has been chosen in situations where concrete was the rational construction material, and poorly designed concrete bridges have been supplanted by well-designed steel alternatives. However, the results of several recent tenders have indicated that for multispan bridges, a well-designed concrete deck is cheaper than the steel-composite equivalent. Exceptions to this are difficult sites, where the ability to crane in or launch the steel beams gives significant savings in falsework, or short bridges, where the absence of economies of scale requires traditional in-situ concrete construction on scaffolding.

Basic Requirements

The present analysis will be limited to prestressed concrete structures. There are two basic components of efficiency in the construction of concrete bridge decks; economy of materials, and economy of labor. The art of concrete-bridge design resides in finding the correct balance between these two components for a particular project.

Traditionally, economy of materials was the principal concern of the designer, while the contractor then attempted to find the most efficient way of building the consultant's brainchild. This division of responsibility frequently led to structures that were theoretically efficient, but which were slow to build, and expensive overall.

A typical example of this approach is the multicell-box type of concrete deck. It is usually necessary to cast these decks on falsework, span by span. Due to the complication of the cross section, and the thin members used to achieve economy of materials, the deck cannot be cast in one continuous pour. The bottom slab is cast first, the forms for the voids erected, and the webs and top slab reinforced and cast in further construction phases. It is unusual to see such decks erected at rates faster than one span every four or five weeks.

Modern prestressed-concrete-bridge design for developed countries is based on minimizing the labor content of the decks, and optimizing the quantities only within the framework of an efficient method of construction.

Building rates of a span every two weeks on relatively small sites, and several spans a week on large projects should now be the norm. For this to be achieved, the designer must consider at the earliest conceptual stage the construction problems posed by a particular site. He must establish, for example:

1. Whether a site is suitable for founding falsework.
2. Whether large-capacity cranes could be used or whether a tidal regime permits the use of heavy floating plant.
3. If the weather during the construction period will allow efficient in-situ construction.
4. How materials will be transported to the construction heads.
5. If there are suitable areas available on or off site for setting up a precasting yard.
6. What are the skills of the local labor force.

The answers to these questions, together with the contractor's specific expertise and preexisting plant, will determine the type of bridge that it would be most economical to build. This thread of thought requires a partnership between the designer and the builder.

Modern Bridge Deck Types

For long multispan viaducts, there are four basic types of bridge deck construction: (1) Cast-in-situ—either on semimechanized ground-based falsework, or using highly mechanized suspended gantries; (2) precast beam and in-situ slab; (3) incrementally launched box girders; and (4) precast segmental-box girder.

Cast-In-Situ Decks

Decks Cast on Ground-Based Falsework

When the terrain crossed is suitable for the use of falsework, this type of construction is used for viaducts up to about 1 km in length. The most efficient deck is the continuous "twin rib" type, for spans up to about 45 m. Although this type of deck uses some 20% more concrete and prestress than more efficient box-type structures, it is very simple to build. Indeed the concrete for a complete span can be cast in one continuous pour.

The decks are built span by span, with joints near the fifth points. The falsework generally consists of girders spanning from the previous cantilever to the pier, frequently with an intermediate support. (A 1.2 km railway viaduct of this type was built at a rate of a span every two weeks.) In urban locations, the 1/15 span/depth ratio required for these bridges is not always available. In these cases, the ribs can be made shallower and wider, with internal circular voids. At the limit, when minimum depth is required, the deck becomes a solid prestressed-concrete slab.

In-Situ Decks Cast on Self-Launching Gantries

For very long bridges, or for those crossing inaccessible terrain, the deck may be cast on a suspended-falsework gantry. These "bridge-building machines" are very expensive and the investment in their first cost, and in the sometimes protracted period of learning to use them efficiently, must be recovered in the fewer man hours required to build the deck. The deck types used are frequently twin rib or single-cell box girder. Twin-rib-type decks can be built with these bridge-building machines at rates up to a span per week. The more complicated box section may take up to three times as long.

In-Situ Free-Cantilever Construction

In-situ free-cantilever construction is ideally suited to the single large span over inaccessible terrain. The minimum falsework required consists of two cantilever carriages, which for segments typically 3.5 m long and decks of medium span weigh some 50,000 tonnes each when fully equipped with shuttering, access gantries, and accessories. A small construction team can build at a rate of a pair of balanced segments each week. This method of construction is also used for multispan viaducts. However, when the construction program is short and several erection teams and sets of falsework are required, the technique becomes less economical.

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Cast-in-situ free-cantilever erection is generally used for spans between 50 m and 250 m. For spans in this range, box sections are almost universally used. Once the bridge-deck area exceeds about 10,000 m^2, precast segmental construction is likely to prove competitive.

Summary

Cast-in-situ decks are very adaptable at coping with variable alignment or geometry. They can be purpose-made for a wide range of spans, deck depths and widths.

For multispan viaducts, this form of construction can be economical if great attention is paid to keeping the deck simple to build. By and large, it should be possible to cast each span of the viaduct in one continuous pour. Where there is a free choice of column positions, cast-in-situ box sections are rarely economical.

Cast-in-situ free-cantilever erection of long spans over inaccessible terrain may be the only viable construction method if the deck area is below the threshold for economical precast segmental construction, and if the bridge is not suitable for incremental launching.

Precast Beam and In-Situ Slab Decks

Standard Beams versus Specials

There are many proprietary types of prestressed precast-concrete beams on the market. It is also common for beams to be purpose-designed for a particular scheme. Whether it is more economical to use a standard or special beam for a particular site depends on several factors, of which the most important is the size of the project.

Standard beams are ideal for relatively small jobs. They generally weigh less than 30,000 tonnes, can be transported on trucks, and can be lifted into place by mobile cranes. However, they are not economical in materials, particularly when they are used at the limit of their span range. Their main use is on bridge decks where the speed with which they can be erected over sensitive sites, such as railway tracks or operating motorways, outweighs other considerations.

Once a bridge exceeds a certain size, it is cheaper to use larger, more widely spaced beams, weighing typically 80,000 tonnes for spans of 33 m. Even heavier beams may be used for spans up to 45 m. These large beams are spaced, typically, at 3 m centers across the deck. Modern methods of analysis allow them to be designed without diaphragms except over each pier.

Continuity

Precast-beam bridges are erected simply supported. In some cases they are subsequently made continuous for live load. Whether this is economical or not depends on the code of practice worked to. If it is necessary to design the prestress to cancel the effects of relative settlement of supports, and moments due to temperature gradients in the deck, and secondary moments caused by flexural creep of the beam concrete, then continuity gives little benefit for the considerable complication in construction.

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Expansion Joints

Decks made from precast beams have more roadway-expansion joints than comparable continuous decks, and hence may be more expensive to maintain. The number of joints may be minimized by bolting together groups of spans.

Summary

Carefully designed precast-beam decks, using purpose-designed beams of adequate structural depth, are among the most economical of bridge decks. They are not particularly attractive, and are not flexible in coping economically with variable span lengths, shallow deck depths, or sharply curved alignments. They need heavy specialist equipment for their handling and erection, and hence are appropriate for large deck areas.

For smaller decks, standard beams are frequently economical provided they are carefully designed, are well short of their limiting span, and are spaced as widely as possible. For very small decks the convenience of beams and designs, which can be bought "off the shelf," often make such decks the obvious choice.

Incrementally Launched Decks

General

Incremental launching is a method of building a bridge deck in segments in a fixed falsework situated behind one abutment, and jacking it forward into place.

As successive segments are built, the deck slides forwards over special bearings situated on each pier. To avoid a span-length cantilever occurring just before the front of the deck reaches a pier, a steel launching nose is attached to the leading segment.

Deck Geometry

For this method of bridge construction to be applicable, the deck must have a regular profile, both in plan and elevation. Thus any constant curve in space can be built. The appropriate span lengths are generally considered to lie between 20 m and 50 m, although longer spans have been built using temporary props between piers. Decks over 1 km in length have been launched by this method.

Deck Cross Section

The deck cross section is normally a box, although this is not essential. Boxes should have only one cell. Twin-rib bridges may also be launched, although a considerable weight of extra prestress may be required for the construction phase. Segment lengths vary from 5 m, with a construction cycle of two days, to 30 m, with a weekly cycle. The deck span-to-depth ratio in most cases needs to be deeper than 1/18.

Summary

This method of construction is extremely economical for a site with the right geometric characteristics, as the falsework required to erect the deck is minimized. Also, the deck construction is reduced to a series of repetitive operations, which can take place under cover. This factory style of construc-

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tion gives the best working environment for high productivity. Material quantities are often slightly higher than for other forms of construction, although careful choice of cross section can reduce this.

Countercast Segmental Construction

General

Countercast segmental construction consists in dividing up a bridge deck into transverse slices. The slices are cast against each other in a special mold so that adjoining faces are a perfect fit, and do not require the use of a jointing medium. These decks are then erected dry or with an epoxy resin filler, which acts principally to waterproof the joint.

Long-Line and Short-Line Techniques

The simplest form of countercast construction consists in setting up in the precast yard a soffit form for the exact final shape of the bridge deck, modified by any necessary precambers, and casting segments against each other in their correct positions. This method is of course only applicable to bridges with very simple deck geometry, and is used for short structures.

Short-line precasting is carried out in a mechanized casting cell. Each new segment is cast between a fixed stop end and the previous segment. The position of the stop-end segment can be finely adjusted to allow for variable curvature of the deck in both planes, as well as variable twist. Thus bridges of any geometry may be built.

Deck Cross Section

The countercast technique allows factory-type construction of bridge decks. The same operations are repeated by the work force each day, in an enclosed factory if necessary, under strict supervision. Intensive external vibration can be applied to the concrete during casting. Hence the method is ideal for the construction of thin-membered box-section decks. However, other types of deck may be cast in this way, including voided slabs and twin-rib decks.

Deck Geometry

The erected shape of the deck is created in the casting yard by the fine adjustments of the stop-end-segment with respect to the casting cell. This deck shape includes the addition of the road geometry to the structural precambers necessary to compensate for deflections due to self-weight, erection equipment, prestress, and time-dependent effects.

The relative rotation of each segment about the three principal axes, with respect to the previous segment, must first be calculated with extreme precision. This calculation is complicated, and most accidents in alignment with countercast bridges are probably caused by mathematical errors or incomprehension at this stage.

Deck Erection

The decks of countercast segmental bridges can be erected by a variety of techniques. One of the most common, generally applicable to bridges over 45 m, is free-cantilever erection from each pier. The segments may be handled by a ground-based crane, shear legs situated on the deck, or by self-launching erection gantries.

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For shorter spans, span-by-span erection on a self-launching girder is very fast, allowing spans to be erected in less than a week. For the largest projects, complete spans may be preassembled and launched into place, giving erection rates approaching a span per day.

Summary

Countercast segmental construction is the ideal way to make efficient box-girder bridge decks. The factory conditions of the precasting yard allow the production of the very highest quality concrete, and the thinnest concrete sections. However, the method is technically demanding of both the designer and contractor. Many segments are cast before erection commences, and errors in the geometry of the segments, poor quality control in the precasting, or subsequent damage in handling a segment can store up serious problems for the erection that are very costly to put right. However, with careful planning and execution, it is a remarkably trouble-free and efficient method of construction. It is broadly accepted that this technique is economical for deck areas greater than 10,000 m^2, however this size is very dependent on the viable alternative methods of construction available and should not be considered an absolute limit.

CONCLUSION

The basic techniques of efficient concrete-bridge-deck construction have been known for some 20 years. Until recently, they were practiced by a few highly specialized firms, and generally confined within national boundaries. Thus precast segmental construction was first used in France in 1962, but little used elsewhere before the 1980s. Similarly, incremental launching was mainly a German technique.

The increasingly competitive world market has led civil-engineering contractors in all countries to search for the most economical methods of bridge construction. It is no longer adequate to design or build in the old conventional ways. Every design or construction decision now has to be analyzed for its economic efficiency, its contribution to earning a profit in a tight market. This is the age of the specialist in bridge design, and this deepening analysis of each element in the building process is leading to ever more rational and economical bridge types.

PART 2. GRANGETOWN VIADUCT CONSTRUCTION

Introduction

Grangetown is the longest precast posttensioned glued segmental viaduct in the United Kingdom and comprises a twin-trapezoidal-box deck made up of 641 precast segments that are 3.2 m long and weigh between 43.5 and 74 tonnes. The 26 main spans range from 70 m to 72 m in length and the 4 end spans range from 38 m to 46 m. Construction of the deck was carried out by the balanced-cantilever method, and the present paper outlines some of the techniques considered and employed. The contract also included the Cogan bridge and viaduct, which are of similar construction but shorter overall.

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PRECASTING

One of the major decisions to make in glued segmental construction is whether the precasting of the segments is sublet away from the site to one of the established precast manufacturing companies or carried out in-house on the site.

After due consideration, it was decided to set up a precast factory on-site for the following reasons:

- Lower unit cost was considered achievable in view of the reduced overhead compared with precast manufacturers, the total number of segments to cast being 641 for Grangetown and 300 for Cogan.
- Full control over the technical and production aspects meant greater flexibility (if required) during construction.
- Adequate storage area was readily available close to the construction head.
- Experienced labor was readily available following recent completion of the East Moors glued segmental viaduct on the other side of Cardiff.

Work commenced in January 1985 with the establishment of a temporary precast factory. The construction program dictated that two precasting molds were to be used for Grangetown and one for Cogan Viaduct. The factory was therefore divided into three bays that were designed, as far as economics allowed, to operate independently of one another. This included provision of a 15 tonne capacity overhead traveling gantry above each bay for handling materials.

By dividing the factory in this manner each mold team would be made accountable for production targets and quality control under the overall supervision of the precast manager. This decision was certainly a significant factor in achieving the required output of one segment per mold per day.

The reinforcement cages, including the posttension ducts, were prefabricated in purpose-made jigs. These were exact timber replicas of the mold itself. Although it would have been possible to manage with one jig for each bay, this would have placed the reinforcement fixing continually on the critical path, and so two jigs per bay were constructed. In areas where deliveries of reinforcement are unreliable there may be justification for providing three jigs if the factory space is available, as the cost of making a jig is relatively small.

The steel molds for producing the segments were supplied by an established steel-form manufacturer. Although a limited number of manufacturers have a wealth of experience in the design and manufacture of steel molds, it is important to realize that unless design and performance requirements are fully specified, the mold may not produce the result required. Early discussion took place with the mold supplier, and a watching brief was maintained during manufacture. Since the success of the project was dependent upon producing one segment per mold per day, attention to details that were likely to impede progress was paramount. Similarly, once the molds were installed it was essential to provide good clear access as far as possible. This need helped create an efficient team of disciplined workers as well as a safe method of working (regrettably not such a common facet of civil engineering).

The 52.5 N/mm^2 concrete used in the segments was supplied by an ad-

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jacent 50 m^3/hr batching plant specially purchased for the contract. Initially the concrete was dispatched to the factory by 2 m^3 capacity skips mounted on powered bogies running along a rail track. This method, however, proved slow and costly to maintain and was replaced by the contractor's own ready-mix trucks. Concreting times varied between 1-1/2 hrs and 2 hrs and generally commenced at 3 p.m.

To ensure the concrete reached the required strength of 12 N/mm^2 to allow striking of the shutter when the shift commenced at 8 a.m. the following day, the segment and mold were fully draped with insulating mats. During the winter period the concrete temperature was elevated to approximately 25 °C by heating the added water, and maintaining a warm atmosphere around the mold with external heaters.

Handling of the segments as they came out of the factory was carried out by a 100 tonne portal-lifting frame on rails. This lifted the segment off its trolley onto the site transporter. The segments were then dispatched to the storage area where they were handled by a 3900 Manitowoc crawler crane.

The match casting of segments by the short-line method clearly requires a great deal of control in the alignment surveys. At each survey stage (i.e. prepour and postpour the following morning) the survey would be repeated a number of times and then checked by another engineer. Once the alignment data had been computed the contractor's senior engineer would check the calculations. Permission to cast or strike the mold would not be given until the senior engineer was satisfied that the survey information was correct. It was important that the precast foreman followed this procedure at all times despite the many pressures to achieve production targets in the man-hours budgeted.

Erection

Another important decision that has to be made at the outset is the method of erection to be employed. Essentially there are three options if the structure is to be constructed in balanced cantilever: (1) Crane; (2) purpose-made lifting frames; (3) launch girder.

At the time of tendering, one of the United Kingdom's leading form manufacturers offered to design and manufacture a purpose-made launch girder and hire it to the contractor for the contract. In view of the access difficulties (two river crossings and one railway crossing, the length of viaduct to be constructed, and the performance figures given by the manufacturer), erection by launch girder appeared to be the most economical solution. A contract was entered into for the hire of a launch girder. The girder was designed to erect both Grangetown and Cogan Viaducts, the latter having a maximum span of 95 m, which dictated the length of girder required at 116 m.

The main components consisted of a central main leg, which was supported on the pier, a rear leg whose support reaction was applied near the end of the previously completed cantilever, and two moveable props positioned on either side of the main leg to provide stability for the cantilever under construction. Segments were dispatched to the construction head along the previously completed deck (or approach embankment at the start), lifted by the traveling crab at the rear-leg position, and then placed into position in balanced cantilever. The moveable props were progressively moved outward from the main leg and placed into contact with the cantilever near the

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ends to resist the out-of-balance moments. Due to the curvature of the viaduct it was also necessary to incorporate slewing movements into the launch sequence, the girder being rotated in plan on its bearings about the main leg.

On completion of the balanced cantilever, the girder was made ready to launch forward to the next pier. The launching was achieved by supporting the girder totally on the moveable props keeping the main- and rear-leg supports clear of the deck. The props were connected to the lower flanges of the girder beams by gripper jacks. Operation of these jacks enabled the girder to be launched forward in a series of movements.

Overall, this method of erection proved extremely slow, with fewer than 70 segments erected in the first 5 months. A further complication with the method was that due to the considerable weight of the girder (320 tonnes) the reaction applied at the end of the cantilever necessitated the incorporation of a substantial amount of additional temporary prestressing. This was difficult and costly to install and impeded access for other works such as permanent stressing and grouting within the precast box. Thus, in March 1986 it was decided to change the method of erection to a crane, which, despite the increased cost, would ultimately prove cheaper provided a contract overrun could be avoided.

Choice of crane was an important consideration and it was decided to hire a 4100 Manitoc Series 3 ringer. The crane was set up adjacent to the piers for both carriageways, and a pair of balanced cantilevers was erected from the one position. Each balanced cantilever comprised a total of 22 segments. The advantage of this method was the availability of "four ends," which gave greater crane utilization and less dependence on the completion of the cantilever stressing. In a matter of days, the erection rate reached an average of four segments per day and peaked at eight in one 12 hour shift including the permanent stressing.

The cantilever under construction was supported on hydraulic jacks seated upon standard military trestling (heavy-duty steel shoring) resting on the pilecap base. The two completed cantilevers were joined at mid span by a "stitch" cast in situ.

The length of the stitch was approximately 300 mm. This reduced the amount of in-situ shuttering and temporary prestress that would have been required otherwise, but it clearly increased the degree of alignment control needed. The alignment of the cantilever was continually checked during construction and related to known casting errors. If, after computation of the results, the projected error proved unacceptable the cantilever was steered back on course by using silica-sand filler in the epoxy glue. For example, it was applied to the top slab to steer it downward or onto one web to steer it sideways. This method proved far easier than the traditional way of using fiberglass and generally produced more predictable results.

An efficient means of access to the face of the segments for the temporary and permanent stressing was an important requirement. It was achieved with purpose-made adjustable platforms fixed to the lifting beam. Thus, both access platform and segment were placed in position in one movement. The platforms were designed to accommodate the strand-pushing machines for installing the cables and fitted with chain blocks to support the stressing jacks. The limited space inside the box of the viaduct prevented the use of powered mechanical plant for handling the jacks. Purpose-made bogies were used to move equipment along the inside of the box, and chain blocks were used to lift the jacks onto the stressing block. The typical erection rate by this method was two cantilevers (eastbound and westbound) in two weeks, which represented 657 m^2 of bridge deck constructed per week.

Summary

Precast glued segmental bridges can be both quick and economic to construct. The fundamental approach to the project's execution, however, must be more akin to that of the production engineer in order to achieve success. Well-thought-out access and material-handling equipment can save substantial time and money over the casting-and-erection period. If specially manufactured segment erection equipment is to be used (such as a launch girder), it is essential that a clear and full performance specification is prepared and adhered to. Finally, the substantial temporary works requirements invariably necessitates a considerable number of minor modifications to the bridge design, and the overall success of the project will be dependent upon the designer's willingness to cooperate fully in this respect.

Part 3. Supervision of Precast Segmental Bridge Construction: Problems and Solutions in Site Control

Introduction

From initial design concept to completion of the bridge deck on-site, the structural design of a precast segmental bridge closely interacts with the method of construction. It is necessary for the designer to consider a method of construction in considerable detail. He needs to select the proportions, configurations and weights of the individual segments and to assess the various loadings and changes in loading on the part-completed structure during erection of the segments. In the case of Torridge Bridge the design was based on the use of a launching girder for deck erection.

After a construction contract has been let under the Institution of Civil Engineers (I.C.E.) Conditions of Contract the successful contractor should submit his temporary works proposals to the engineer. These will include methods for segment precasting, handling, erection, and the temporary and permanent stressing sequences. Whilst the engineer's design assumptions will dictate to a large extent the method of construction, there is still scope for flexibility of approach. It is inevitable that the contractor's detailed method of construction and plant will differ from those on which the design was based and the engineer will need to satisfy himself that the bridge will not be overloaded or unstable at any stage of construction. This assessment is carried out in advance of the approval of the method statements and of the start of the works but to produce optimum performance there is a constant need for refinement and modification on-site. Consequently, supervisory staff needs to understand both the capabilities of the constructional plant and the loadings it imposes on the structure at the various stages of erection, if they are to respond quickly to any problems.

Compared with the more conventional type of static falsework soffit support, segmental erection using the balanced-cantilever method of construction is a dynamic method in which the potential for disastrous errors is ever

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present. Temporary works must be continually monitored to ensure that the approved method statement is rigidly adhered to in practice, because the margin for error is small.

A high level of technical input is required from site supervisory staff to exercise the proper degree of site control. Strong support is also necessary from the head-office design team because many problems require complex analysis beyond the scope of a normal site establishment. Precasting work and segmental erection progress very quickly. If delays are to be avoided good communications are essential between the engineer's designers, the contractor's designers, and the site personnel. It is essential to have telex or fax communication between parties, so that vital information can be confirmed quickly in writing.

A close working relationship between the contractor's and the engineer's personnel is necessary to achieve the common goal of maximum progress with optimum safety.

Segment Precasting Operations

The most impressive aspect of this method of construction is the erection of the segments at the bridge site, so it is easy to forget that the line, the level, and the appearance of the bridge superstructure is determined primarily in the casting yard. If the segments are properly made, they will automatically produce a superstructure of pleasing appearance and correct profile as they are fitted together. In addition, problems associated with cable threading, parapet construction, and deck finishes are minimized.

Some discretion can be exercised as to the degree of site control necessary in the casting yard. The minimum control is simply to accept or reject completed segments or part of the completed superstructure on a quality-control basis outside the casting yard, leaving the contractor a "free hand" to manufacture the segments. This approach is normally based on the fear that any interference with a high-output casting procedure is likely to lead to large claims for delay. However, as so much of the quality and the speed of bridge construction is determined in the casting yard it is highly desirable that site control is implemented there from the outset. In common with all the aspects of segmental bridge construction, emphasis should be given to quality assurance to minimize the time taken for quality-control procedure. This involves a study of the contractor's method of construction and his resources to ensure that a satisfactory end product should result, assuming agreed procedures are properly implemented. At this stage, it is important that supervision and inspection requirements are incorporated into the proposed precasting and erection cycles.

Problems in the Precasting Yard

Some of the potential problems that can arise and their consequences are:

- Poor precasting shed layout: Slow progress; disruption to precasting cycle; safety problems.
- Inadequate casting-bed foundations: Loss of time due to remedial works; alignment problems due to settlement.
- Inaccurate duct or reinforcement fixing: Slow progress; duct misalignment

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leading to stressing problems; lack of cover.

- Inadequate concrete mold: Slow progress; bad fit segment to segment; duct misalignment leading to stressing problems; damage during striking mold; poor surface finish.
- Incorrect engineering detail: Structural problems; stressing problems; incorrect bridge profile; durability.
- Poor-quality concrete: Inadequate strength; thermal/shrinkage cracking; slow strength gain leading to loss of progress.
- Careless handling: Structural damage; distortion.

The first four aforementioned problems, involving equipment and facilities, are best avoided by identifying them and having them rectified prior to giving consent to the contractor's proposals.

ENGINEERING DETAIL

Incorrect engineering detail falls into two parts: Failure to maintain the correct bridge profile segment to segment; and incorrect shape or incorrect assembly of components for an individual segment.

Building the bridge profile in accordance with the contract drawings is the contractor's responsibility and he will supply the "casting curve" from which the alignment of each segment will be determined. Therefore, control is confined to a line-and-level check, before and after casting, to assist in maintaining setting-out accuracy. A workshop drawing for the manufacture of each segment should be prepared by the contractor and thoroughly checked by the supervisory staff to avoid any difference of interpretation or errors at source. The drawing can then be used in the precasting shed for both manufacture and inspection of each individual segment. A full-time precasting inspector will check for compliance as work is produced so that only minimal time is required for final checks before concreting a segment. By using this method, a considerable degree of engineering control was introduced into the manufacture of segments at Torridge Bridge, without ever interfering with the 24 hr casting cycle.

Many of the problems associated with poor-quality concrete and careless handling are common to all heavy civil engineering, but some do arise as a direct result of the conflicting requirements of this type of work.

CONCRETE QUALITY

A high-strength/high-workability mix is needed for box segments, and it is necessary to use a water-reducing agent or plasticizer to obtain both properties. It is wise to specify a concrete-placing trial comprising a wall and part of the bottom of a box segment. It should incorporate typical reinforcement and ducting to assess the adequacy of the concrete-placing techniques and the workability of the mix. In the bottom half of some segments, reinforcement, and ducts may be so congested that free-flowing concrete of very high workability is required. Modification of the approved mix with an increased dosage of plasticizer is one solution, but care must be taken to check the slump of the approved mix prior to adding additional plasticizer. If this precaution is not taken, excessively wet concrete may escape detection and later be responsible for low concrete strength in the completed segment.

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As prestressed segmental concrete must have a high strength, it needs to have a high cement content. This makes the concrete susceptible to alkali-aggregate reaction. Unless petrographical analysis proves beyond doubt that the aggregates are inert, the amount of alkali in the cement must be limited to a safe level, at which no reaction will occur. This is normally achieved by using a blended cement in which a proportion of ordinary cement is replaced by an alkali-free cementitious material such as ground blast-furnace slag or pulverized fuel ash. Once it has been established that the materials and the mix design are satisfactory, control must be maintained by insisting on a cement certificate indicating the alkali content of every batch of cement received on-site in advance of its use, so that mix adjustment can be made if the alkali content varies significantly. In addition, samples of concrete used on-site should be periodically sent for laboratory analysis of cement content and cement blend to confirm that the concrete is being produced in accordance with the approved design.

A reduction in alkali content of the cement to satisfy durability requirements will also reduce the rate of strength gain of the segment concrete. As a result, it is likely that elevated-temperature curing will be necessary if the concrete is to achieve sufficient strength overnight to permit removal of soffit formwork in the morning; an essential requirement for a 24 hr casting cycle. Laboratory trials are necessary to establish the appropriate curing temperature before precasting work commences. It is then important to ensure that the correct early-curing regime is maintained for each segment manufactured. Extra concrete test cubes should be made from the segment concrete so that some can be cured with the segment and crushed to verify the strength of the in-situ concrete before approval is given to remove the formwork. The immature concrete should then be cured by the use of covers or a spray-on curing compound and protected from adverse weather conditions if necessary.

Handling Segments

Segments must be moved away from the casting area quickly to avoid congestion. Consequently, they have to be handled whilst the concrete has relatively low strength, and careful consideration must be given to the way in which the segments are lifted and supported. The segments will be placed in storage for at least a month and probably for much longer. It is essential that they are stored properly, with their weight supported evenly to avoid distortion of the box due to concrete creep. If the segments are stored on the approach roads to the bridge, it will be necessary to verify that the embankments and pavements can withstand the loading without any adverse effect.

Building the Superstructure

The superstructure of a segmental bridge can be built in two different ways. If there is suitable access under the bridge, the segments can be lifted into position using a crane. Otherwise it is necessary to place segments from the bridge deck using a launching girder. The latter method was selected for Torridge Bridge.

The superstructure construction involves almost total integration of per-

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manent and temporary works. Any failure in one will greatly affect the other. The temporary works are primarily the contractor's responsibility, but because of the interaction with permanent works and safety considerations, the engineer needs to satisfy himself that the temporary works will perform effectively. An independent design check should be specified in the contract and this should be supplemented by further checking of critical points by the engineer's staff.

Launching Girder

A launching girder is usually designed for the erection of one bridge only because big bridges seldom have sufficient in common with one another to plan for continuity of work. A girder needs to be mobile and lightweight, but capable of carrying heavy loads in many modes of operation. Apart from an independent design check, a thorough review for potential problems should be made of the workshop drawings and performance manual. Care should be taken to ensure that wind bracing is satisfactory and that during operation the girder can be made safe quickly in high winds. When the girder has been built, the most effective site check is to carry out commissioning trials on the ground in which the equipment is subject to performance tests. These essentially comprise deflection and overload tests to ensure that the girder will perform properly over the whole range of working conditions.

Erection of Segments

Erection of segments by the balanced-cantilever method, involves a complex series of operations, which requires a principal method statement for the whole span. Detailed method statements for aspects such as stressing sequences and gluing will also be needed. It is necessary to identify from the contractor's method statement where and how site control needs to be exercised to ensure compliance with the agreed procedures. This is best done by combining all the relevant information into a brief but thorough checklist of the deck-erection operations. A suitably qualified engineer should then supervise every operation on-site and sign the list alongside each operation as it is satisfactorily completed. Work must stop immediately if operations are not being carried out correctly. Radio or telephone communication between the checker and senior staff is essential to ensure that this is done.

As the job progresses, reviews of procedure may arise to improve performance. However, no alteration to the agreed procedure should be permitted until it is established that there will be no adverse effect on either the temporary works or the bridge structure.

It is important to check with great care the position and level of the first segment erected on the pierhead. As segments are added on either side of the pierhead unit and as the cantilevers grow in length, any error will increase proportionately. There may be an opportunity to rotate the superstructure on its bearings onto line before the guide bearing is fixed in position, but this would normally take place after only a few segments have been erected. If the cantilevers are going off line, some correction can be effected by packing the joints between segments, but only small improvements are possible. A great deal depends on getting the precast segments right before assembly begins.

Forming the Superstructure

As individual segments are erected, a continuous concrete-box girder is gradually formed. The continuity is achieved by gluing and stressing the segments together and a number of problems can arise during these operations.

The segments are glued together with an epoxy-resin adhesive. There must be sufficient time available after mixing the adhesive to allow operatives to spread the material over one of the mating faces before it becomes too stiff to handle. Different formulations are necessary depending on the ambient temperature during application. Laboratory testing of the material is necessary to confirm that it has the specified properties. Once the adhesive has been approved, it is worth carrying out an application trial to ensure that the technique is satisfactory and can be done quickly enough.

The supervisory engineer must ensure that during erection the temporary stressing across the joint between segments is maintained at a low compressive stress, which will result in a good contact until the glue has set hard. Permanent stressing, which produces higher compressive stresses, may then proceed. A technician should be present whilst each joint is being made to check that the adhesive is properly mixed: slight variations in the mix proportions can affect strength and setting properties considerably. In addition, material samples should be taken for strength and curing tests. It is also important to witness that all the stressing ducts are clear of glue after a joint has been formed.

The construction of a segmental bridge involves the supervisor in a massive program of prestressing operations, incorporating both temporary stressing with high-tensile bar and the systematic stressing of the main tendons. Most main tendons will have to be stressed in stages. It is most important that all the stressing loads and sequences are agreed on beforehand and implemented in practice. The erection of segments using a launching girder tends to work on a 24 hr cycle with segments erected by day and stressed by night. Therefore, engineering supervision is required on a shift basis to supervise operations, check load/extension results, and give quick decisions to avoid any interruption of the sequence of working.

When constructing balanced cantilevers, it is wise to complete a span before grouting any of the ducts for the main tendons in case further stressing is necessary. This situation can arise if the cantilevers are not constructed to the correct profile and additional road construction depth is necessary to form a new vertical alignment. The prestressing may need to be modified to compensate for the additional deadweight of the road. When a span is satisfactorily completed adjacent ducts should be grouted in a continuous sequence. This mitigates the effect of grout migrating from duct to duct. Leakage through the segment joint is due to poor jointing technique. Proper supervision of the jointing operation greatly reduces this problem.

Apart from tendon ducts, numerous ducts, pockets, and access holes are necessary as part of the temporary works during construction. Each one is a potential source of maintenance and durability problems unless it is reinstated under proper supervision and control. Wherever possible, infilling should be done with low-shrinkage concrete before the permanent stressing is completed. Inspection of this work needs a high priority because failure to carry out proper reinstatement may result in a loss of effective cross section of

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the box, which will lead to an increase in working stresses when the bridge is in service.

Although every effort is made to ensure that a bridge is built to the correct profile, things can go wrong. Differences do arise between the actual and the theoretical flexibility of the cantilevers. Small errors in the method of erection or the precasting work also have a disproportionate effect on the final shape. Embarrassing high points can occur at mid span, where cantilevers meet. When this happens a new profile must be developed for the surface of the road, which will give an adequate depth of road construction over the high points. Sight lines, ridability, visual appearance, and additional deadweight must all be taken into account before accepting a new profile. It is of great assistance if the designer has incorporated a substantial downstand on the parapet beam, so that it is not obvious that the cast-in-situ beam takes a different line to the segmental box. A new profile is likely to be formed from a series of flats and curves, which is difficult to assess for visual appearance, even when it is drawn to a large scale. Access to computer graphics provides an invaluable aid when selecting the best line.

Summary

A great deal of forethought is needed before attempting to start the cycles of segmental bridge construction on-site. Site control is an essential element of the construction work and should be incorporated into the program in advance by agreement with the contractor to avoid conflict when work is in progress. If all parties are committed to cooperation and free exchange of information, a mutual confidence will develop that is essential for successful completion of this type of construction.

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