Prefabrcication:
The Natural Construction Process

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Lecture delivered
on Tuesday November 12, 2002
at the Institution of Structural Engineers, London

The Fellowship Chairman, Dr R M Kimber, in the chair
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After graduating in structural engineering from the University of Manchester, Institute of Science and Technology (UMIST) Dr Taylor worked for three years with Sir Alexander Gibb & Partners and fourteen years with the Cement & Concrete Association before joining Dow-Mac Concrete Limited (now Tarmac Precast Concrete) in 1978 as Chief Engineer and subsequently as Technical Director. Whilst in employment at the Cement & Concrete Association Dr Taylor completed a PhD on the fundamental behaviour in shear of reinforced concrete. At Dow-Mac, Dr Taylor has been responsible for the technical side of the Company’s activities having direct responsibility for design, quality control, quality assurance, and research and development. Over the years Dr Taylor has been a member of over twenty national and international committees, won numerous awards, published or contributed to over sixty publications and was President of the Institution of Structural Engineers during 1993/94.

Abstract

Prefabrication is one of our oldest and most successful manufacturing techniques. In all forms of construction, apart from reinforced concrete and masonry, it dominates. On an industrial basis it is accepted in civil engineering, ship building, car and aircraft manufacture without question. For smaller equipment including consumer goods and computers, modular methods of design and manufacture dominate. It is only in the construction industry, perhaps with its tradition of hand craft work on site, with stone masons, bricklayers, welders and carpenters, that we find that it is not always the market leader.

This lecture is intended to give a philosophical justification of prefabrication, to celebrate its successes in construction and to show the part it must play if the construction process is to be re-engineered.
Prefabrication: The Natural Construction Process

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Introduction

Prefabrication is one of our oldest and most successful construction techniques. In all forms of construction, apart from reinforced concrete and masonry, it dominates. On an industrial basis it is accepted in civil engineering, ship building, car and aircraft manufacture without question. For smaller equipment, including consumer goods and computers, modular methods of design and manufacture dominate. It is only in the building industry, perhaps with its tradition of hand craft work on site, with stone masons, bricklayers, carpenters, etc., that we find resistance to the good sense of its use.

Inefficiency in the construction process, Fernand Ledger

Prefabrication has an intellectual justification in the thoughts and theories of the leaders of the industrial revolution. Adam Smith expressed the benefits of the division of labour to a specialised work force and factory as:

"This great increase of the quantity of work is owing to three different circumstances. Firstly, to the increase of dexterity in every particular workman; secondly, to the saving of the time which is commonly lost in passing from one species of work to another; and, lastly, to the invention of a great number of machines which facilitate and utilise labour and enable one man to do the work of many".

Adam Smith, 1776
The Wealth of Nations

Adam Smith pointed out some of the advantages to be obtained from maximising factory based construction:

- Enhanced skill of operatives.
- Development of machines.
- Speed.
- Reduction in cost.
He left unsaid the other main advantage of prefabrication:

- Improvements in quality.

It is the intention in this lecture to explore the process by which we construct our Civil Engineering Structures, with particular emphasis on transportation, to see whether a greater consideration of prefabrication would be worthwhile.

After a consideration of the philosophy of prefabrication, progress in highway structures will be highlighted, particularly with respect to bridge engineering in particular of precast concrete construction.

**Historical development**

The Victorian Engineers took their lead from the earlier pioneers of the Industrial Revolution and tackled many projects in ways which were then innovative, to produce structures which could not be made without prefabrication.

Stephenson in 1845 moved the main box girders for the Britannia Bridge across the Menai Straits on barges to be then jacked up on their final abutments. Brunel did the same thing with the tubular tied arch on the Tamar Bridge.

These massive structures were not manufactured in factories, but were assembled in safe locations (prefabricated) and moved to their final location. It was probably these spectacular successes that encouraged civil engineers to favour prefabrication.
Concrete structures have also been similarly constructed and moved in a variety of ways. Transportation by floating—Mulberry Harbours and offshore oil platforms, by launching and by towing are all common.

The difficulty of the site as a work place is an important spur.

Adam Smith recognised the potency of the ‘division of labour’ in improving the efficiency of manufacture. In his book an example is of the making of nails. Instead of one person making a complete nail, much greater production is achieved if the workers concentrate on individual tasks in which can then be very efficient, passing the part completed nails from one expert specialist to another, down the line to completion. From this came the substitution of persons by machines for more and more of the basic sub tasks.

In 1908, a Model T Ford cost $805 when it first went to market. In 1909/10, 18,664 were produced and in the next year 34,528. The assembly line was developed to cope with this demand. In 1913 a Model T was assembled in 12½ hours, in 1914 this was reduced to 36 minutes. As a result motor cars reached a whole new mass market as they were affordable by the middle class yet in 1914 Ford was able to double his workers’ pay to $5 per day.

**Discipline of prefabrication**

Prefabrication brings advantages of better ‘buildability’ and speed in the whole structural range, from the most massive to the most simple. It is only necessary to visit a prefabricated bridge structure being erected on site for one to appreciate the benefits of the dry form of construction, no deterioration of site stored materials, an absence of falsework and shuttering, and the absence of a large and often badly controlled workforce. The erection process from factory to truck to final location on site minimises opportunity for damage and for inferior work to be built in.

**The description of Prefabrication also brings many benefits from an often disregarded opportunity in design, the advantage of the discipline.**

Some of the most inspiring works of human creativity comes from the skilled use of a limited language. In music for example a limited number of notes and instruments are capable of providing the most stirring of results. Indeed, there appears to be more beauty in the use of the musical language in a disciplined classical way than in more recent, freer use of sound. Prefabrication has this same opportunity, the observer notes the shape of the small components and appreciates how these can be built up with only minor modifications to a totally different, but readily understandable whole.

The aesthetic discipline can also pick up and emphasise, to advantage, a further practical necessity, the handling of joints.
Design considerations

In all forms of prefabrication the presence of joints brings three immediate requirements; the need to have sufficient strength, the need to avoid abrupt failure modes and the need to cope with manufacturing and construction tolerances:

- Strength of joints.
- Durability.
- Tolerance.

Bridge joints invariably leak. A typical example found in the USA

Integral construction eliminates joints between deck and abutment. A joint which is easier to maintain still exists behind the abutments

From the aesthetic point of view a structure which is proud of its joints, in which joints are well articulated and detailed to express their function and load paths can be very successful.

In bridges and other structures exposed to the external environment, joints must be detailed for maximum durability; sometimes they are expressed and sometimes not. When joints are expressed, however, very attractive structures can result.

Integral construction eliminates carriageway joints. This detail still allows simply supported beams to be used

All structures have joints and these create local problems of concentrated forces and force resultants in the area immediately around the joint zone.

Saint Venant stated this principle clearly:

‘Forces applied at one point on an elastic structure will induce stresses which, except in a region close to that part, will depend almost certainly upon their resultant action and very little upon their distribution’.

Saint Venant

SY Vermont’s Principle illustrates the two designs: local effect and global effect

Away from joint zones, precast concrete design is no different from monolithic reinforced or prestressed concrete design. Even within joint zones the same rules for bearing and bond apply. A beam to beam joint, a segment to segment joint or a beam to column joint can all be understood in terms of internal struts and ties and a successful design will usually result if these concentrated forces and any further secondary forces from their interaction are satisfied. The only difference in precast construction is the additional problem of tolerances. It is easy to imagine how a physical displacement of a supported member from
its correct support position can result in higher flexural forces on a cantilever bracket for example, for which it may not be designed. Similar displacements of reinforced members may result in there being no overlap of reinforcement for one member to the other. Joint design must always take account of the likely construction variations, whether intended or not.

These aspects of joint design are not unique to precast concrete; steel or timber construction also have similar problems which are, of course, solved in ways appropriate to each material. Bolted or welded steel connections always require a detailed analysis in the Saint Venant ‘zone’.

Development of precast concrete in bridges

From early beginnings in the 1900s, the main use of the concrete bridge in the UK is related to the period of national recovery since 1945 and the growth of the motorway network from 1960.

In 1945 there was a need to reconstruct our ports and bridges after the war time devastation. There were shortages of building materials, particularly steel. Prestressed concrete had been used and Britain was able to benefit from the pre-war knowledge of the material not only ‘in-house’ but brought back from France, Germany and Austria. Britain was already manufacturing prestressing railway sleepers by the long line process and a natural way forwards was to develop pretensioned prestressing as a tool for decking in roads and bridges.

The first design code for prestressed concrete, published in 1951, covered both pre and post tensioning and, significantly, introduced a design process which considered service load and ultimate load criteria.

In the late 1950s a common interest group, The Prestressed Concrete Development Group (PCDG) was formed which prepared a number of significant reports and, in particular, developed a national range of pretensioned bridge beams. An inverted tee beam for infill deck—solid slab construction, a standard box beam and a range of I beams for beam and slab construction were all introduced at this time.

These new beams largely replaced the proprietary beam sections that were offered by the different UK manufacturers and since that time the manufacturers, through trade associations with input from academics and our national bridge authority, have further refined the standard bridge range. The development of this range and its current status will be described later in this lecture.

Concrete bridges of reinforced concrete construction and of post-tensioned construction are also common, reinforced concrete commonly being used for voided and solid slab construction of short spans and post tensioning for longer span and box girder bridges.

The requirement for decking for bridges as our motorway network was built between 1960 and 1990, and the geography of the UK, has resulted in the greatest demand in terms of bridge numbers for spans up to 35m.

In 1960, when this latest phase of bridge building started, analytical techniques were in place to analyse plates by load distribution theory and this was used extensively for bridge decks of all but the highest skews. There was a tendency also to introduce within-span diaphragms in beam and slab bridges. The use of grillage analyses and the ready availability of computers from 1965 onwards resulted in an ability to analyse more extreme cases and to eliminate in-span diaphragms.

Precast concrete bridge beams have been produced in significant numbers since 1960. Once the concept of standard beams was developed the range of types was agreed. Three types of construction were catered for, solid slab, beam and slab and voided slab construction. Figure 1 shows the main beams with their dates of introduction and with comments as to type of construction and other notes. The first wave of beam types was developed by 1972. In the late 1980s a re-engineering round was carried out by the manufacturers with the support of the profession and academics. The result was the Y beam (Taylor et al., 1990).

The full range of standard bridge beams

The Y beam was developed specifically to improve durability, to allow greater concrete cover, to aid continuity over supports and to ease integral construction. Without doubt, precast concrete pretensioned bridge beam decks are among the most successful and durable forms of deck construction used in the last 50 years but the opportunity was taken to improve this good experience by providing higher cover.
Currently there are five companies and at least six factories serving the demand for pretensioned bridge beams in the UK.

The need for integral bridges

The understanding of the need for integral bridges came from a detailed review of the performance of our bridge stock.

In 1989 a study of some 200 randomly selected Highway bridges was carried out by Wallbank (Wallbank, 1989). In this study, commissioned by the Highways Agency, the bridges which were distributed around England were inspected with respect to the performance of the concrete in the deck and substructures (some of the bridges had steel girder deck beams). The type of bridge varied, with bridges carrying trunk roads, class A roads, minor roads and farm access, over the same range of road types and over water and open ground. Age varied with the year of construction being between 1920 and 1985 with the majority of the subjects being constructed between 1960 and 1980 as would be expected with the concrete bridge stock. The areas of study carried out by Wallbank were as follows:

- Visual Condition.
- Cover to reinforcement.
- Concrete quality:
  - Cement content.
  - Water/cement.
- Carbonation.
- Chloride contamination.
- Alkali silica potential.
- Sulphate contamination.
- Top surface.

The test work, on site and on retrieved samples, was particularly thorough. The main conclusions are illuminating and are quoted from the report.

‘One of the main recommendations arising from the study is that every effort should be made to prevent bridge deck joints from leaking; these are causing untold damage through chloride contamination of the deck ends and the substructure. Repairing or replacing joints, together with cleaning of bearing shelves, should be major maintenance priority.

To prevent contamination due to spray, it is recommended that all concrete surfaces exposed to spray but sheltered from the rain should be treated by impregnation with silane. It is also suggested that such surfaces be washed down after each winter.’

The report did not specifically recommend continuity or integral construction as it was aimed at giving advice on maintenance of the current stock but the inference was obvious.

At the same time as the Wallbank survey being carried out, the Prestressed Concrete Association (PCA), the UK pretensioned bridge beam manufacturers’ association, started its re-engineering exercise. As a part of this the PCA sent Dr Edmund Hambly to the USA to observe progress in pretensioned bridge beam deck design. This was considered useful as the work carried out by Mattock, Kaar, Kriz, Hognestad and Hanson (Karr et al., 1960) and published in a series of Portland Cement Association reports covered many of the points raised by UK engineers as difficulties in design. These difficulties were the control of sagging support moments from creep and delayed shrinkage and the design of support moments as reinforced concrete incorporating the ends of the prestressed beams in reversed bending. Designers treated these with various degrees of rigor, producing the problems in checking and certification.

Hambly returned to the UK having seen that the Portland Cement Association work had been largely superseded by the development of integral bridges (Hambly and Nicholson, 1990).

The integral designs do not, in many cases, attempt to sustain sagging support moments but in ignoring them allow a benign crack over supports at the soffit and retain continuity in a crack free situation at the top surface of the bridge deck. Such cracking is illustrated in Figure 2.
The Highways Agency continued with its own research spend and supported subsequent research including further studies by Hambly, Pritchard (Pritchard, 1963), work by the UK Transport and Research Laboratory, Cambridge University and others. Interest developed to the stage that in 1993 an IABSE Colloquium held in Cambridge had 24 research papers concerning structure and substructure mostly emanating from the UK.

Work by Pritchard (Pritchard and Smith, 1991) in which a number of UK continuous bridges were surveyed led to an HA standard being published (Highways Agency, 1996a) requiring continuity and recommending forms of potentially successful construction using precast prestressed beams.

Finally, the attention moved from continuity to integral construction and the Highways Agency published its standard The Design of Integral Bridges (Highways Agency, 1996b). This standard requires that 'all bridges are to be continuous over intermediate supports and bridges with overall lengths not exceeding 60 metres and skews not exceeding 30° to be integral with their abutments.

Briefly stated therefore, the integral bridge is a bridge without movement joints and which is integral from one abutment to the other thus giving the maximum resistance to penetration of chloride from above.

This summary of the progress towards integral bridges in the UK is incomplete without recognising that our masonry arches have been integral from the time of their introduction and that a number of concrete integral bridges have been constructed from the beginning of our motorway construction era without them being named as integral. Hambly (Hambly, 1997) gives a review of these structures.

We are still in the learning stage in the design process and work is continuing in design offices throughout the country, in continuing research and by the new concrete bridge common interest group, the CBDG (Concrete Bridge Development Group).

It is important to recognise that the problems with bridges that are addressed by integral construction are problems at joints. The problem afflicts bridges of all types and materials but the joint is still the danger area.

Lessons for the future

It is constructive to consider how the principles of prefabrication apply to the use of precast concrete bridge beams and to identify why they are successful. At the same time it may be possible to look at other areas where its use should be encouraged.

Undoubtedly, prestressed bridge beams are a success story. They have satisfied a major part of the market and must therefore have had first cost advantages. In the long term, when our procurement processes truly reward whole life costs this should strengthen their market position.

The experience of concrete bridges in the field has driven design to some detail changes, cover, silane, etc. and to some changes in form, continually and integral construction. Factory made bridge beams have not shown themselves to have a significant maintenance burden.

The success of the prefabrication of bridge beams and the acceptance of the whole industry of standard sections is not just due to the qualities of the product. The original support of Government in accepting the PCDG standard cross sections was crucial.

Standard cross sections are not the same as standard beams or standard bridges. The standard section concept allows the manufacturer to provide a beam to the bridge engineer’s design and does not force the engineer to accept a standard beam. Thus the designer has control of the whole bridge design but can still obtain the benefit of cost savings in the use of standard moulds and can get supply from a number of manufacturers.

Attempts by manufacturers to persuade designers to accept standard details, moving from a standard section towards a standard beam have always been difficult to realise. The considerable amount of work on the design of standard bridges by the Department in the early 1980s was even more unsuccessful.

Prefabrication appears to be most acceptable when the following conditions are met:
1 The solution is technically correct in the short and long term.

2 The solution is cost effective.

3 The solution can fall within the current accepted design process.

4 The solution is aesthetically acceptable.

5 The solution allows for a choice of provider.

Bridge beams do give solutions in all of these areas so why are not more highway hard landscape components prefabricated? The short answer is that they are. A whole range of prefabricated systems are available for soil retention, safety barriers, gantries, sound barriers, etc. The harshness of the site environment and need for speed in road construction drives the acceptance of prefabricated solutions.


It is interesting to compare this with the much lower penetration of prefabrication into building construction. Here, prefabrication is seen as difficult and costly to design, restricting in choice of provider. In cost terms prefabricated building structures always gain market share when the market is overheating and site labour costs rise significantly beyond costs in factories. The current re-awakening of interest in new forms of construction procurement is, we are told, going to result in more prefabrication, indeed this seems to be already the case. Increased use will not be successful in the long term, however, until the five conditions previously mentioned are achieved.

References

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<thead>
<tr>
<th>BEAM</th>
<th>SECTION</th>
<th>SPAN RANGE (m)</th>
<th>INTRODUCED</th>
<th>FORM OF CONSTRUCTION</th>
<th>DEPTH RANGE OF BEAM (mm)</th>
<th>NOTES</th>
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<td>INVERTED T BEAM</td>
<td><img src="image" alt="Inverted T Beam" /></td>
<td><img src="image" alt="Span Range" /></td>
<td>1951</td>
<td>SOLID SLAB</td>
<td>380 - 915</td>
<td>PCDG design still in production</td>
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<td>BOX BEAM</td>
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<td><img src="image" alt="Span Range" /></td>
<td>1955</td>
<td>VOIED</td>
<td>510 - 1910</td>
<td>PCDG design not an HA currently preferred type</td>
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<td>I BEAM</td>
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<td>1965</td>
<td>BEAM &amp; SLAB</td>
<td>510 - 1910</td>
<td>PCDG design went out of use relatively quickly</td>
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<td><img src="image" alt="Span Range" /></td>
<td>1970</td>
<td>BEAM &amp; SLAB</td>
<td>720 - 1360</td>
<td>Originally conceived with a concrete bottom connection to give a voided construction</td>
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<td>1972</td>
<td>VOIED</td>
<td>800 - 1600</td>
<td>A popular beam provides a simple means for providing continuity with an in situ plug</td>
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<td><img src="image" alt="Span Range" /></td>
<td>1990</td>
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<td>Re-engineered beam, replacing M beam</td>
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<td>1992</td>
<td>BEAM &amp; SLAB</td>
<td>1500 - 2000</td>
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<td>1995</td>
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