Development of Sustainable Forms of Construction

A. E. Long and S. E. Taylor
Queen’s University Belfast, Northern Ireland
R. K. Venables
Crane Environmental Ltd. UK
J. Kirkpatrick
Owen Williams Consulting Ltd

ABSTRACT: Initially in this paper, a brief overview of a recently established COST Action “Sustainability of Constructions – an Integrated Approach.” is given. Secondly, details are given of recent research at Queen’s University Belfast on two innovative forms of construction, both of which have the potential to be highly sustainable. The first is on un-reinforced concrete bridge desk slabs and the second is the development of a flexible concrete arch system for short span bridges with no steel reinforcement.

1 INTRODUCTION
The built and natural environments are inseparably linked. Energy, materials, water and land are all consumed in the construction and operation of buildings and infrastructure to such an extent that sustainable development can be said to depend on the built environment. The world’s cities have a major impact on emissions of ‘green house gases’ and global warming: they take up around 2% of the earth’s surface but account for nearly 80% of the carbon emissions from human activities. The urban environment influences our living conditions, social well-being and health. Thus the performance characteristics and quality of our infrastructure are of fundamental importance to urban sustainability and the well-being of our environment. The significance of this should not be underestimated especially if it is borne in mind that our infrastructure accounts for at least 50% of our national wealth.

Sustainability issues in construction are characterised by their complexity, the diversity of those involved and the need for innovative and special solutions. As the largest and most fragmented industry, the construction sector faces huge challenges in the pursuit of sustainability. Sustainable construction is a way for the industry to move forward, taking into account environmental, socio-economic and cultural issues.

Enhanced sustainability can be achieved through an integrated approach and by adopting innovations in technologies as well as by avoiding over-complex and high-energy-consuming solutions. A science-based approach is essential for transforming the potential of the so called “enabling technologies” into practice. Thus information and communication technology, biotechnology and advanced industrial materials represent some of the opportunities to move towards more sustainable construction processes and products.

Recognising the need for an integrated approach to advance sustainability within construction a COST Action C25 was initiated by the European Commission in 2006. This action is supported by over twenty European countries and its main objective is to “support the science-based development of sustainable construction in Europe through the exchange of scientific results concerning design tools, assessment methods, advanced materials and technologies as well as construction processes, both for new construction and the rehabilitation of existing”. More detailed information on this Action is provided in this paper complemented by details of bridge research at Queen’s University on two technological innovations which could lead to much more durable and more-sustainable forms of construction.

2 COST ACTION C25: SUSTAINABILITY OF CONSTRUCTIONS – AN INTEGRATED APPROACH

2.1 Background and concept
COST (European Co-operation in the field of Scientific and Technical Research) represents a bottom-up approach to research, and trans-national committees have been involved in various research themes (Actions) in difficult fields since the early 1970s. In 1991 COST Urban Civil Engineering Technical Committee was established and COST
C25 is the 25th Action undertaken under the umbrella which has representatives from Architecture, Planning and Civil Engineering and can include participants from up to 34 member states largely from within Europe. This action follows on from a number of earlier actions which directly or indirectly had their focus on sustainability issues.

2.2 Issues being addressed in COST Action C25

The development of the concept of ‘Sustainable construction’ is aimed at ensuring more-economical use of finite raw materials and reducing, or mitigating against, the accumulation of pollutants and waste. The complete cycle of sustainable construction activities comprise the ways in which built structures and facilities are procured and erected, used and operated, maintained and repaired, modernised and rehabilitated, and finally dismantled for reuse or recycling. Compared with other industrial products, those in construction are long-lasting. This fact emphasizes the need to incorporate sustainability principles at an early stage in the design and development of construction projects. More specifically the following aspects need to be considered.

2.2.1 Environmental assessment methods and tools

Major civil engineering and development projects are subject to Environmental Impact Assessments as part of the development of their design and to secure planning approval. Yet the assessment of environmental impacts over the lifetime of built facilities (life-cycle environmental assessment) is fraught with uncertainty. Ideally, such life cycle assessments, in addition to estimates of life cycle costs, should be made available to clients before construction work begins, and many clients, architects and consulting engineers already take detailed account of environmental aspects in their designs, e.g. consideration of service life in combination with structural design. However, much better tools for life-cycle environmental and cost assessments need to be developed and integrated with each other. This would enable different strategies for infrastructure projects to be evaluated during design e.g. long life vs design so that repairs and rehabilitation can be carried but without prohibitively expensive disruption (e.g. Tinsley Viaduct in the UK). What such improved tools need are, for example, much better information on the life cycle performance and environmental impacts of materials and components used in civil engineering and major construction projects, including their embodied energy.

Performance assessment tools and award schemes such as BREEAM and CEEQUAL need further adoption in industry as targets and rewards to project teams for improved performance – see www.breeam.co.uk and www.ceequal.com.

2.2.2 New materials, products and technologies

New materials, products and technologies offer longer-term opportunities for the reduction in environmental impacts. For example, the latest construction products such as lighting, heating and cooling systems can play a major role in improving the energy efficiency of buildings. It is also important that life cycle approaches to improving environmental performance are adopted not only for products but for construction works as well. Construction performances need to be viewed in terms of functional units, how they perform throughout the life-time of a built facility and what happens to them when deconstruction or demolition takes place. Focusing on an integrated and holistic approach, research is necessary as the associated problems are interrelated and cover a wide spectrum – typically a single building can consist of many basic materials and thousands of separate products. The challenge is how to measure and manage the impacts of construction projects. Generic performance based design and product development technologies offer tools for the management of research and development work.

2.2.3 Reuse and recycling of materials

Reuse and recycling of materials and components achieve a rate of over 80% in some Organisation for Economic Co-operation and Development (OECD) countries, but it should be noted that much of the material is used in low-value-added forms. Increasing use of recycled waste for structural applications is one way of positively addressing such sustainability impacts.

2.2.4 Environmental management

Environmental management of the construction process, for example for a new building, a bridge or for a renovation project, is now a very well-developed process, used by the majority of major UK construction firms. It necessitates an integrated and performance-based approach for project management so as to optimise the overall function of the completed project. Improved methods of integrating environmental and fiscal analyses would be helpful so as to take into account the different phases of the life-cycle.
2.2.5 Energy management

Energy-efficiency in buildings is one of the most environmentally benign ways to save energy. From the viewpoint of the EU, it has the highest priority on the three key issues identified as an area of necessary actions. The Directive on Energy performance of buildings aims at improvements in energy-efficiency-related measures, and action plans in this area are expected to grow in the future. Improvement in energy efficiency brings direct benefits for urban sustainability.

2.3 Roles within COST Action C25

Professor Luis Braganca (Portugal) is the Chairman of COST C25 and the two of the Authors (A. Long and R. Venables) have been accepted as the UK representatives. Three Working Groups are proposed:

- **WG1** – Global Methodologies, assessment methods, global models and databases
- **WG2** – Eco-efficient use of natural resources in construction (materials, products and processes)
- **WG3** – Life-cycle performance.

R Venables is likely to contribute to WG1 on the basis of his long commitment to sustainability and his contribution to the establishment of CEEQUAL (Civil Engineering Environmental Quality Assessment and Awards Scheme). This scheme has now been successfully applied to projects in UK/Ireland, with the total value of projects that have been or are being assessed recently passing £2b (€2.9b). A Long anticipates that his research on structures and materials could be usefully applied to WG3 in relation to life cycle assessment and the utilisation of innovative techniques to enhance the sustainability of structures.

3 IMPROVING THE SUSTAINABILITY OF CONCRETE BRIDGE DECKS BY DESIGN

3.1 Background

Bridges with spans of up to 30m constitute the vast majority of road infrastructure bridges in service across the world – whether it be for overpasses/underpasses for motorways or for minor river crossings. Within this category of bridges concrete deck slabs are widely used whether in combination with pre-cast pre-stressed concrete beams or steel girders. A similar type of deck can also be utilised for many medium span bridges hence the importance of designing a durable deck system cannot be overemphasised.

Over the past 20 years it has been found that many concrete bridges (concrete was selected in the 1960/70’s for its inherent durability) have exhibited problems, such as spalling, associated with reinforcement corrosion. Such problems are particularly prevalent in marine environments or where freezing/thawing conditions require the intensive use of salt to prevent the formation of ice. In the latter case the vulnerability of the reinforcement in the deck slab is exceptionally high and in many instances deck slabs have to be repaired/replaced at great cost within 20-30 years. This causes great disruption to traffic and the associated costs of congestion are high.

A further problem for bridge deck slabs is that they have to be assessed structurally to ensure that they can carry the heavier lorries now on our roads. These deck slabs would in many cases be found to be unsatisfactory were it not for an inherent strength which is not taken into account in normal flexural design approaches. In particular it is accepted that the capacity of the slab elements of beam and slab decks is greatly enhanced due to the restraint provided by the beams and diaphragms. This enhancement has been recognised by a number of bridge authorities worldwide by incorporating it into their national design codes. Whilst BS5400 [1978 & 1990] does not recognise this the current UK assessment codes [BD44/95] for concrete structures do allow arching action to be included in the assessed capacity of deck slabs. The recognition of arching action is most important as it can mean the difference between a bridge deck passing or failing the assessment requirements.

In this paper the greatly enhanced strength associated with arching action, which is clearly of benefit for increased loadings, when taken into account in the design process can be shown to produce concrete bridge decks which are more durable than current designs. Any associated increases in costs will be more than compensated for by the anticipated increase in life expectancy before repairs are needed.

3.2 The concept of arching action in slabs

With the advent of Johansen’s [1962] yield line theory in the 1940s designers and researchers felt that at long last they had a prediction method for slabs which would provide realistic strength estimates. However, the tests carried out by Ockleston [1955] on interior panels of the Old
Dental Hospital in Johannesburg revealed collapse loads of 3–4 times those predicted by the yield line method. This enhanced capacity was attributed to the development of an internal arching mechanism arising from the restraining effect of the surrounding panels.

Where a beam is restrained against longitudinal expansion, the concept of arching can best be understood by referring to Fig. 1. With the development of tension cracks at mid-span and at the supports the beam tries to expand longitudinally but as it is restrained, corresponding forces are induced which allow it to sustain a substantial load on the basis of the arching thrusts which develop as the deformation increases.

Figure 1. Arching action in a typical bridge deck slab

Similar actions take place in two-way systems where a dome or membrane rather than an arch is generated and this phenomenon is generally referred to as "Compressive Membrane Action" (CMA) The extent of the enhancement provided by compressive membrane action, over and above the flexural strength, depends on the degree of restraint provided by the surrounding structure. A typical load deflection curve with the notional contributions of CMA and flexural action separately identified is given in Fig. 2.

Figure 2. Interaction between flexural and arching action

3.3 Relevance to bridge deck slabs

Tests on model bridge deck slabs in the Civil Engineering Department, Queen's University, Kingston, Canada, in the late 1960s revealed considerable reserves of strength against punching failure [Tong & Batchelor, 1971]. The cause of this enhancement was correctly identified as CMA and its particular relevance to transient concentrated wheel loads was recognised. Here it is important to note that bridge decks represent one of the first areas to be considered appropriate for the utilisation of these design concepts. This is largely because the major localised loading is transient in nature and hence creep, which may reduce the enhancing effects of CMA, is of little importance.

On the basis of small scale model tests a conservative design method was produced. Thus in the Canadian design standards [2005] for beam and slab bridges, nominal transverse reinforcement, only 0.3% was required to resist concentrated wheel loadings as opposed to the 1.7% based on flexural design requirements. Similar design concepts are now accepted in various states in the U.S.A. and to date no adverse effects have been detected from these reductions in levels of reinforcement.

3.4 Research on arching action in the UK

3.4.1 Validation tests in Northern Ireland

In the knowledge of the research carried out in Canada on AASHTO girder based beam and slab bridge decks it was decided that parallel tests should be carried out on spaced M-beam (essentially a range of depths of prestressed I-beams with a narrow top flange and a broad bottom flange 1m wide) decks to determine whether similar reductions in transverse reinforcement were possible. This would allow a slightly larger M-beam to be used at a spacing of 1.5m or 2.0m with consequent savings relative to smaller M-beams at 1.0m spacing. In order to establish the strength of the slabs spanning between beams a one-third scale model bridge deck was constructed in the laboratory and tested at Queen's University Belfast, in the late 1970s.

The design of the prototype slab for the two 112.5kN wheel loads using the equations of Westergaard [1930] indicated that steel reinforcement of the order of 1.7% was required. For test purposes areas of reinforcement equivalent to approximately 1.7%, 1.2%, 0.5% and 0.25% were provided in the model along with three panels equivalent to 2m spacing and two panels equivalent to 1.5m beam spacing providing a total of 20 panels for testing.
### 3.4.2 Model test results and prediction method

The ultimate load capacity of the 20 test panels was determined as the load which caused the loading shoe (simulating the wheel load) to punch through the slab in the characteristic manner. It was found that there was very little variation in the ultimate load capacity of all the panels even though the transverse reinforcement varied from approximately 0.25% to 1.7%. In comparison with USA [1979] and United Kingdom [1978] design code predictions (Fig. 3) the results of the tests on the one-third scale model with the M-beams spaced at up to 2m apart showed considerable enhancement over the design capacity of the standard slab. This enhancement can be attributed to the considerable in-plane restraint that is inherent in bridge deck slabs.

![Image](33x405 to 306x597)

Figure 3. Test results of one-third scale model bridge deck

Figure 3 clearly shows that the codes do not give a satisfactory prediction of the punching shear capacity of typical bridge slabs and a more appropriate method which allows for in-plane restraint was therefore developed. For rigidly restrained bridge slabs, the effect of reinforcement upon the ultimate capacity is small as is evidenced by the results of the model test. Thus a method of prediction has been derived to allow for the compressive membrane forces generated within the slab. This method makes use of an effective steel reinforcement ratio, and full details of the method and its derivation are given in Kirkpatrick et al, 1984. As can be seen from Fig. 3 the proposed method of predicting the punching shear strength of reinforced concrete bridge slabs gives good correlation with the results from the one-third scale model. This method has now been endorsed by the UK Highways Agency and is included in BD81/02 [2002].

### 3.5 British Cement Association (BCA) model tests

Jackson [1990] reported the results of a series of tests on the slabs of half scale bridge decks. These were carried out in the BCA laboratories and the results obtained for the spaced M-beam configuration confirmed the findings of Kirkpatrick et al [1984]. It was concluded that even though a sophisticated finite element model, which allowed CMA effects to be taken into account, had been utilised, the prediction method of Kirkpatrick was considered to give conservative estimates of the ultimate capacity. In this paper Jackson took account of global as well as local effects and even when the diaphragm was not included in one of the models the measured strength was still higher than that predicted by Kirkpatrick, 1984.

### 3.6 Serviceability of deck slabs

The ultimate load tests referred to above have indicated that strength is not critical in the design of deck slabs - however, designers also have to satisfy the serviceability limit state requirements. The widths of the cracks induced in the slabs were monitored during the model test in the Queen's University of Belfast and it was found that under service load conditions no cracks resulted. However, as scale effects can affect the accuracy of these measurements full-scale tests [Kirkpatrick et al, 1986] were subsequently carried out on a bridge built by the Northern Ireland Roads Service. This bridge incorporated beams at 1.5m and 2m spacing, and the reinforcement varied from 0.25% to 1.7% in the standard 160mm thick deck slab.

The tests showed that current crack control formulae are not applicable because of the enhanced performance which results from the development of compressive membrane action. Initial cracking occurred at loads well in excess of the design service loads and even after cracks had been induced by severe overloading it was found that the slabs still satisfied the serviceability limit state requirements. The findings of this research have led to the adoption of a less conservative design approach for M-beam bridge deck slabs by the then Department of the Environment for Northern Ireland [DOE, 1986]. Provided certain restraint conditions are satisfied, the use of a nominal 0.5% reinforcement in the slab is now acceptable.

### 3.7 Review of the advantages arising from CMA

From a structural viewpoint the following benefits are evident:
1. Reduction in reinforcement (from 1.7% to 0.5% or less)
2. Same slab depth for greater spacing of beams
3. Lower overall cost of bridge superstructure as one larger beam at 2m centres is less expensive than two smaller beams at 1m centres.

Thus substantial reductions in costs can be achieved whilst at the same time retaining comparable strength and durability. However if the long-term durability of the bridge deck could be increased at a modest increase in cost then the whole life cost could be reduced as can be shown schematically in Fig. 4. Thus the challenge to designers is to achieve the type of relative performance achieved by the CMA deck (enhanced durability). Significant progress of this front has been achieved in Canada and the UK in recent years.

3.8 Improved sustainability by design

3.8.1 Canadian Developments

The beneficial effects of CMA prompted the development in Canada of a novel reinforcing system [Mufti et al, 1987]. In this system, the in-plane restraint to the slab is provided by external steel reinforcement and the control of cracks due to temperature and shrinkage is provided by relatively inexpensive polypropylene fibres. Since these fibres are not affected by de-icing salts, a deck reinforced by them is not only inexpensive but is likely to be highly durable. The feasibility of a number of possible reinforcement arrangements has been assessed via tests on half-scale models of steel beam/concrete slab composite systems. Arising out of these model tests the Canadian authors have enough confidence in the proposed concept to suggest that conservatively designed fibre reinforced concrete deck slabs could now be used in actual bridges and a number of these bridges have been in service for nearly ten years.

3.8.2 Developments in Northern Ireland and the UK

The system developed in Canada is not applicable to decks with pre-cast prestressed concrete beams which tend to be significantly more popular across the world. Thus a number of alternative approaches have been the subject of ongoing research both in the laboratory at Queen's University and on site in conjunction with the Department of Regional Development- DRD (NI) Roads Service [Taylor et al, 2001 & 2003; Taylor & Mullin, 2005] This work focuses on the following subjects:

1) Concrete - As well as considering the addition of fibres, advantage is being taken of the fact that for a given degree of restraint the strength of slabs developing CMA is significantly enhanced by increases in concrete strength as illustrated in Fig.5.

2) Reinforcement - Apart from considering the lower percentages of top and bottom reinforcement (0.5% vs. 1.7%) site and laboratory tests have been carried out on:
   i) Conventional steel reinforcement located in a single layer at the centre of the slab (greatly increased cover).
   ii) Glass fire reinforced plastic reinforcing bars.

Both approaches have performed well, as anticipated, and it is clear that by using high strength concrete (with or without fibres) in conjunction with corrosion free reinforcement, bridge decks could be produced which should be virtually maintenance free. Because of the lower percentages of reinforcement these need not have a higher initial cost than conventionally decks hence it could be of enormous benefit to bridge owners.
3.8.3 Field tests on Corick Bridge (NI)

Following laboratory work, tests were carried out on a reinforced concrete beam and slab bridge in Northern Ireland which incorporated novel reinforcement type and position [Taylor et al, 2007]. The tests were carried out in collaboration with the Department of Regional Development (DRD), Roads Service, and Northern Ireland. Some comparisons have been made with arching theory described in BD81/02 [Highways Agency, 2002] which came about as a result of previous research at Queen’s University.

The Corick bridge tests corroborated the findings of laboratory models and showed that the deck slab behaviour was virtually independent of the percentage of reinforcement. This challenges current flexural analysis which gives a direct correlation between the deck slab strength and the amount of steel reinforcement. Additionally, the slabs strengths were far in excess of those predicted by the standard flexural theory. This will allow for CMA concepts to be incorporated into relevant national design codes as is the case in Canada and in the UK. The enhanced strength and serviceability of laterally restrained slabs to be taken into account in the assessment of beam and slab bridge decks. This will allow for:

i) the enhanced strength and serviceability of laterally restrained slabs to be taken into account in the assessment of beam and slab bridge decks.

ii) CMA concepts to be incorporated into relevant national design codes. Already this is accepted in Ontario, Canada and in the UK.

iii) the benefits of the increased design capacity associated with CMA being taken account of in the slab elements of box girder bridge and other forms of cellular structures.

iv) the development of highly durable deck slabs, which will be virtually maintenance free.

The net effect of all the above is more cost effective bridge decks which exhibit greatly enhance sustainability relative to existing designs.

4 A NOVEL FLEXIBLE CONCRETE ARCH SYSTEM FOR SUSTAINABLE BRIDGES

4.1 Background to the novel arch system

Masonry arch bridges are one of the oldest forms of bridge construction and have been around for thousands of years. Brick and stone arch bridges have proven to be highly durable as most of them have remained serviceable after hundreds of years. In contrast, many bridges built of modern materials have required extensive repair and strengthening after being in service for a relatively short part of their design life. This section describes the development of a novel flexible concrete arch system that has the potential to be highly sustainable due to the low or zero amount of steel reinforcement.

It is no longer economically viable to construct a masonry arch in the traditional method due to the cost of skilled labour required to build the accurate centring and to cut the masonry blocks. Progress on this type of work is usually slow and can be weather dependent. In order to provide a viable alternative Queens University of Belfast, in collaboration with Macrete Ireland Ltd, are developing a flexible...
concrete arch system made of un-reinforced pre-cast concrete voussoirs. The arch is constructed and transported in the form of a flat pack using a polymer grid reinforcement to carry the self weight during lifting but behaves as a masonry arch once in place.

Basically there are two options for the construction of the arch unit. The voussoirs can be pre-cast individually, laid contiguously horizontally with a layer of polymer grid material placed on top. An in-situ layer of concrete, approximately 40mm thick, is placed on top and allowed to harden to interconnect the voussoirs. The same unit can be made in a single casting operation by using a shutter with wedge formers spaced to simulate the tapered voussoirs. Both forms of construction are shown in Fig 6. The arch unit can be cast in convenient widths to suit the design requirement, site restrictions and available lifting capacity. When lifted, the wedge shaped gaps close, concrete hinges form in the top layer of concrete and the unit is supported by tension in the polymer grid. The arch shaped units are then placed on a precast footings and all self-weight is then transferred from tension in the polymer to compression in the arch.

This is in line with advice given by the UK Highways Agency [1995b] where the arch form, plain structural elements and the elimination of corrodible reinforcement are recommended.

4.2 Materials

Control samples of the polymeric reinforcement were tested to ascertain the material properties. The polymer grid is available in a range of mesh sizes and strengths. The manufacturer’s data sheet also gave the longitudinal and transverse tensile strength in kN/m. Table 1 summarises the results of material tests carried out at Queen’s University Belfast. The differences in the measured and specified values for the tensile strength may be accounted for by the difference in the test method. The initial 0.35m wide arch used a 100/15 Paragrid® but a stronger grid, 150/15, was used in the 1m prototype arch for the lifting and placing of the arch. The concrete used for casting the voussoirs was the standard pre-cast mix used by Macrete Ltd with a 7-days compressive strength of ~40N/mm² and a 28-day compressive strength of ~55N/mm².

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Tensile strength of material from manufacturer (kN/m width)</th>
<th>Tensile strength of material from test results (kN/m width)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100/15</td>
<td>100</td>
<td>43.6</td>
</tr>
<tr>
<td>150/15</td>
<td>150</td>
<td>72.2</td>
</tr>
</tbody>
</table>

4.3 Manufacture of the arch unit

A prototype arch unit of 5m span, 2m rise and 2.5 m internal radius was constructed and lifted. This arch required twenty-three voussoirs which were 1m wide and 200mm deep with a 40mm slab interconnecting in-situ screed. The arch was lifted at approximately the quarter span points with additional nominal support at the mid span region. During lifting the arch drags at the each end and the mid span point tends to sag; hence the need for the additional support. When the end cantilevers are fully effective they produce a hogging moment in the mid span region which assists in the formation of the arch. During this operation a critical case occurs when the arch is fully formed and suspended at the lifting points. A maximum bending moment occurs at the lifting points for the cantilever ends and to simulate this condition a series of short beam elements were tested to establish the capacity and to investigate the rate of creep in the low modulus polymer reinforcement. A summary of the results of these tests is given in Table 2 and it was found to give an adequate factor of safety during the lifting procedure. The lifting sequence is shown in Fig. 7.
<table>
<thead>
<tr>
<th>Arch Load Test No.</th>
<th>Applied Ultimate Load: excluding the self weight (kN)</th>
<th>Ultimate Moment: including the self weight (kN.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.0</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>16.0</td>
<td>8.3</td>
</tr>
</tbody>
</table>

The arch unit complete with tapered seating is shown in Fig 7c. Subsequently, an anchor block detail was designed for the seating of the arch ring. The anchor block caters for the slope of the last voussoir enabling the arch to form correctly. It also provided some lateral restraint to the arch ring both during construction, prior to completion of the arch system with spandrel walls and backfill, and in the long-term under live loading.

4.4 Stability test

4.4.1 Test set-up
To assess the flexibility of this system, a stability test under backfilling operations was conducted and the arch unit was monitored for horizontal deflections, vertical deflections and strain at the voussoirs joints. It was originally intended to backfill the arch with Type 6S granular backfill under the Specification for Highway Works, Volume 1 [1998]. However, after a preliminary cost estimate for this span, it was decided to trial the use of lean mix concrete as a backfill option. Shuttering for the backfill was set-up independently to the arch ring to allow free movement during the placement of the concrete.

4.4.2 Test procedure and results
The backfilling operation was carried out by placing approximately 250mm deep layers of concrete to each side of the arch up to 1.5m horizontal distance from the back face of the anchor block. The distribution of load to either side of the arch ring was aimed at minimising the effects of asymmetric load. The depth of the concrete was measured and the transducer and strain gauge readings were recorded at each increment of backfill load. The readings showed a reasonably symmetric response to the backfilling operation.

The maximum movement in the crown was 0.8mm upwards in the back face and occurred at the full height of the concrete backfill. This was due to the lateral pressure of the wet concrete creating an inwards movement at the sides of the arch which in turn caused the crown to rise. As the concrete hardened, the lateral pressure reduced and the deflection response at the crown reversed in direction. That is the upward movement ceased and the crown deflected very slightly downwards. The results of the stability tests showed very little movement in the arch ring and it was concluded that the arch was stable under the backfill operations.
4.5 Live load testing of the arch system

The 1m prototype flexible concrete arch system as shown in Fig. 8 was tested in accordance with the requirements of Macrete Ltd. and following the guidelines in BS8110: Part 2 [1985]. A simulated static wheel load was applied at the midspan and the third span of the arch ring. The single wheel load, for the intended category of bridge, is 5.75t. However, for both loading locations the arch system carried over 35t without showing signs of distress (that is, six times the single wheel load).

4.6 Analysis of the arch unit

An analysis of the arch unit was conducted using ARCHIE, a numerical analysis package which allowed for interaction with the arch backfill as this software is also used by the DRD Road Service in Northern Ireland for load assessment analysis of their arch bridges [Highways Agency, 1997 and 2001] validation using ARCHIE was important. The arch unit was analysed under different wheel loading conditions and deflection profiles were similar to those for the load test. The predicted ultimate capacity was highly conservative when compared with the actual load which was safely carried by the prototype arch system.

4.7 Conclusions for the novel arch system

Experience has shown that arch bridges are highly durable structures requiring little maintenance in comparison with other bridge forms. Thus, the objective of the new Highway Agency Standard [2004] is welcomed especially if it encourages a renaissance in arch building using unreinforced masonry materials.

The novel arch system has been demonstrated, in tests reported in this and other papers, to be a viable alternative to long established methods of construction and the following advantages have been identified:

1. As the Arch system is cast horizontally it can conveniently be transported to site in a “flat pack” form.
2. As centring is not required during installation this greatly simplifies the process and enhances the speed of construction.
3. As there is no corroding reinforcement the long term durability should be assured.
4. Initial estimates would indicate that the system is cost competitive with alternatives such as RC box culverts which do not share the aesthetic benefits or the longevity of an arch.
5. Ease of access to restricted sites. Here the pre-cast voussoirs can be brought to the site separately where they can be transformed into a flexible arch and then lifted into position, in the usual way.

A complete 5m wide arch bridge with a 5m span and 2m rise complete with spandrels, fill and surfacing is currently being constructed. This bridge will be load tested and all necessary data recorded to compare with theoretical predictions. A replacement bridge is also planned in conjunction with DRD (NI) Roads Service.

Current data indicates that in the UK alone almost 3500 bridges with spans between 3m and 9m need to be strengthened or replaced at an estimated cost of £80 million. Thus there is obviously a potential market for this short span bridge system that guarantees high quality pre-cast concrete units, ease of transport, simplicity of erection and exceptional durability. From all view points the system represents a very sustainable alternative for the future.

5 OVERALL CONCLUSIONS

The establishment of COST Action C25, which only commenced its work in late 2006, recognises the need for an integrated approach to advance sustainability within construction. The input from twenty countries will allow best practices from across Europe to be shared and the development of assessment methods will assist in the identification of sustainability issues. Once designers and contractors have a better indication of what they are looking for they will be better placed to take sustainability into account right from the inception of a project. In this way and by developing
innovative technologies to overcome difficulties progress can be accelerated in this important field.

The two examples of innovative approaches to bridges, ie. unreinforced deck slabs and the flexible concrete arch, share the following positive sustainability features relative to conventional designs:

- Little or no maintenance throughout their life
- Greatly extended lives

Since these improvements can be achieved at little or no additional cost the problems associated with traffic disruption/congestion when a bridge is being repaired/replaced can be minimised. This recognition of the significance of full life cycle costing, as opposed to the minimum initial cost approach, is very important from the sustainability viewpoint.

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