

Transport Research Foundation Fellowship Lecture  
MISC23

# Sustainable bridges through innovative advances

Joint lecture of the Institution of Civil Engineers  
and the Transport Research Foundation

Professor Adrian E Long OBE, FEng  
Queens University, Belfast





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Professor Adrian E Long OBE, FREng, Queens University, Belfast

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# Professor Adrian E Long, OBE, FREng

## Queen's University Belfast

Adrian has been Professor of Civil Engineering at Queen's University Belfast for over 30 years. As well as lecturing, he has supervised a number of research projects both for the university and with industry. He is also a Fellow of the Transport Research Foundation. Prior to becoming a Professor, Adrian worked in the Toronto office of Fenco, on the design of highway and railway bridges.

Adrian was ICE President between 2002 and 2003.

### Abstract

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Sustainability is a key issue which must be addressed in the design, construction and lifelong maintenance of civil engineering structures. This lecture will look at sustainability in relation to bridges.

Motorway bridges built in the 1960s and 70s had design lives of 120 years; however many showed signs of deterioration after only 20-40 years. This led to much debate on the issue of initial versus full life cycle costing which is still ongoing today. To address the highly complex issue of the sustainability of bridges, the author will discuss a number of specific areas:

- The use of innovative in-situ testing equipment to assess the long term durability of concrete
- Designs which allow repairs to be carried out on a bridge whilst it is in use
- Innovative structural designs which will extend service life at minimal additional cost

## **Quentin Leiper, President of the ICE**

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It is my great pleasure to welcome all of you to the Institution of Civil Engineers this evening. Whether you join us here in the Telford Theatre or via our Interwise software system (which enables members from all over the world to listen to this event live or, if they wish to, at a later date), I welcome you all to tonight's joint Institute of Civil Engineers (ICE) and Transport Research Foundation (TRF) Fellows Lecture.

This is the first joint lecture between the ICE and the TRF and we are delighted to welcome Professor Adrian Long as tonight's speaker; certainly no stranger to the institution, of which he was President between 2002 and 2003 (and what an excellent President he was) and indeed, no stranger to TRF where he is a Fellow. Also, I should like to welcome Professor Rod Kimber, Chairman of the TRF Fellowship and to Alan Stilwell, Chair of the Institution's Transport Board.

It gives me great pleasure to invite Professor Rod Kimber to the lectern. Rod joined TRL and TRF 10 years ago to lead corporate research and the development of TRL's scientific and engineering capability. He is a visiting Professor at Imperial College London and has extensive experience of transport research, research management and national policy formulation.

## **Rod Kimber, Chairman of the TRF Fellowship**

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I am very pleased to be here this evening to be able to introduce our distinguished speaker, Professor Adrian Long, well known to us all. But first of all, I want to take a minute or two to say a word about TRF and our relationship with the ICE, because it lies at the heart of this evening's event. The TRF group of companies is non-profit distributing, is limited by guarantee and was established for the impartial furtherance of transport and related research, consultancy and advice. It has formal Scientific Research Association status and its main significance to us this evening is that its main subsidiary is the UK's Transport Research Laboratory (TRL).

The Fellowship of TRF is, in turn, an associated body of eminent transport professionals and academics whose interest again is the impartial furtherance of research and professional activity. ICE and TRF already have strong links and a strong mutuality of interest; and it is this that we want to develop together. Let me give you three small examples of co-working. Several of our scientists and engineers are members of the ICE advisory panels, for example, on bridges and waste resource management. Secondly, we have at TRL young graduates who come into the profession and we have a training scheme which ICE manages and oversees, and that sets them off and helps them onto the first ladder to the profession and that gets

them chartered status. And thirdly, we have good links with the Institution's publishing arm, Thomas Telford, and we have co-published a number of books together. So it is this juxtaposition of interests that we want to develop this evening.

This lecture therefore is a step in that direction and I am delighted that it is going to be given by our speaker, Professor Adrian Long of the Queen's University Belfast, who is well known to us all. Let me recite just one or two little bits of background. After receiving his doctorate from the Queen's University Belfast, Adrian moved to Canada and worked as a professional bridge designer and then as assistant professor at the Queen's University Kingston. In the early 1970s he returned to Queen's University Belfast where he became full professor and also subsequently, Head of Department and Dean of the Faculty of Engineering. His research over a period of 30 years has had a great deal of impact and among many achievements – I could not begin to recite the full list, let us just single out one or two: he was awarded the Royal Society Esso Gold Medal; he is Fellow of the Royal Academy of Engineering and he is Founding Fellow of the Irish Academy of Engineering. Adrian was awarded the OBE in 2006.

Adrian's association with transport goes back a long way. In fact, in the late 1980s and early 1990s, he was a visitor to TRL in the days when it was part of the public sector, before privatisation. Now the role of Visitor was a distinguished and normative one – it was to ensure high standards were maintained and to push up the status of the organisation, both nationally and internationally. Adrian played a key part in that and there are many of us at TRL who are most grateful for it – it was a lasting achievement. And he is, of course, past President of the ICE and a TRF Fellow. So I am delighted to be able to welcome Adrian who is going to speak to us this evening on Sustainable Bridges Through Innovative Advances.

## **Adrian Long**

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I am delighted to see so many people here tonight. It is great to see the Telford Theatre full. Could I thank you Mr Chairman and Mr President for your kind remarks – I just hope I can live up to your expectations. Could I also thank TRF for electing me to their Fellowship – I greatly appreciate this honour they have bestowed upon me and especially as, Rod has already said, I have had strong links with TRL for many years. TRL is very clever when asking you to become a Visitor – it does not give you an expectation of a lot of hard work, but it was, though most enjoyable and very challenging, and I enjoyed it immensely. I would also like to acknowledge with gratitude the input of many research students, colleagues and friends down the years to the content of this particular lecture.

## Introduction

Tonight I am going to focus on, first of all, a brief introduction to what I understand to be sustainability. Then sustainability issues as they affect bridges and then move on to some work we have been carrying out over many years at Queen's on the development of novel in-situ test methods with the objective in mind of producing more sustainable concrete structures. Then I plan to move on to sustainable concrete bridges by design, and to give you a brief introduction to a novel flexible concrete arch system which we are currently developing with a pre-cast concrete construction company in Northern Ireland.

### Why sustainability?

In 2002 the comment was made by the then Minister of State for Industry and Energy, Brian Wilson that: 'civil engineering has a major contribution to make to this process, as both a major employer and generator of wealth and as a profession with the technical skills to deliver major improvements to the built and natural environment'. It was good to have that level of support at that time.

Something said by Roger Venables, who I am delighted is here tonight, was that 'the goal is sustainable living

and sustainable development is the process that will get us there' (Fig. 2).

This he highlighted in his ICE Brunel lecture delivered across the world in 2001 and 2002. Because of his tremendous impact on chairing the Sustainability Board of the ICE at that time, I was delighted when he accepted our invitation to become the Royal Academy of Engineering Visiting Professor for Sustainability at Queen's. He has made a tremendous impact over the years.

We aim to reduce the environmental impact of our life and of our work as civil engineers and to maximise the utilisation of materials, and ensure that we re-use all that is possible. Recycling and minimising energy and water use is therefore very important. All of these other features are very important for trying to get to grips with the whole concept of sustainability (Fig.3).



Fig.1

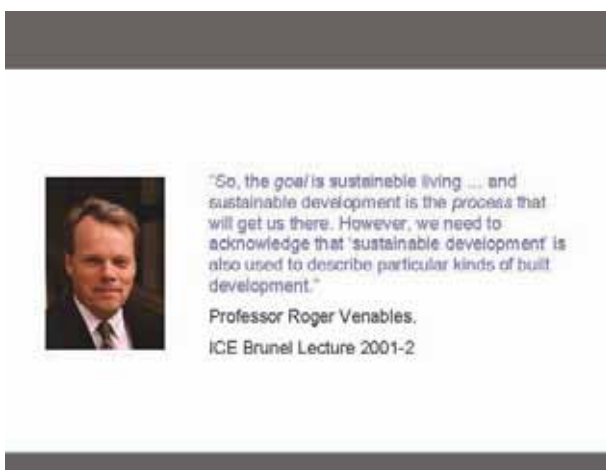


Fig. 2



Fig. 3

The ICE on 17 December 2002 set forth its objectives, and sustainable development became absolutely central to civil engineering so that we could organise ourselves accordingly. This was highlighted in the appropriate edition of *New Civil Engineer* the following week (Fig. 4).



Fig. 4

One of the things that as an Institution we were committed to, was an ICE Sustainability Charter. With the help and support of Roger at that time, I was privileged to launch that Charter in June 2003. Somewhat earlier CEEQUAL (www.ceequal.com), which I will be mentioning briefly, had been launched. The other aspect that I will highlight here was the introduction of the Engineering Sustainability Journal to try to get more of our members to become aware of this very important issue (Fig. 5).



Fig. 5

CEEQUAL (Fig. 6) stands for Civil Engineering Environmental Quality Assessment and Award Scheme. Interestingly enough, this was only introduced four or so years ago and to date, £2 billion-worth of projects have been accredited by Roger and his team. This is, I think, a tremendous achievement and brings great credit to the Institution and to the profession.

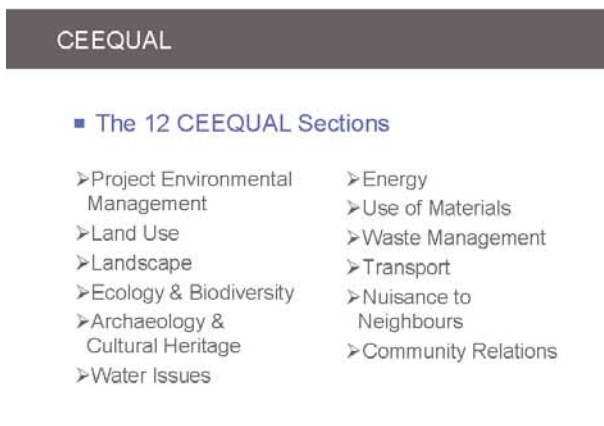


Fig.6

A number of issues are highlighted in Fig. 6. An individual project is not likely to satisfy or require a tick-box in all of these. You have to look at them, consider your own project and decide which are relevant and important and go through the process. And here I could just perhaps highlight something that I had not appreciated – why have a CEEQUAL scheme? Is it just getting on the bandwagon? No. I think having a competitive system is very important

– it encourages engineers to buy into it. If you are a senior engineer in a company or a senior civil servant in a particular department and you see that someone in another company/department is involved in projects that are achieving high gradings in CEEQUAL and yours are not, you can rest assured you will be putting pressure onto your staff to perform better in the future. The whole process of accreditation of sustainability issues is very important in improving and enhancing the quality.

## Sustainability issues affecting bridges

What I want to move on to now briefly is some sustainability issues as they influence bridges. I want to refer to a paper published by David Collings in December 2006 in Bridge Engineering – a very recent paper. I am delighted to say that David is here tonight. David is an experienced designer and he was keen to ensure that sustainability, not just cost, should be taken on board when we compare different forms of construction.

In his paper he considered a ‘generic bridge’ with a span of 120 m over a wide river and with 66m approach spans on each side (Fig. 7). A fairly representative form of construction with a total deck area 4,000 sqm and a combination of short spans and longer spans typical of the range of structures that might well be part of one’s design portfolio within a company.



Fig. 7



Fig.8

He considered a basic girder system, a more sophisticated tied arch and a cable stayed system. He also tried his best to take into account temporary works, repair and maintenance costs for these different forms of constructions – and they were obviously different – and then he combined that with three different forms of construction, steel, concrete and steel-concrete composite construction (Fig. 8).

Within the area of sustainability, two forms of energy are very important (Fig. 9). One is the ‘embodied energy’ which is basically the energy consumed during the construction process. If you think of a bridge, the total energy consumed is relatively high; whereas for, say, something like a hospital, the energy consumed in the construction is relatively small. If then you look at the ‘operational energy’ of these forms of constructions, it is very high for a hospital type building and very low for bridges. And here I will just make this slight qualification for bridges: operational energy is low except when there is excessive congestion as a result of repair, or the maintenance of a structure.

Figure 10 is taken straight from David’s paper and gives comparative values. I will not go through it all, but move on to the subsequent diagram (Fig. 11). It shows three different spans – 20 m, about 90 m and 120 m – and

also shows the comparative costs for steel, concrete and composite construction.

Not unexpectedly, a well engineered long span structure can be less expensive than a poorly engineered short span. Longer spans tend to be more expensive than shorter spans, except you can, with good engineering, close that down and in fact swing it in the opposite direction. One thing that I found extremely interesting is that architectural forms, the arch and, say, a cable stayed system, basically have a premium – they are more expensive, they have more embodied energy than a basic girder. And if you go the next step to a distorted form, the arches of which are sloping, then they are even more expensive or more energy absorbent. So comparative studies of the nature that David has taken on board here are extremely important and extremely useful.

When I worked on bridge design in Toronto, the good designers in the company had little back-of-envelope calculations showing the relative costs of different forms of construction which were extremely useful in deciding which form to select. It is something that I have noticed here: that the trend of results from embodied energy is quite similar to that for the cost per square metre – those two things tend to run hand in hand.



Fig. 9

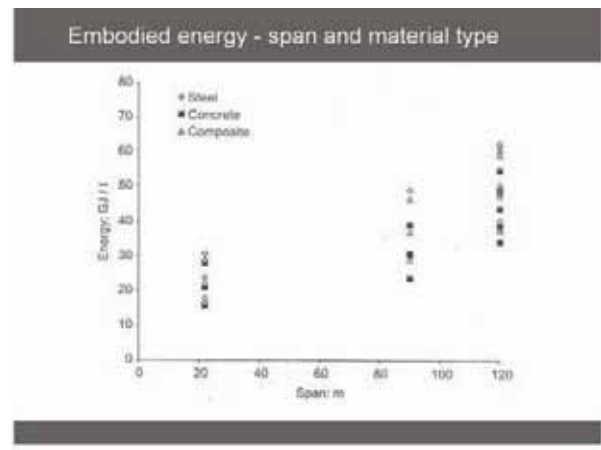


Fig. 11

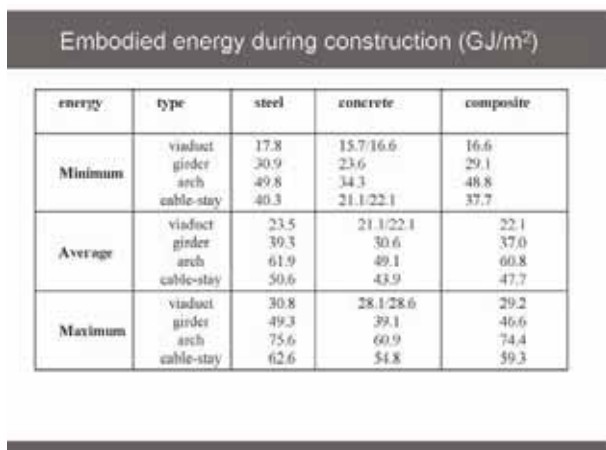


Fig. 10



Fig. 12

## Repair, maintenance and congestion

I will now move on to a slightly different scenario. When I was President of the ICE, I had the privilege of visiting the Tinsley viaduct. It is a bridge which carries the M1 and the A631 over the Don valley just north of Sheffield. It is a 1,000 m long viaduct that has 20 spans and that crosses two railway lines, a river and a canal; the traffic is roughly 115,000 vehicles per day. It was found to be having difficulties right from the day it was constructed because it was a plate girder construction. There were a lot of changes just after it was constructed and it had to cope with the increased load requirements of 40 ton-lorries.

### Repair, Maintenance & Congestion

- Tinsley Viaduct M1-A631 over Don Valley
- 1000m long, 20 spans, 2 rail + river + canal,
- carries approx 115,000 vehicles/day
- 40t lorries, need for replacement



Fig. 13

To replace that particular structure would have cost £200 million, but the congestion associated with closing down the M1 and the other roads have been estimated at £1.4 billion. Now there are ways and means – and I have gained some advice from TRL – in calculating the cost of congestion. One of my students has been struggling to get to grips with this in a project this year so I did a quick back of envelope calculation and came up with a rough costing of £1.2 billion; I thought that was near enough to suggest that these were reasonably valid calculations. So basically you are looking at a total cost of £1.6 billion. Obviously the cost or the environmental impact was far too great. A

### Tinsley Viaduct

- Replacement cost £200m but
- Congestion during construction £1400m
- Cost/Env Impact too great!
- Complex strengthening – kept open
- Minimal congestion – repair cost £80m
- Net saving of £1500m



Fig. 14

complicated but very sophisticated strengthening process was therefore taken on board, and during the peak traffic times the bridge was kept open (it was only closed for a few hours at night). As a result, the structure was repaired at a cost of some £80 million with a minimum of congestion; a net saving to this country of £1.5 billion. Not many other industries can claim such a success.

## Design factors

It is very important that we look much more seriously at total lifecycle costs, as opposed to the initial costs, because initial cost will quite often not give any indication of the long term cost of a particular form of construction. You must look at the ease of repair of the structure, you must compare and contrast the steel versus concrete, whether in fact one is more sustainable or less sustainable. And then in any design we must try and look at the potential impact on congestion. Is maintenance and repair going to cause a lot of congestion? Is that added cost going to be something which is taken into account?

### Design Factors

- Total life cycle vs. initial cost
- Ease of repair
- Steel or concrete
- Cost/Env impact of congestion
- Durable Materials, minimal maintenance, avoid replacement



Fig. 15

## Development of novel in-situ test methods

I will now discuss research work related to durable materials, and how to make the materials longer lasting. I will talk about forms of construction which have minimal maintenance and avoid the need for replacement, and then another form of construction, the arch, which tends to be very durable, strong and aesthetically pleasing.

I will very quickly skate through the development of novel in-situ test methods for concrete – you will be all relieved to find out that even though I have a professorial title, there will be no differential equations here tonight, it is a more generic type of presentation.

I became involved in in-situ testing because of the trouble with high alumina concrete structures in the mid seventies. We developed the pull-off test but as soon as one system was developed the goal posts had moved, and durability became more important. One of the ways of quantifying

## In-situ testing of concrete

- HAC Problems – Pull-off test
- Durability – Permeability tests
- Chloride ingress – Diffusion test



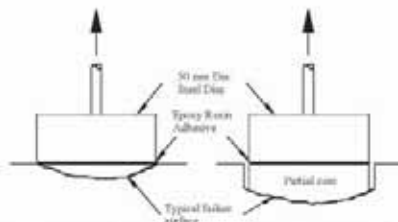
Fig. 16

durability was to carry out permeability testing, so we developed something for that as well. More recently, diffusion testing has become important when considering the whole problem of chloride ingress into concrete.

### Pull-off correlation

The pull-off test is very simple. You simply place a disc onto the concrete with an epoxy resin and (as long as the concrete is weaker than the epoxy resin) when you try to pull it off, fracture occurs in the concrete. Believe it or

## Measurement of strength



Schematic diagram showing the procedures used to complete a Pull-off test



Fig. 17

## Pull-off correlation

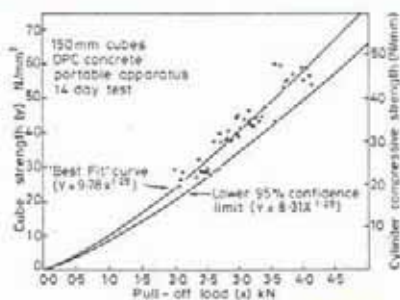


Fig. 18

not, you can get a good quality correlation between cube compressive strength and pull-off strength. I do not think I have ever seen as good a quality correlation as these; this young gentleman, after he had finished his first class honours got a PhD and decided to go into the ministry – maybe he had a guilty conscience.

### Absorption and permeability testing

I was at a conference a number of years ago and I saw someone carrying out an ISAT test which is a standard test for permeability of concrete. I thought it looked very cumbersome so we decided to produce a test which is easier to use on site, and this led to the development of the Autoclam. This test allows you to carry out water absorption which is basically the ISAT test but for air and water permeability under pressure. The equipment can be used on site as well as in the laboratory.

I will not go into the details but basically Figure 20 shows a classification curve that we produced. The left hand axis shows the permeability index: we looked at the degree of disruption that resulted in concrete subjected to the freeze-thaw and did a cross correlation. And you can see that when the permeability index is high, it tends to fall apart in freeze-thaw. When it is very low, it is very stable and therefore a highly durable concrete.

## Absorption & Permeability testing

- ISAT → CLAM → Autoclam
- Water Absorption, Air & water permeability
- On Site & in Laboratory



Fig. 19

## Freeze thaw damage varies as permeability

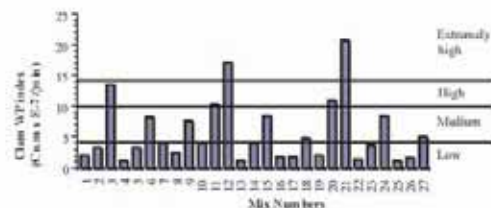


Fig. 20

## Diffusion testing

If there is high concentration of chloride outside, then it will diffuse into the concrete and subsequently cause corrosion of the reinforcement. To test this you must go to your bridge or your construction, extract a core and carry out laboratory tests. To avoid this we have developed the Permit Ion Migration Test which allows you to test on site and in the laboratory.

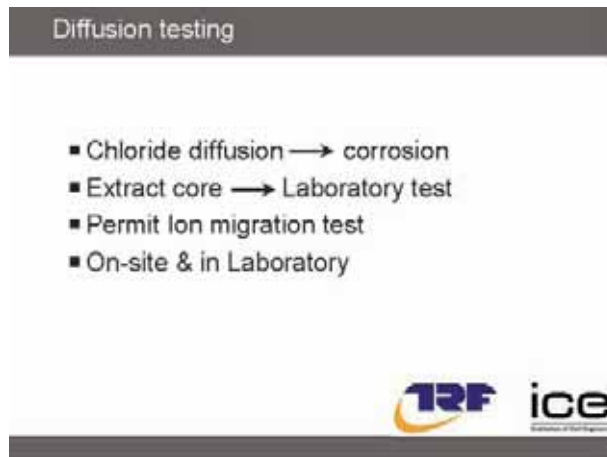


Fig. 21

### Permit Ion Migration Test

Basically it is very simple. There are two concentric cylinders placed on the concrete surface and then sealed to prevent any flow between them along the surface of the concrete. The inner cylinder contains a chloride solution, a negative electrode and the outer cylinder positive electrode.

Current flows from the inner to the outer electrode and chloride is driven through the concrete; this allows you to classify the quality of the concrete for diffusion. This can be applied to a horizontal surface and to a vertical surface.

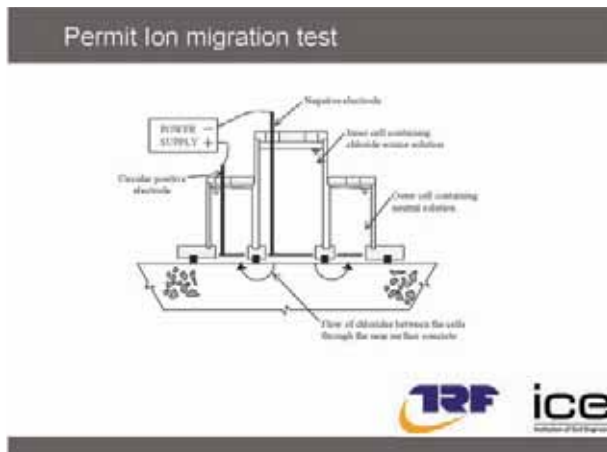


Fig. 22

As yet we have not cracked the problem of trying to put it on the soffit but, by and large, I have seldom, if ever, seen problems with the soffits of bridges; they tend not to be a problem from the point of view of durability.

Figure 23 shows a cross correlation between a standard laboratory measurement of the in-situ migration index and the in-situ type test with the laboratory based: you can see the correlation is very good for something of this nature. This is a much more effective and useful test than the American AASHTO test.

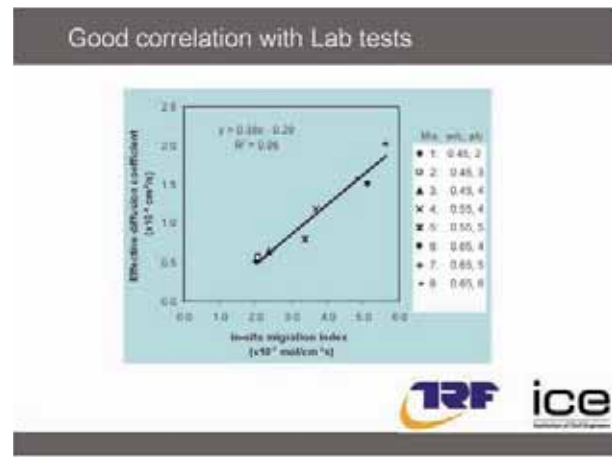


Fig. 23

### The tests in practice

So are all these pieces of test equipment any good? Is there any experience of using them in anger? In the late 1990s we did some testing on motorway bridges in Northern Ireland and we persuaded the Department of Environment Road Service to allow us to look at six different types of bridges to determine if there were any signs of corrosion; whether there was de-lamination; and to carry out site inspections, much more detailed than would be required normally in order to see how we could classify which sections required to be repaired and which did not.



Fig. 24

We were also involved with the Dickson Road Bridge in Montreal with a colleague of mine from McGill University, Montreal. This was a multispan bridge which was constructed in the late 1950s (you have probably read recently about a collapse of a bridge deck in the Montreal area and it was probably built around about the same time).

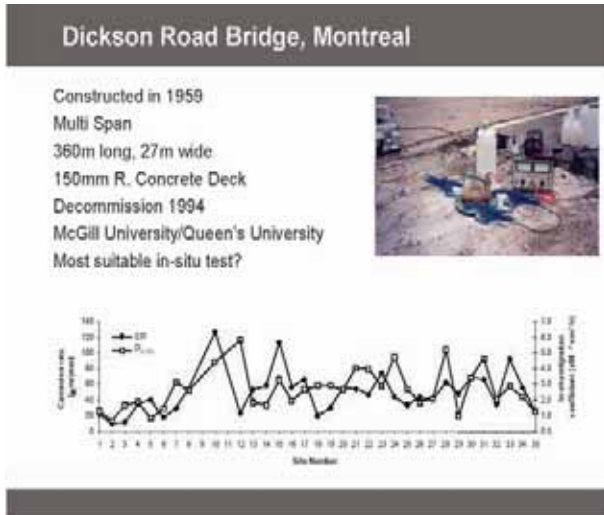


Fig. 25

The bridge had been taken out of the highway network in the Montreal area because it was showing signs of distress and, to some extent, had been superseded. But the authorities were persuaded not to demolish it until there was an opportunity to carry out some testing, which we carried out with McGill University using the Autoclam and the Permit. The results show that there is a remarkably good correlation between the corrosion rate and the Permit in-situ migration test. This is quite good correlation for something that is as highly variable and vague as this. In drawing some conclusions on those field tests, it is absolutely important to realise that regular monitoring is essential, and one of the problems we have is that we tend to do it intermittently, or sometimes we do not do it until there is a problem. There is a need for good detailing and

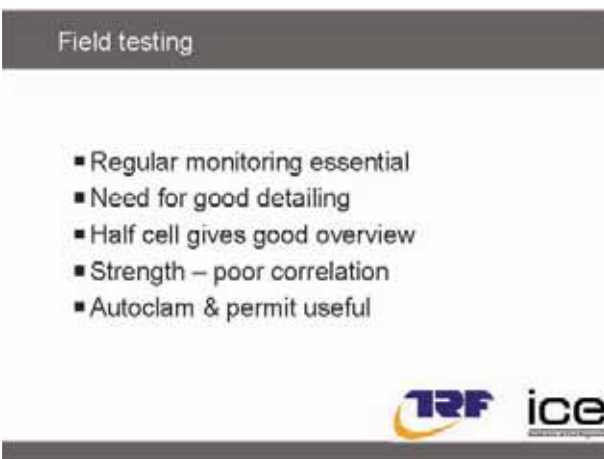


Fig.26

the concept of integral bridges is very important. The basic problem with bridges in Northern Ireland was leakage through the decks at the bearings, as a result, the retaining walls and the abutments were all experiencing problems of corrosion. The old standard half-cell test is remarkably good for giving an overview – it is a very basic test and very useful. We found that strength was largely irrelevant but the Autoclam and the Permit Ion Migration Test were extremely useful.

**Mix design for durability**

One aspect of carrying out tests and research on durability of concrete is that we looked into the possibility of producing a mix design for durability. We like to have concrete which is strong enough and workable, but we tend not to worry about durability. Figure 27 is a three dimensional plot which shows that very high water cement ratios sometimes get more durable concrete than ones with much lower values. It is all to do with aggregate cement ratios and so on; it is obviously more sustainable the less cement you have got in the mix. This is a good test result and I initially was very suspicious, but if you look at the basic theory and concepts of concrete durability, you will see that this stacks up because the total water content is, in fact, reducing.

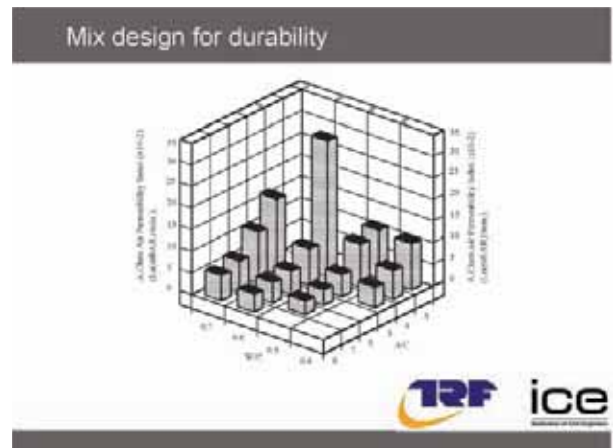


Fig. 27



Fig. 28

Figure 28 shows the equipment that we developed: the Permit on the left, the Limpet in the middle and the Autoclam on the right. One of my colleagues, Professor Basheer, is marketing and promoting the use of the equipment to industry and in fact some of these pieces of equipment are in use in many parts of the world, such as China and New Zealand.

## Sustainable concrete bridge decks by design

In this section I will examine the design of structures which ensures their sustainability; not looking at the concrete but considering the structural form and, in particular, beam and slab bridge decks.

The reinforced concrete deck slab form of construction, is widely used in combination with pre-cast, pre-stressed concrete beams or steel girders. They are also used for somewhat longer spans with steel girders as well. But what you need is a deck system which is durable.

### Beam and Slab Bridge Decks

- Reinforced concrete deck slabs
- widely used in combination with:
  - Pre-cast pre-stressed concrete beams
  - Steel girders (also medium span)
- Need for a durable deck system

Fig. 29

### Reinforced Concrete Deck Slabs

- Selected for bridges in 1960/70's
- Proven in building BUT
- By 1980/90's durability problems in bridges
- Corrosion/spalling due to chloride ingress:
  - Salt spray close to carriageways
  - Piers from leaking movement joints
- Also strength – heavier trucks/lorries

Fig. 30

These particular deck slabs were widely used in the 1960s and 1970s in new bridges throughout the UK and in various parts of the world. They had proven their worth in buildings located in much less hostile environments, but by the 1980s and 1990s durability problems were coming in to play.

Corrosion and spalling due to chloride ingress were particularly evident from the action of salt spray over parts of the structure close to the carriageways and at the piers from leaking movement joints. Another problem was that they had to be strengthened to carry heavier trucks or lorries. (I was talking a couple of weeks ago to Neil Hawkins from the University of Illinois about the very effective system that they have in North America for inducing corrosion in bridges – they do not sprinkle salt over the roads, they spray it with a salt solution and, in some ways, I think that is almost the ideal requirements for inducing corrosion in bridge decks.)

## Enhanced strength of slabs and Compressive Membrane Action (CMA)

In the 1950s, Ockleston carried out some tests in a dental hospital in South Africa and he found that the strength of slabs was far in excess of that predicted by yield line analysis, which was then the best method for predicting strength. He came to the conclusion that it was because of arching action.

### Enhanced strength of slabs

- Ockleston's tests 1955
- 3-4 times Y.L. Predictions
- Arching action
- Compressive membrane action



Fig. 31

To illustrate: if you have two basic blocks which are restrained laterally you do not need to have any reinforcement in them; when you apply a load they will wedge and you will get an arch forming (Fig. 32). They are immensely strong – if you try to take the first brick out of a wall you will soon realise what arching action is.

Similar actions take place in two-way systems, where a dome or membrane rather than an arch is generated, a phenomenon that is generally referred to as Compressive Membrane Action, or CMA. The load deflection curve without arching action is of the standard form, but with arching action, you tend to get a considerably higher peak

(Fig.33). Sometimes this compressive membrane action contribution can be three and four times as great. The late RH Wood, who I visited in 1964, was an absolute enthusiast of this and if we had had the airport out in the Thames estuary at Maplin, it was going to take advantage of that concept.

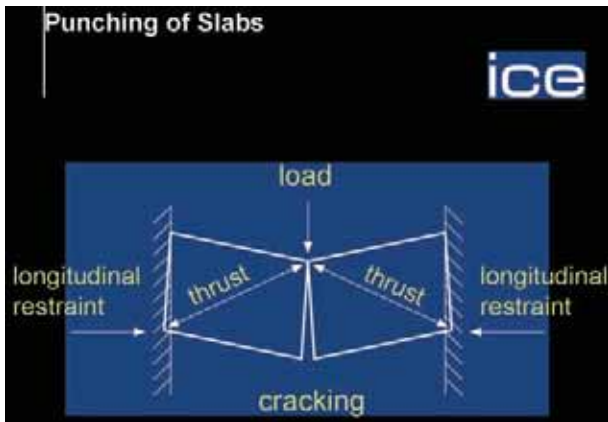


Fig. 32

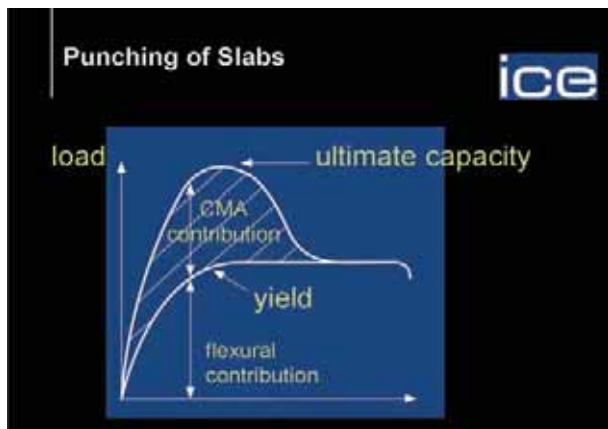


Fig. 33

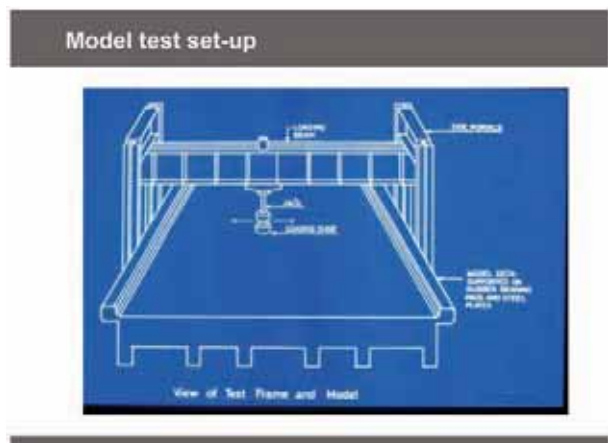


Fig. 34

So, is it possible to assess the strength of bridge deck slabs? We carried out a third scale model test to see if we could use the same slab, which had been designed for a span of 1m (the standard M-beam) and extend it to 1.5m or 2m with

the same amount of reinforcement and the same thickness (which would be a tremendous step forward) by taking advantage of compressive membrane action.

There had been tests carried out on a similar type of construction in Kingston in Canada when I was out there and we found that the actual capacity was much greater than the design wheel load which, as you can see from Figure 35, is less than 20kN.

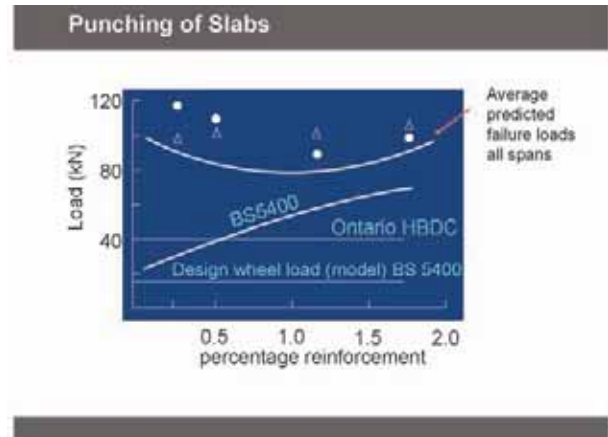


Fig. 35

You can see from Figure 35 that the test results were very high, and, interestingly enough, they suggested that if you increase the percentage reinforcement, Standard BS5400 would predict that the strength would increase, whereas the Ontario bridge Code (which took account of membrane action) suggested that it would not. In test results, the biggest variation arose from the fact that we could not make all the slabs the same thickness: some of them were slightly thicker, some of them were slightly thinner and as a result of working at third scale. This indicated that the bridges were very strong and what was happening was that as the wheel load came on, it tended to form an arch to the next adjacent beam (Fig. 36).

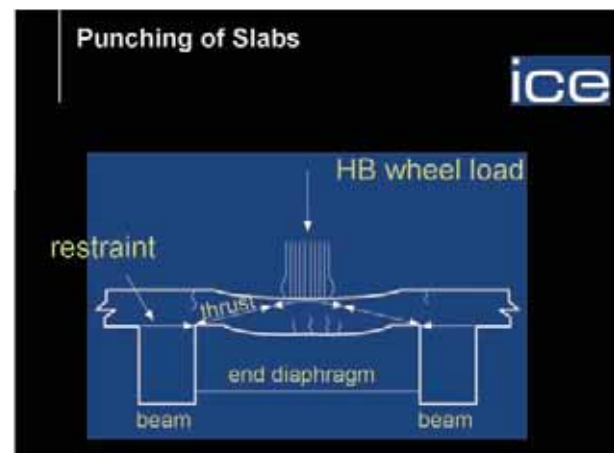


Fig. 36

So the bridge construction is okay for strength but is it going to satisfy serviceability requirements? We carried out some bridge tests on a Clinghan's bridge over a stream in County. Down, Northern Ireland (Figs. 37-29). We load tested it, we measured cracks and we came to the conclusion that it was perfectly satisfactory from the point of view of strength and from the point of cracks and serviceability.



Fig. 37



Fig. 38

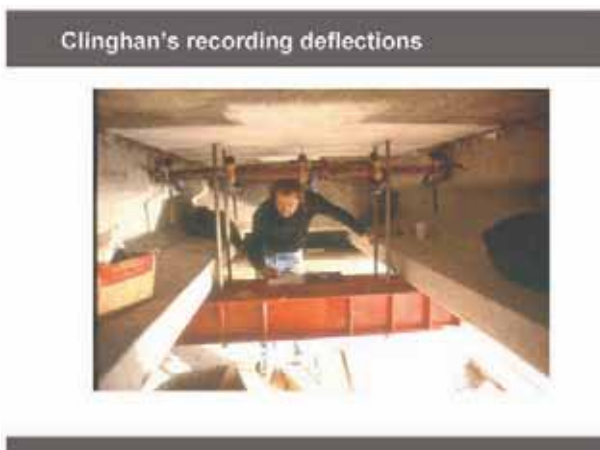


Fig. 39

## Advantages of using CMA

The advantages of using CMA are that we could reduce the reinforcement from the conventional 1.7% to 0.5% (we did not want to go as low as the Canadians, they were using 0.25%). We could get away with the same depth of slab for twice the spacing and, as a result of that, the overall cost of the bridge was reduced because one larger beam turned out to be significantly less expensive than two smaller beams; and the whole structure had comparable durability.

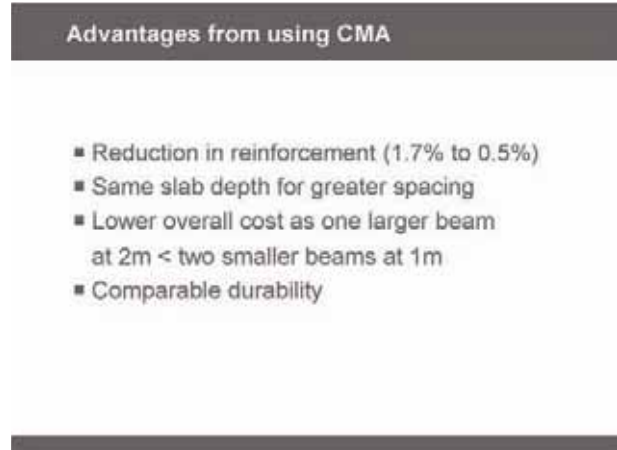


Fig. 40

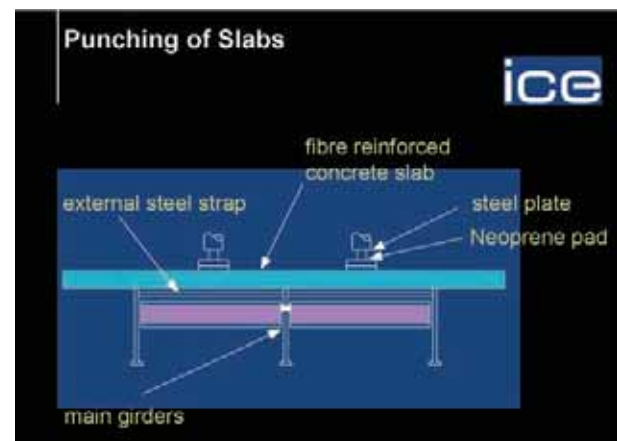


Fig. 41

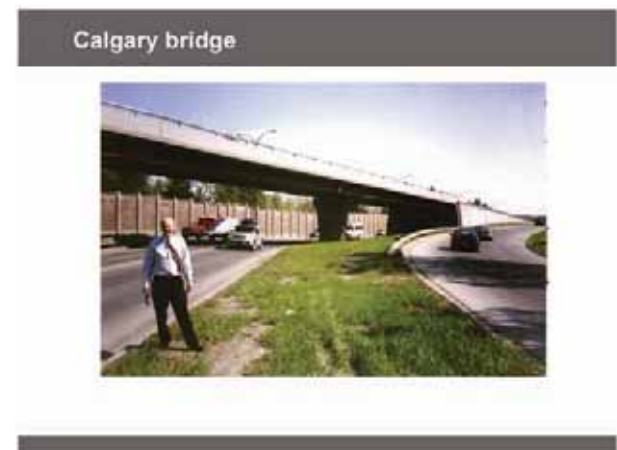


Fig. 42

Meanwhile the United States, and Canada in particular, were developing their own concept and one of the concepts they were working on was a steel concrete composite system with an external steel strap and polypropylene fibre reinforcement in the deck slab.

I visited one of those bridges in Calgary in 2003 and you can see the reinforcement welded to the girders (Fig. 43). This was effective and has been in service now for a number of years.

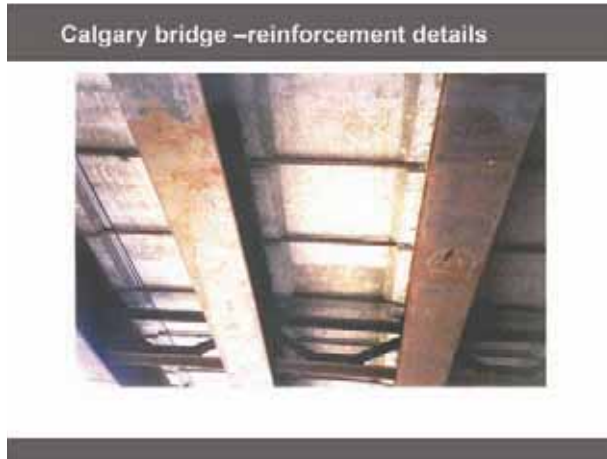


Fig. 43

The Canadian system uses steel girders, which are not nearly so popular in this part of the world, where there are largely pre-cast, pre-stressed concrete beams. We therefore decided to consider (jointly with the DRD Road Service (NI)) whether there was any benefit of using a higher strength concrete possibly with Polymer fibres or whether to adopt a totally radical alternative to putting the reinforcement top and bottom (which, as engineers, you are taught is the logical thing to do). With these solutions you have got much greater cover and to get rid of the possibility of corrosion altogether, you could use glass/carbon fibre reinforced plastic. The goal is to produce a maintenance-free deck slab system.



Fig. 44

We looked at this and found that, although Standard BS5400 does not indicate it, there was definitely a strength increase with higher strength concrete, as we thought would be likely. We also found that the conventional system was no different from the centrally reinforced system; so by putting the reinforcement at the centre, you got the same strength. This is a step forward.

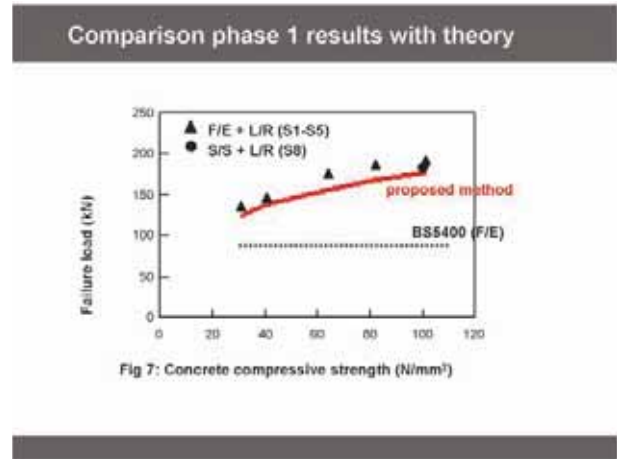


Fig. 45

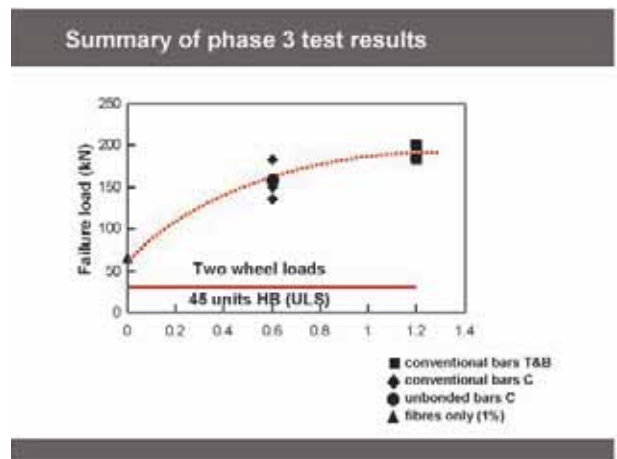


Fig. 46

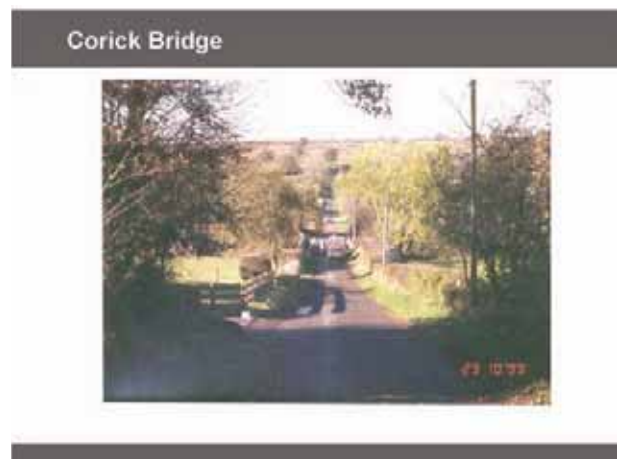


Fig. 47

The strength in the laboratory was perfectly alright but again we were concerned that if you put the reinforcement in the middle, you are going to get cracks, which are well beyond the limits you require. So jointly with the Road Service we undertook some tests on a site on a bridge near Dungiven. This picture shows the reinforcement layout, some with central reinforcement and some with double layers.

Photo 8: deck slab reinforcement



Fig. 48

Test panel arrangement

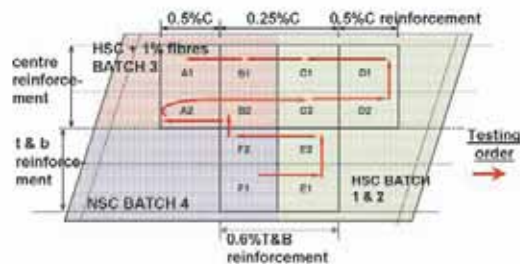


Fig. 49

Figure 49 shows the different variables: central reinforcement; different percentages and double layers of reinforcement; and different percentages. Again, we did load testing as before and we came to the conclusion that it was perfectly satisfactory.

What I am showing in Figure 51, which is very simplistic, is the basic unit costs or the embodied energy for a normal standard deck form of construction.

Obviously there will be a period of time when the structure does not need any repair or maintenance but then you may have to carry out some repairs, and ongoing maintenance will increase the cost over the full life. The compressive membrane action system is less costly but gives a similar trend.

Typical test arrangement

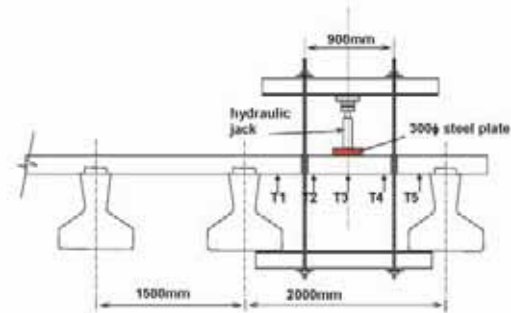


Fig. 50

Beam and slab superstructures



Fig. 51

But if you then adopt the totally different strategy of central reinforcement or even non-corrodible reinforcement, you could end up with a slightly more expensive system but with virtually no repair or maintenance costs. Over the life of the structure, you will end up with a very much more sustainable bridge system.

As far as the compressive membrane action research, or arching action, is concerned, the benefits are now well understood. You get improved strength, you also get

Conclusions – CMA Research

- Structural benefits well understood
- Improved strength / serviceability
  - Less problems for assessment
- Incorporated in Ontario & UK codes
- Highly durable decks – maintenance free



Fig. 52

improved serviceability and that has been very useful in assessment codes here in the UK – many bridges have satisfied the requirements when you use compressive membrane action. I believe the approach is now being incorporated into design codes for bridges that are going to be applied right across Canada. We end up, I think, with very durable decks that are largely maintenance free.

## A novel flexible concrete arch system for sustainable bridges

I will now move on to talk briefly about a novel flexible concrete arch system that we have developed at Queen's, jointly with a company in Northern Ireland called Macrete Ireland. A colleague, Gordon Millington, said to me in the early 1990s it's a terrible shame that we've got these wonderful arch bridges all across the country; they're strong, they're durable and they are aesthetically pleasing and yet we're not building them any more. Why not? And he said that something should be done about it. That was a challenge, but we have made a considerable amount of progress since then. One of the biggest problems is the labour costs associated with centring. It is little wonder that we do not use arches when you have to think of the costs associated with centring.



Fig. 53



Fig. 54

Looking at the commercial feasibility, there are many potential clients such as DRD, the railways, the Highway Agency and contractors. A tremendous number of people would be interested in arches because they are currently using them; believe it or not, there are 3,500 arch bridges in Northern Ireland alone, with over 60,000 in the UK.

## Details of the concrete arch system

We will now look at the details of the system that we have been investigating: the method of construction, the materials for manufacture, the testing that we carried out – I will be very brief on that – and then the manufacture of the first prototype.

### Method of construction of an arch unit

Figure 55 shows first of all the construction of the arch, using pre-cast, individual voussoir concrete blocks. On the construction bed we bring in a pre-cast concrete block, put another one adjacent to it, and so on. Polymeric reinforcement is used because in an arch, the last thing you want is reinforcement that will corrode. We then put in a layer of concrete cast in-situ on the top of that and, after the concrete has cured, you can lift it. The alternative is to cast it in-situ using formwork with preformed wedges with the polymeric reinforcement held in place.

One of the things that I just want to highlight is that we prefer the pre-cast one because there are difficulties with the in-situ system (Fig. 56). We initially started off with the in-situ system in the laboratory. How do you produce these accurately machined wedges? We tried some polystyrene forms and, as you can imagine, when you put the concrete in they tend to wobble sideways. so that did not work.

We have also tried other systems but they are very difficult because you have this problem of restricting the movement of the wedge during casting and then, once you have got it cast, how do you actually take it out of the form without wrecking the arch? One of the proposals that someone has suggested is that you turn it upside down although we have not tried that.

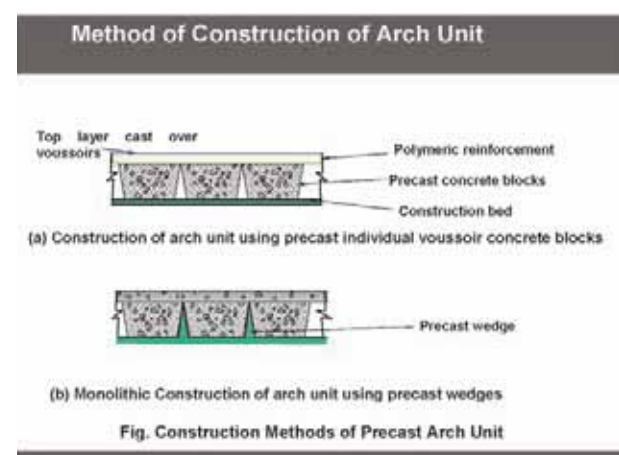


Fig. 55

### Method of Construction of Arch Unit

- Pre-cast Voussoirs preferred as:
- Difficulties with in-situ:
  - Robust, accurately machined wedges
  - Restricting movement during casting
  - Removal of formwork/damage

Fig. 56

As far as the reinforcement is concerned, we just simply use a fairly standard 'PARAGRID' reinforcement (Fig. 57). We wanted to make sure that it was strong enough for this particular application, so we tested it as a beam. The manufacturer was suggesting that in fact it would fail at a tensile strength of 100 kN per metre, but we found it was 43.6 kN/m (Fig.58).

### Paragrid Reinforcement

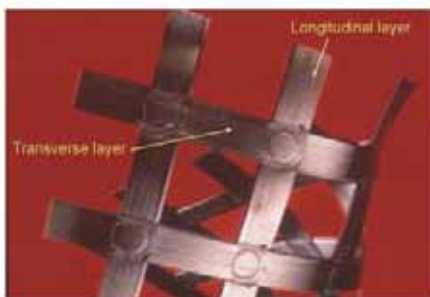


Fig. 57

### Paragrid material (Test Results)

Sample ID	Tensile strength of material from manufacturer (kN/m)	Tensile strength of material from test results (kN/m)
100/15	100	43.6
150/15	150	72.2

Fig. 58

### Stability test: backfill operations



Fig. 59

I am not saying that their test results were wrong, but for this particular application these were the best and safest ones to use and we have found that they work very well. To assess the flexibility of the system while being back filled a stability test was conducted (Fig. 59): the arch was monitored for horizontal deflections; vertical deflections; and strain at the voussoir joints. After a preliminary cost estimate, it was decided to use lean mix concrete for

### Load Test on Arch unit



Fig. 60

### Results of third span Load Test



Fig. 61

backfill. The total cost difference was very little and we felt that the labour costs were greatly reduced.

Having installed a precast footing we dropped the arch into place and then poured the concrete in layers. We found that during this process the structure was very stable and the process worked very well.

We then did loading tests on it, putting up a single 1m wide unit carrying a load of something like 35 tons (about six times what it needed to carry). We now have a full 5m-wide bridge which we have load tested and measured deflections. These are grossly exaggerated were perfectly acceptable and tended to come back to zero when the load was removed.

Figure 62 gives you an indication of the process. You can see that it is lying flat and that if you lift it up gradually, forms into a perfect arch form.

We have assessed the bridge analytically using Archie, the system that is used for checking bridges in Northern Ireland. This again indicates that it has lots of reserve strength.

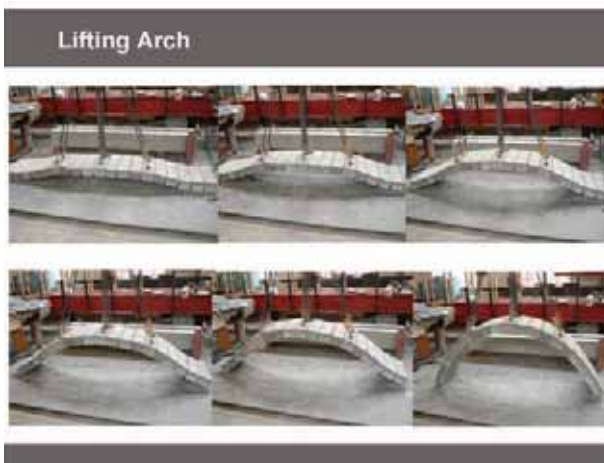


Fig. 62

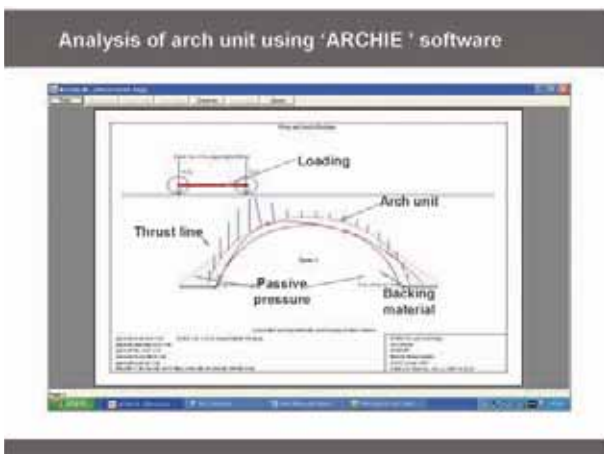


Fig. 63

## Advantages of the flexible concrete arch

Figure 64 illustrates some of the advantages of flexible concrete arch. It can be cast horizontally and delivered flat packed to site. They can then be stacked up together on a lorry which you cannot do with arches. Erection is simple and speedy; you just simply lift it on site and there is no need for centring. It is also highly durable – there is no corrodible reinforcement – and according to Macrete Ireland, it is cost competitive compared with reinforced concrete box bridges and culverts, which they also manufacture.

Advantages of flexible concrete Arch

- Cast horizontally, flat pack delivery to site
- Simple / speedy erection as no centring
- Highly durable as no corrodible reinforcement
- Cost competitive with RC box culverts



Fig. 64

This gives you a summary of the overall concept of the flexible concrete arch, which is – aesthetic, durable, strong but has no need for centring. The –prototype, which was used for load testing, was not a particularly elegant arch but you can see that once it has been manoeuvred into position it is very stable and has dropped into position on the wedges which are the correct angle. It tends to not wobble around too much at all and is very strong once you get it backfilled with concrete.

INNOVATIVE FLEXIBLE CONCRETE ARCH

**MASONRY ARCH BRIDGES**

- AESTHETIC
- DURABLE
- STRONG

**BASIS OF NEW CONCEPT:**

Precast

Polymeric reinforcement

Individually cast voussoirs

**TRANSPORT & INSTALLATION**

FLAT PACK

EASILY LIFTED

NO CENTERING

ICE R&D Fund, Macrete Ireland & Queen's University Belfast

**LOAD REQUIRES**

**CENTRING**

In-situ

Formwork

Fig. 65

## Concluding remarks

In these concluding remarks could I first of all just, emphasise that broadly speaking, the transportation network in this country is absolutely vital to economic growth. I think this was a point that was made by Martin Snaith in his TRF lecture so we need to get that right and anything that we can do to avoid congestion during the construction of bridges and highways will give a huge benefit. If we can produce more durable bridges that require little or no maintenance, there will be less disruption and less congestion. We must seriously look at total life cycle costing or total life cycle sustainability. A little bit of extra cost during the design stage will more than reduce the cost of construction. That is something which still seems not to be appreciated by clients but it is absolutely crucial. We must also do our best to integrate sustainability into the design process and I think the comparative studies, like that done by David Collings, can be extremely useful and helpful in that context.

### Concluding remarks

- Transportation network/economic growth
- More durable bridges - less disruption
- Total life cycle "cost"
- Integrate sustainability into design



Fig. 66

In terms of our own work, there is no doubt that we can enhance the durability of the concrete in structures. Many good examples exist throughout the country where contractors have really gone out of their way to produce highly durable structures that have proven to be very satisfactory after 40 or 50 years. But the slightest bit of laxness means compromising this good work. I think we can produce bridge deck slabs, which are maintenance free and take advantage of compressive membrane action, could be very useful in this context.

I would commend to you this concept of the flexible concrete arch. I think it has considerable potential and think of it as an arch which is strong, aesthetically pleasing and durable because there is no corrodible reinforcement: it could be a very sustainable solution. Thank you very much indeed for your attention.

### Innovative advances / sustainability

- In-situ tests – enhanced durability
- Maintenance free Bridges. CMA for deck slabs and integral concepts
- Flexible concrete Arch – short spans



Fig. 67

## Discussion

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*Alan Stilwell, Chair of the ICE's Transport Board*

Adrian, thank you very much indeed for that. A fascinating lecture that will, I am sure, promote much discussion.

### *Question*

Thank you for such an interesting presentation. On the flexible arch system, you showed the system with uniform wedges along the length of the arch. Have you actually tried or considered using variable shaped wedges along the length to achieve different profiles of the arch?

*Adrian Long*

We have not, but there is no reason why not. Obviously you could produce an elliptical arch but cost effectiveness would suggest that the simple circular arch has a lot to be said for it. I was giving a presentation in Kenilworth a month or so ago and one chap who is involved in church buildings got quite excited because he thought he could produce Gothic arches by putting in an extra big wedge up at the top so that you get a double curve system. We have not tried that one yet but it is the sort of thing that you could try and I think it should be feasible. We are walking before we run!

### *Question*

Adrian kindly referred to my [David Collings'] paper during his lecture, so while I have got a captive audience I will just remind everybody to read it who has not read it – it was in the Bridge Engineering Journal last year. One of the conclusions of the paper that I would like to reinforce is that, as engineers, we actually need to consider the sustainability issues upfront. In design, I think we need to be fairly broad. There is the choice of form but I think it comes down even to the question of who orders the concrete: where does he get it from? Does he get it from a supplier who gets his supplies from a sustainable source, or from somebody using a process that is not as sustainable? The question has to cascade right down through the designer's organisation and into the contractor's organisation. I think that is something that, as an industry, we must look at in that it has got to affect all our quality assurance systems, looking at not just cost but the amount of carbon that is being put into the atmosphere.

*Adrian Long*

I agree. I think one of the real problems is, and certainly this was the situation I met as a young bridge designer, that one was not looking into the whole impact of that bridge on the traffic flow or the maintenance and so on. I think now we are much more aware of the interaction with transportation people and so on. I do honestly believe that

there is no reason, even if it is in a simplistic way, why you cannot take into account the potential costs of disruption as a result of having to close the bridge down, or even close down a couple of lanes. That is something which is quantifiable. At least then you can use the information to persuade the agencies involved that it is worthwhile spending a little bit more at the initial design stage so that you avoid this problem in the future. I totally agree with your point on ordering concrete is extremely useful; we were making some model tests of the arch system in the laboratory and we ordered some low strength concrete so you can guess what type of concrete we got. To get low strength, what do you do? You add more water instead of a lean mix concrete, and we ended up with a pea soup that just came spewing out through all the little voids. So, at the end of the day, we need to be more conscious of what we want. It would have been much better to have low workability but low cement and high aggregate content concrete.

### *Question*

Civil engineers use codes of practice and design standards in everything that they do. To me, sustainability will not be achieved within the industry in the design of infrastructure unless it is embedded into standards and codes of practice. How is that achieved?

*Adrian Long*

I think there are people here in this particular audience who could answer that question much better than I. People in the geo-technical engineering area have more freedom to exercise good engineering judgement than we in the structural area. I think, though, it is a difficult balance to achieve, and I personally feel that we have to be careful that we do not become too prescriptive in our codes. We need to leave a certain amount of freedom for engineers to exercise good engineering judgement. The trouble, though, is that inevitably there will be someone who does not exercise good engineering judgement and we will have failures. It is a difficult balance to achieve and I am afraid I do not know the answer to that question. Maybe some of my colleagues in the audience would like to comment on that particular aspect. Have you any comments yourself?

Questioner

I do not have an answer per se but I do think that in unpacking sustainability you consider social, economic and environmental issues, and design standards do not do that, so there is a problem right upfront on that level. They also focus on specific issues such as load performance or strength which are fundamental to certain performance requirements but not sustainability performance requirements. So codes of practice and design standards need to be much broader in the social, economic and environmental indicators that they are looking to measure performance on.

### *Adrian Long*

Yes, it is a double edged sword in that the more prescriptive one becomes, the more tied one's hands are. In some ways, I would almost prefer to see issues like sustainability, which are not absolute black and white, left to the discretion of engineers who are capable of handling it in a professional manner. And I think that is one of the reasons why we need to have procedures like CEEQUAL and various other things to increase the awareness of members of the profession as to the key aspects of sustainability.

### *Question*

What is interesting about the point that is being made here is that standards are about guidance. Some of them are very much associated with safety and I would agree that we definitely want to put safety as one of our highest priorities. But standards do not exist on their own, and probably the thing I would like to emphasise most in the discussion we have heard tonight is that any bridge engineer will no longer think only about the structure but about how that structure is going to operate, and in what environment. And with that comes a much wider world of standards and guidance, which are all about a good sustainable approach to construction, to maintenance, to use and to operation. We have to recognise as bridge engineers that it is a lot more complex world we probably exist in nowadays, and I certainly would expect any bridge engineer to be educated in that whole environment and not just the issues which are already very important. So we definitely want to be sure about our safety capability and our serviceability but we also want to understand it within sustainability, and I think our standards and specifications give that freedom.

### *Adrian Long*

No need to respond to that, except to say that I think we as professionals have to be willing to exercise that responsibility ourselves.

### *Question*

Thank you for your kind remarks about my [Roger Venables'] contribution. I am not sure I live up to those but I just wanted to contribute to this last question about trying to introduce standards for applying sustainability thinking to, in this case, bridge engineering. My plea would be, please do not. Let us keep the standards for the things that we think we can get a handle on these days. There are all sorts of people in this room and we think we know something about sustainability, but the week after next we will realise that we knew less than we thought. It is still a subject of which our understanding is developing at a prodigious rate, and I do not think we yet know enough about it to try and write down standardised approaches. Where you are, what you are working with and all the rest of it have dramatic influences on what the right decision is for a particular project when you are trying to, in my view, find the least unsustainable solution. I think one

of the things that surprises people about the CEEQUAL scheme is that I actively encourage people not to go cherry picking environmental improvements in order to win the highest score. I think we have to focus on civil engineering making the right judgements about the materials that they use, the structural form that they use and then, having decided that, try and deliver the project with the least adverse environmental impact they possibly can - and then they score on CEEQUAL whatever they get. I think we, at our peril to the structural safety of bridges and other things, start skewing our decision making too much on the grounds that material 'X' is we think (at the moment) environmentally less bad than something else. I think it is a really dangerous route. Let us keep the sustainability bit in the guidance field. Let us keep the standards bit for the things we think we understand.

### *Question*

Compressive membrane action (CMA) is a well proven phenomenon but one problem in the past has been the interaction of the local CMA and global actions at the relevant section. Have you looked at this aspect or are there any proposals to include recommendations in design codes?

### *Adrian Long*

Yes, I am aware of this. There has been some work done by Dr Jackson, who I think works now in bridge design with Gifford & Co and whose PhD I was external examiner for while he was with the C&CA (Cement and Concrete Association), as it was then. It was found that you could still develop compressive membrane action even though there was localised interaction with global actions. Basically, what they thought was that if one of the beams deflects relative to the other, you will not get the compressive membrane action in that slab. But in fact, they found that it was still there and still effective. And some of the work that was done in the early days in Kingston by an Australian student: the first tests on a two span steel girder system which didn't have any transverse diaphragms, found that CMA was still very effective. Diaphragms may not be as important as we think because I think actually what is happening, is that it's a localised effect from one wheel and the rest of the slab will not expand. thus CMA is generated. So it is a compressive membrane action rather than an arching action in that context. Thus, as it has been addressed, I do not think there is a major problem.

### *Question*

People who have worked in the railway industry for a number of years have become conscious that we would not have a network at all if the original structures, of which we rely on thousands, had not been over-designed not just by 20% or 50% but by a factor of 2, 5 or 10. I am not convinced the original designers intended them to carry loads ten times or more of what they could have foreseen at the time and if anyone looked at you now and suggested

you should design a motorway viaduct to carry a moving load of 440 tons, not 44 tons, they would think you were a bit mad. But it is a pointer to the fact that our opinion on sustainability and our opinion on how we do design things are still miles apart, because if we want an infrastructure that will still work in 100 years then over-designing by 50% is not the question we should be asking but some other factor altogether.

### *Adrian Long*

Yes, I think that is very true. One thing that never ceases to amaze me is that if you test arches, the reserve strength is enormous. We had a model test in the laboratory and I think it was 20 times the design load it was carrying and it did not look particularly good at that time but it was still carrying it. So I think there are huge reserves in arches and I think that is one of the reasons why arches are superb. Those Roman bridges were not designed for 40 ton trucks but they are carrying them perfectly satisfactorily; they were grossly over-designed but has it done any harm? They were very sustainable structures. Maybe we can learn from that. It does not cost an awful lot more to get a little bit of extra strength in a bridge deck and not have the problem of having to upgrade it subsequently.

### *Question*

One of my concerns is that we seem to be making our existing bridges more sustainable by extending their life and not necessarily replacing them with a more sustainable bridge - your Tinsley viaduct being a good quote. If it costs £1.5 billion because of today's traffic congestion, what is the traffic congestion at the end of its life when you have just extended it by 30 to 50 years?

### *Adrian Long*

Yes, that is a major problem. Basically the fact was that that particular bridge was going to cost so much to replace that they had no other option. They just had to think very seriously and be clever in their structural engineering. Now the question you are in essence asking is that in 50 years what are they going to do? And I think there are a huge number of infrastructures right across the country that will cause us comparable problems; when you think of bridges on the M25, bridges where there is heavy traffic, there is a real problem there and we are not actually facing up to it the way we should. But I think it is a bit like the nuclear debate to some extent; it is a major difficulty and major problem, you just have to think maybe more cleverly. And I think that there may well be again a clever solution, and if that particular structure, which is a steel structure, is very well maintained and as long as the actual loading levels do not increase dramatically, I would have thought it should be sufficient. For most of the Tinsley viaduct's life actually it was only running two lanes – it was only recently that it was increased to three lanes, so it has been a defective bridge for many years from the point of view of strength and it was only after the strengthening that they

were allowed to use it up to the full width. So I agree with you, I think there is a major problem there. There is a time bomb waiting to hit us in the future. How we react to it is going to be difficult.

### *Question*

A couple of quick comments from a local authority perspective. Firstly, the issue about guidance on sustainability issues and whether that is included into standards – I would certainly echo caution on that. We get plenty of guidance at a higher level and part of our skill as bridge engineers is to translate that into real things we can do. Recently in Hampshire we have reconstructed a conventional brick arch bridge as a trial project, and we have found something like a 20% penalty for doing that in terms of initial construction costs. It is something we are looking at quite closely. But the other point is that I would certainly echo your comments about whole life costing. I think most people would now accept that this is the way forward and as we further develop our asset management plans it is clear that this is the way we should be going. The real difficulty is how can we encourage those who make funding available for structures to come up with extra money early on to save money in the long term whereas we are really being pushed to do it the other way round and say, 'well, you are going to get less money this year than you had last year and less money the year after and you have got to make the best you can with the stock you have'.

This is more of a comment than a question but it is really echoing your comments about the importance of whole life costing and recognising that, within the whole life, the most effective way of using our money is to spend more in the short term. But how can we encourage those who provide the funding for our infrastructure to stump up the cash now rather than 10 years time?

### *Adrian Long*

That is something which is bigger than the individual; where, as a profession and as an institution of structural engineers, we should be working to actually make this point to those people who are making the decisions: it is not the initial costs, it is the long term costs that you should be looking at. I think it then behoves us to take into account aspects related to the difficulties of congestion. And I think this is where David Collings' paper has been very useful in that it tries to give a quantification of all these different issues. If we can show that by spending an extra so much at the initial stage it will save you an immense amount in the long term, then that will help persuade the particular agency or Government department. But I think we can perhaps help as an institution to try and drive this forward through the traffic and transportation boards etc. I think it is very important that we do that as a group because you are not going to win an individual battle, but if you work together as a team, you can actually deal with it.

*Alan Stilwell*

And perhaps I could just add to that – maybe it is a case of making sure that the responsibility for all of the costs in the future resides at the right place. That would exercise minds a little.

**Question**

Concerning the discussion earlier about clients, many of us here end up a little bit further down the supply chain. It is extremely hard to get arguments such as this one accepted when, if you are the contractor, you have got to satisfy your shareholders: it is hard for us to try and argue on a short term increased spend – it is very hard to achieve for probably over about half of our customers.

*Adrian Long*

You are absolutely right. I think this is something a bit like the problem of trying to persuade the Government that the greatest beneficiary of civil engineering or structural engineering research is in fact the Government; it is a bit like the client actually deciding on the basis of evidence provided by the designer and the contractor that this is the best way forward. You cannot blame the contractors or designers – they present the information, and you have then to hope that clients will take the issue on board. That requires us to have as effective an input to these different agencies as is possible.

**Question**

Our clients include Network Rail and the Highways Agency and we have patched up many of their bridges to extend their lives. We have recently saved a 37 year old bridge on the M20 for the Highways Agency by installing a brand new steel composite bridge onto it. But the codes do not cover things like that. Sustainability is nothing new for those of us who remember the good old times – we keep reusing old things. I think society has just become very wasteful. I do not agree with all the mechanisms of carbon footprints but I think sustainability makes good economic sense. Really, I think ICE is at the heart of it. I think engineers should take control back as the champions of infrastructure, and we bring in architects to help us become a bit more artistic.

*Adrian Long*

We all tend to exercise our sustainability options when we perhaps spend a little bit extra to get a car which is more sustainable than something which is a little bit less expensive, something that will last longer and so on, and at the end of the day it is the value for money over the lifetime. So I think that there is no reason why we cannot do something similar for bridges.

*Alan Stilwell*

Thank you all very much. I would like to pass back to Rod Kimber now to sum up this evening's session.

*Rod Kimber*

Adrian has sketched a picture which ranges widely and picks out all sorts of implications. The first thing to note, of course, is that in a consumer society like ours, bridges are one of the few products that can genuinely claim to be sustainable. Current design standards incorporate a design life of 120 years, and many bridges have lasted for a lot longer than that. In fact, there are many celebrated examples of Roman bridges still working well today - that is the meaning of sustainability in a nutshell. But the point I think that has emerged from Adrian's lecture is that we cannot take any of this for granted. Many bridges built more recently have had much shorter lives and we have had to do much more to them. You have heard about the problems, how they can be identified and what can be done to prevent similar problems occurring in the future through the use of some of these new and innovative approaches in design and construction. We hope that the adoption of such approaches should therefore lead to more sustainable construction in the future; that they will come together within a bigger frame. What emerges directly is that there is a need for bridge designers to think more widely.

One of our speakers talked about a 'wider world' when considering the design and construction of new bridges – it is no longer enough just to look for a technical solution for bridge design in isolation. Engineers also need to look at the impact of the structure, going much more widely across the environment as a whole, and much more widely than, for example, just its direct visual impact. We need to take account also of the resources required to construct and maintain the structure throughout its life, the energy required to provide those resources and the impact of maintenance on the road user, not just in terms of the inconvenience and delays, which can be enormous in themselves and produce an extremely important component in the equation, but also the environmental damage caused by the congestion – the secondary, knock-on, effects. All of this points to whole life costing arguments in the round but there are many and expert parts to the whole thing, and there is no glib answer to it: design is a complex business.

Overall I think Adrian has shown that a) traditional engineering research, b) sustainability arguments, and c), implicitly, the Highways Agency's objective of reducing congestion and improving the reliability of journey times – are all closely interrelated and should not be treated separately: we really do need to look at the interactions. It follows from this that any shift away from so-called hard engineering research in its own right would risk leaving a significant gap. I am sure that we all want to avoid that. What we really need is a genuinely holistic approach that is multidisciplinary and does not focus on one area at

the expense of another. That argument has come through abundantly in the discussion.

So what, then, at first sight we might have expected to be a relatively specialised lecture on innovative approaches to bridge design is, by its implications, far more wide ranging. It addresses a key part of the larger jigsaw of providing a sustainable road network. In significant measure then, the ideas developed here point not only to bridges but to all parts of the road network. And the integration of those arguments is something that, as I have said, is an expert and very wide-ranging and difficult task, but one that is extremely important to us all. So that then is a moral that we can take from this lecture, which I, for one, found extremely interesting and stimulating.

### *Alan Stilwell*

I can add little to Rod's summing up, except to say that for me it has been a thoroughly enjoyable evening – an excellent lecture from Adrian and a really good contribution from the floor. It felt like we could go on much longer. I hope you will join me in thanking Adrian sincerely for the effort that he has put into coming here tonight and to presenting his lecture.

### *Adrian Long*

Could I just thank you all for your attention and your interest. It was great to see so many here tonight and I am much appreciative of the quality of the audience. I found it most enthralling and it is great to have had this opportunity. Thank you very much indeed.

## References

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