Sustainable Bridge Construction Through Innovative Advances

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ABSTRACT: Sustainability is now recognised as a key issue which much be addressed in the design, construction and life long maintenance of civil engineering structures. In this lecture, generic aspects of sustainability will be briefly discussed, but the main focus will be on its application to bridges. Motorway bridges built in the 1960's/70's had design lives of 120 years; however many were showing 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.

In order to address the highly complex issue of the sustainability of bridges the following specific areas which impinge on this important subject will be considered:

1. The impact on sustainability of different forms of bridge construction and maintenance/repair/replacement strategies.
2. The utilisation of innovative *in-situ* testing equipment for assessing the long term durability of concrete.
3. The development of innovative structural designs for bridges which inherently have greatly extended lives at minimal, if any, additional cost.

1. INTRODUCTION

The built environment has to co-exist with the natural environment with which it is 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.

The burden placed by construction on our natural resources can be estimated from the embodied energy i.e. the total primary energy that has to be extracted from the earth to produce a specific product – usually measured per m^2 of plan area. In addition the operational energy used during their lifetime has to be taken into account. The relative proportion depends on the form of construction. In general, a bridge has high embodied energy and low operational requirements whereas a hospital with its demanding service conditions has a high proportion of operational energy. However for bridges the relative proportions for these energies depends on the extent of maintenance/repair during their lifetime. If minimal maintenance/repairs are required the operational energy may be only marginal however if extensive repairs are necessary and considerable disruption/congestion results the energy consumed can increase dramatically. Thus the challenge for designers is to achieve the minimum total energy used over the 120 year design life and to persuade the client that a sustainable approach is preferable to a minimum initial cost design.

In order to contribute to a better understanding of the highly complex issue of the sustainability of bridges a number of specific aspects which impinge on this important topic will be discussed:

1. The relative merits of different forms of construction from the sustainability viewpoint.
2. The utilisation of innovative in-situ testing equipment which will allow the durability of concrete bridges to be assessed.
3. Technological innovations which could lead to much more durable and sustainable forms of construction for concrete bridges based on:

    (a). The enhanced strength of deck slabs arising from arching action
    (b). A novel flexible concrete arch system

In the latter two instances the approach adopted in research at Queen's University Belfast, carried out with the industry, will be placed in context.

2. SUSTAINABILITY ISSUES AFFECTING BRIDGES

2.1 *The Environmental Impact of New Bridges*

The embodied energy from the use of construction materials is a source of concern to engineers when planning, designing and constructing a bridge. However relatively little advice or guidance is given in the literature as to the relative merits of different forms of construction. In this context a recent paper by Collings [1] presents the results of a comparative study, derived from an actual project. A bridge in the UK over a river of width 120m with 66m of approach spans on each side was considered. The total deck area was over 4000m^2 and this bridge allowed consideration of the shorter spans on the approaches as well as the main river span. Three basic forms of construction were considered for the river span; a profiled girder; a tied arch; and a cable stayed bridge. Constant depth girders were use for all the approach spans. Temporary works were included as was an estimate of the likely repair, maintenance during the life time of the three basic forms of construction; steel; concrete; and composite construction.

Useful comparative tables and graphs are included in the paper by Collings [1] however the results summarising the impact of the span and the form of construction on the embodied energy are only included in this paper. The estimates of the embodied energy during construction (per m^2 for bridge deck) are tabulated in Table 1. Values vary from approximately 16 to 75 GJ/m^2 of deck with the short span concrete structural form giving the lowest values and the all steel or composite, longer span structure the highest. The embodied energy is also presented graphically in Fig. 1, where it can be clearly seen that longer spans consume greater embodied energy/ m^2 (not unexpected as the cost/m^2 also follows these trends). Figure 1 also implies that a well engineered longer span bridge using local materials, recycled steel and sustainable cement can be almost as environmentally friendly as a shorter span structure where sustainability issues are not considered. Table 1 and Fig. 1 also indicate that at the spans under consideration the more architectural solutions (arches, cable stayed) have a higher environmental burden for all materials (as well as a cost premium). Further comparative studies of this nature, by experienced designers, need to be encouraged so that the most appropriate forms of construction, from the sustainability viewpoint, are selected.

Table 1 Embodied energy during construction (GJ/m^2) for various structural forms and materials (from Collings [1])

Energy	Type	Steel	Concrete	Composite
Minimum	viaduct girder arch cable-stay	17.8 30.9 49.8 40.3	15.7/16.6 23.6 34.3 21.1/22.1	16.6 29.1 48.8 37.7
Minimum	viaduct girder arch cable-stay	17.8 30.9 49.8 40.3	15.7/16.6 23.6 34.3 21.1/22.1	16.6 29.1 48.8 37.7
Average	viaduct girder arch cable-stay	23.5 39.3 61.9 50.6	21.1/22.1 30.6 49.1 43.9	22.1 37.0 60.8 47.7

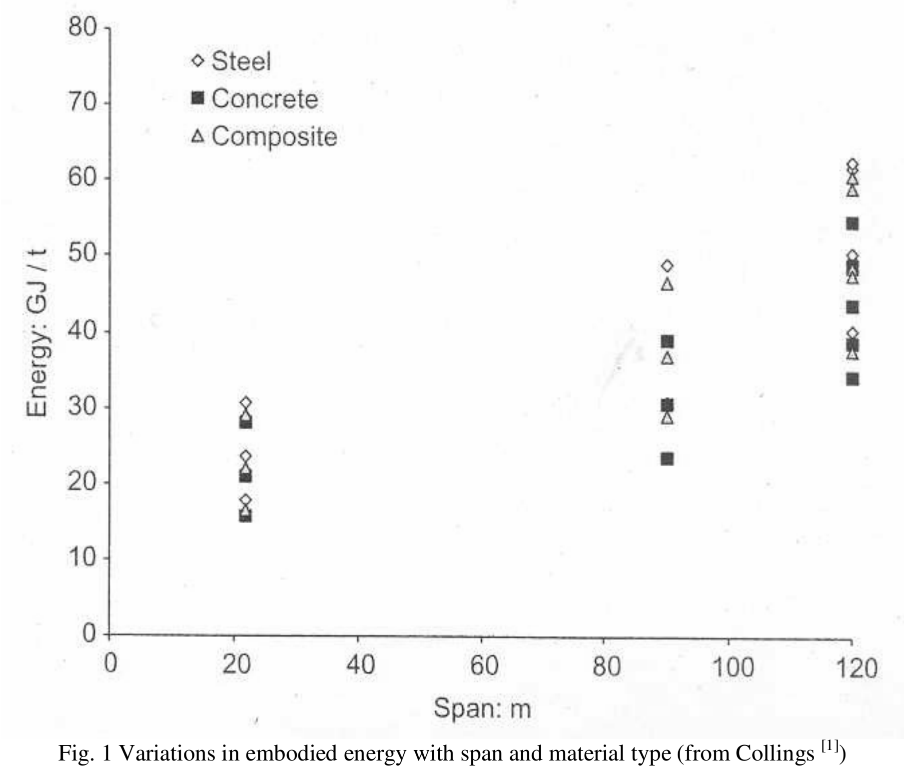

Fig. 1 Variations in embodied energy with span and material type (from Collings [1])

2.2 *Repair, Maintenance and Congestion*

All bridges will require some form of intervention during their lifetime and ideally this, as well as all other aspects, should be taken into account in the design process. Even the most basic maintenance will cause congestion but the impact of replacement can be much greater as exemplified by the Tinsley Viaduct.

The Tinsley Viaduct is a twin deck steel/concrete composite beam girder bridge which carries the M1 motorway and the A631 trunk road across the Don valley near Sheffield. The 1km long structure has 20 spans and crosses two railway lines, the River Don and a canal. As a strategic part of the motorway network, the viaduct carries approximately 115,000 vehicles per day. However in the late 1990's it failed to satisfy the requirements for the introduction of 40t lorries and decisions had to be taken on whether to strengthen or replace the structure.

A replacement bridge was estimated to cost £200 m however the associated cost of congestion over the 2-3 years period of construction was considered to be around £1400m. This enormous additional cost, not to mention the associated environmental impact of congestion, was clearly unacceptable and in the end it was decided to carry out a complex strengthening process whilst keeping the viaduct open for traffic except for a short time each night. In the end the Viaduct was repaired for £80m with minimal congestion resulting – a net saving of £1,500m.

From the viewpoint of the impact of congestion this extreme example demonstrates the importance of having bridges which can be repaired whilst effectively remaining in service. In this regard steel is more amenable to strengthening however the availability of carbon fibre composites allows comparable action to be taken for concrete bridges. It should also be noted that he cost/environmental impact of congestion is an ever increasing problem as many urban bridges built in the 1960's are now in need of remedial action. This should be considered, even if only approximately, in the total life cycle design of future bridges. Whilst this may increase the design cost the long term savings could be enormous.

The relative importance of congestion also requires designers to think carefully about the selection of durable materials and the most appropriate form of construction. As a consequence in the future it will be even more important to build bridges which require minimal maintenance and ensure that premature replacement is avoided.

2.3 *Total Life Cycle "Cost" of Bridges*

Whilst the initial "costs" are useful it is the "cost"/"energy use" over their full life that is more significant. In this context the importance of adopting Integral Bridges [2] for relatively short spans is highlighted. Basically by designing a bridge without movement joints and which is integral from one abutment to the other the maximum resistance to chloride penetration is obtained. As a further step the timely and appropriate application of protective coatings which can be applied whilst it is in service, can delay the need for bridge repair. Thus, by using these methods and some of the innovative approaches detailed later in this paper the life of specific types of bridges can be greatly enhanced and the total life cycle "cost"/"energy use" reduced.

3. DEVELOPMENT OF NOVEL *IN-SITU* TEST METHODS

3.1 *Background*

The single most important parameter that leads to premature deterioration is the ingress of moisture into the concrete [3,4]. Thus, the permeability of concrete to the macro-environment during its service life can be used as a measure of its durability.

In the development of a holistic model for concrete deterioration, Mehta [4] has considered the influence of environmental factors on the various deterioration mechanisms involved. In essence, the permeability influences the primary method of transport of moisture and aggressive ions into the concrete and subsequent increases in the permeation properties are responsible for the increased rate of damage. Thereafter, crack growth (which depends on the fracture strength) accelerates the penetration of aggressive substances into the concrete and the spiral of deterioration continues downwards. The interdependence of all these factors and the importance of permeability/transport properties and strength are clearly illustrated in the holistic model in reference [3].

3.2 *Measurement of Durability Related Properties*

Recognising the importance of these parameters researchers at Queens University Belfast have responded by developing the following three *in-situ* test methods and the associated novel test equipment:

1. The "pull-off" test [5] for measuring TENSILE strength of concrete using the 'LIMPET';
2. Permeation testing [6] utilising the 'AUTOCLAM'; and
3. Assessing the diffusion characteristics of concrete using the 'PERMIT' [7].

All the three *in-situ* tests have been used on site to assess the corrosion induced damage to the Dickson bridge in Montreal [8]. The tests indicated that strength did not correlate well with the levels of deterioration but permeability and diffusivity provided much useful information.

3.3 *Conclusions on in-situ Test Methods*

In the assessment of durability, the following potential uses for strength, permeability and diffusion testing have been identified:

1. *Estimating the life of new structures:* Here the equipment has been used to develop a "mix design for durability" [9] and important trends have been identified (Fig. 2) which could be extremely relevant to new construction.
2. *Assessing the remaining life of existing structures:* The good correlation between permeability indices and durability characteristics can allow remedial action to be taken before irreparable damage has occurred.

Thus, it is essential for practising engineers to work closely with those involved in relevant research. In this context the 'LIMPET', the 'AUTOCLAM' and the 'PERMIT ION MIGRATION TEST' (Fig. 3) could be invaluable tools for generating useful data.

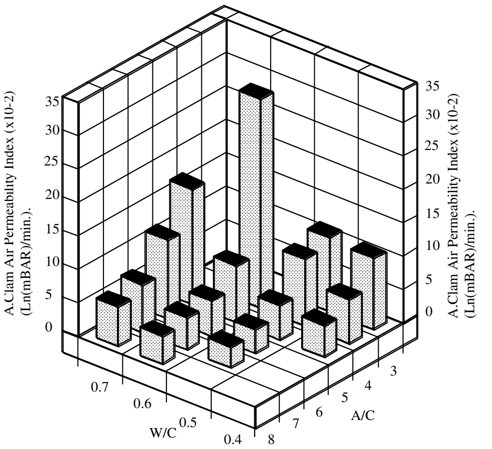

Fig. 2 Influence of mix proportion on Autoclam air permeability index

Fig. 3 Permit, Limpet and Autoclam (from left to right)

4. TECHNOLOGICAL INNOVATIONS FOR ENHANCED SUSTAINABILITY

4.1 *Background*

Bridges with spans of up to 30m constitute the vast majority of road infrastructure bridges in service across the world. Within this category of bridges concrete deck slabs are widely used whether in combination with pre-cast pre-stressed concrete beams or steel girders. In addition, Arch bridges have been widely used in the past for shorter spans and even though their durability is unquestioned their labour intensive methods of construction have rendered these unpopular in recent decades. Technological advances to overcome some of these problems will now be briefly described.

4.2 *Design of bridge deck slabs based on arching action*

By taking the structural advantages of arching action into account in the design process [10] and [11] the following benefits can be achieved:

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 (Fig. 4). Research has shown that significant enhancement to durability/sustainability can be achieved by utilising:

1. Concrete with fibres to reduce cracking or taking advantage of the fact that for a given degree of restraint the strength of slabs developing arching action significantly increases with concrete strength.
2. Conventional steel reinforcement located in a single layer at the centre of the slab (greatly increased cover).
3. Glass/carbon fibre reinforced plastic reinforcing bars.

These approaches have performed well in laboratory and field tests 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 (Fig. 4).

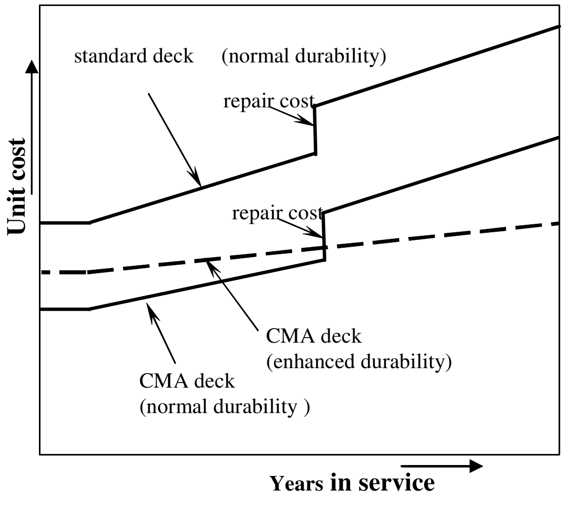

Fig. 4 Comparison of the total unit cost of beam and slab superstructure over their service life

4.3 *Development of a novel flexible concrete arch system*

Brick or stone masonry arch bridges have been utilised for thousands of years and have proven durability. However, it is no longer economically viable to construct a masonry arch in the traditional way due to the cost of accurate centring and the preparation of the masonry blocks. In order to provide a viable alternative Queens University Belfast, in collaboration with Macrete Ireland Ltd, have developed a flexible concrete arch system made of un-reinforced pre-cast concrete voussoirs. The arch system is constructed and transported to site as a flat pack arch. A polymer grid reinforcement is used to carry the self weight during lifting to form a masonry arch. The preferred method of construction of the arch unit is as follows:

> *The voussoirs can be pre-cast individually, laid contiguously in a horizontal line with a layer of polymer grid reinforcement placed on top. An in-situ layer concrete, is placed on top and allowed to harden to interconnect the voussoirs.*

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 precast footings and all self-weight is then transferred from tension in the polymer to compression in the “voussoir” elements of the arch.

The novel arch system has been demonstrated [12], 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 corrodible reinforcement the long term durability is assured.
4. The system is cost competitive with less aesthetic RC box culverts.

5. CONCLUDING REMARKS

The sustainability of our infrastructure is now accepted as a key issue in many parts of the world and it is essential that the construction industry recognises the important role it has to play and responds positively to the associated challenges. Within our transportation network, crucial for the continued economic growth of out nation’s bridges form a critical part. Deficiencies in the durability/strength of bridges which necessitate repairs/replacement can lead to considerable disruption/congestion within the network and have a very negative impact on sustainability. Thus, bridge engineers will have to integrate aspects of sustainability, such as the relative merits of different forms of construction, maintainability and associated congestion, into the total life cycle cost design process.

Innovative research carried out over the past 30 years at Queen’s University Belfast has been aimed at increasing the durability of concrete structures and bridges in particular and has led to the following conclusions:

1. The availability of improved in-situ test methods paves the way for greatly enhanced durability by design for new and existing concrete structures.
2. Advances in structural design based on research on arching action in bridge deck slabs can lead to virtually maintenance free systems.
3. The flexible concrete arch system, which can be transported to the site in “flat pack” form and avoids the need for centring, has great potential.

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