Life-cycle considerations in the selection and use of bridge expansion joints

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Summary

Bridge expansion joints are often subjected to great challenges, such as large movements and relentless dynamic loading, and thus require proper periodic maintenance and, from time to time during the longer life of the bridge, replacement. Consideration of the long-term costs associated with the joints – including for supply, installation, maintenance, and replacement of the joints, and other costs such as those resulting from the traffic disruption caused by replacement works – demonstrates the importance of devoting adequate attention and expenditure to the procurement, installation and maintenance of high-quality joints. Indeed, the initial costs of supply and installation have been concluded by leading authorities to be insignificant in relation to the costs of joint replacement works, especially when user costs are considered. Recognition of this, and consideration of the measures which are proposed to assist in implementing a long-term strategy, can help minimise the life-cycle costs of a bridge's expansion joints – for the benefit of owners, users and society at large.

Keywords: Expansion joints; bridges; life-cycle costs; durability; maintenance; replacement; user costs

1. Introduction

In the responsible management of any construction project or asset management programme, life-cycle considerations must be to the fore. This is now widely recognised, even if this recognition has, to a large extent, regrettably not yet translated into consistent practice. A great deal has been written to assist engineers and owners in the assessment of life-cycle issues, and the field of bridges is no exception - for example, with the 2003 report, "Bridge life-cycle cost analysis" [1], published by the Transportation Research Board of the American National Research Council as Report 483 of the National Cooperative Highway Research Program (NCHRP). The field of bridge expansion joints, however, is considerably more specialised than that of bridges in general, and a concise commentary on the life-cycle considerations of these critical bridge components is not known to the authors. This paper seeks to provide such a commentary, in the hope that it will offer useful guidance to bridge owners, designers and constructors.

2. The challenges faced by bridge expansion joints

A bridge's expansion joints are generally considerably lighter and less robust that the rest of the structure which supports them, and at the same time must facilitate deck movements and rotations while subjected to dynamic, fatigue-inducing loading from traffic. The expansion joints of a bridge which is crossed by 50,000 vehicles a day, for example, will be subjected to well over a billion axle loads, or mini-impacts, during a 40-year service life. This enormous figure explains why the expansion joints of any bridge require proper maintenance throughout their lives, and why they will be likely to require replacement several times during the life of the main structure. It also illustrates well the importance of careful consideration, during selection and design of the bridge's expansion joints, of the complete life-cycle of the main structure and of the joints themselves.

3. Life-cycle Cost Analysis

As noted by NCHRP Report 483 [1] in relation to Life-Cycle Cost Analysis (LCCA): "LCCA is essentially a technique for considering the economic efficiency of expenditures". It goes on to define Life-Cycle Cost (LCC) for a bridge in terms of its constituent parts, as follows:

$$LCC = DC + CC + MC + RC + UC + SV \quad (1)$$

where

DC = design cost,

CC = construction cost,

MC = maintenance cost,

RC = rehabilitation cost,

UC = user cost, and

SV = salvage value.

Life-cycle cost analysis thus represents a great improvement on the "traditional" approach often used in the construction of infrastructure, which considers only the initial direct costs of design and construction (i.e., the terms DC and CC in the equation above). This is explored in more detail in the next section, for the specific case of a bridge's expansion joints.

4. The importance of consideration of life-cycle costs in the selection, design, installation and maintenance of bridge expansion joints

It can be inferred from the foregoing statements that it is important that the complete life-cycle of a bridge's expansion joints be carefully considered when selecting, designing, fabricating, installing and maintaining them. This can be confirmed by closer analysis of the life-cycle costs, starting with a definition of what they include. Equation 1 above, formulated to define the life-cycle costs of a bridge as a whole, can reasonably be considered generally applicable also to the expansion joints within the bridge, especially considering that an expansion joint is essentially a small bridge at the end of a deck section of a big bridge (both being likely to allow sliding movements on their own bearings or sliding pads, and both being subjected to direct traffic loading). Adapting Equation 1 slightly for use in relation to expansion joints:

$$LCC = ISC + IIC + IMC + DRC + UC \quad (2)$$

where

LCC = life-cycle cost,

ISC = supply cost,

IIC = initial installation cost (at time of bridge construction),

IMC = inspection and maintenance cost,

DRC = direct replacement cost, and

UC = user cost.

(Note that the salvage value of an expansion joint may be neglected in such an exercise and is omitted from the above equation).

It is important that the life-cycle to which reference is made is that of the bridge structure, and not of particular expansion joints which are installed on the bridge at a particular point in time (e.g. at the time of the bridge's construction). This is an important distinction, because only consideration of the bridge's life-cycle will take account of the most significant costs associated with its expansion joints: the cost to the owner of periodic replacement works, and the user costs that accompany those works.

The first 4 of the 5 costs in the equation above (ISC, IIC, IMC and DRC) are classified as *Agency Costs*, which are carried by the responsible agency or bridge owner, as opposed to the *User Costs* (UC) which are carried by the bridge's users (which include motorists and others who cross the bridge, and possibly the businesses and residents of nearby areas that rely on the bridge for access).

It should be recognised that these cost groups can be viewed differently in a philosophical sense; initial supply and initial installation costs are certainly necessary and worthy of an appropriate level of expenditure, but direct replacement and user costs should be kept to a minimum. Inspection and maintenance costs fall somewhere in between, being both absolutely necessary (to the extent required by a well selected, detailed and installed joint) and worthy of proper expenditure, but the need for further maintenance effort can and should be avoided. It should also be noted that the cost groups are interrelated; money wisely spent on the supply of a high quality product and on proper installation and maintenance will increase expansion joint life and thus reduce replacement costs and the associated user costs, while money unwisely saved on supply and installation will result in increased maintenance costs, as well as increased replacement and user costs.

The significance of each of these cost groups is discussed below.

4.1 Initial supply and initial installation costs

The costs of supply and installation in a new bridge of its expansion joints depends on many project-specific factors, such as (perhaps most significantly) movement range and length, but the costs are somewhat related to the costs of construction of the bridge as a whole: the movement range (and cost) of the joints depends on the length (and cost) of the bridge; and the length (and cost) of the joints increases with increasing width (and cost) of the bridge. Therefore, anecdotal evidence of the costs of supply and installation of expansion joints on a large bridge, as a percentage of the overall construction costs of the bridge, may be considered to give a reasonable indication of the relative costs on other structures. NCHRP Report 467 [2], for example, records that the total installed cost for two modular expansion joints, "each with a movement capacity of 915 mm (36 in.) was USD 800,000 or 1.2 per cent of the USD 63,000,000 total cost of the Lacey V. Murrow floating bridge in Seattle". A typical range of 0.5% to 1% of the construction cost of a bridge is presented by Braun [3]. These are clearly very small percentages for the parts of the bridge which are arguably subjected to the greatest challenge.

As well as comprising only a small percentage of the bridge construction costs, the initial cost of supply and installation of the structure's joints is also small in relation to the future costs of maintenance and replacement should the joints perform poorly. Indeed, NCHRP Report 467 [2], in commentary about the above-mentioned construction cost data, goes on to note that the initial cost of supply and installation is "insignificant" in this context – a view shared by the Transport Road and Research Laboratory (TRRL) in the United Kingdom [4].

4.2 Inspection and maintenance cost

There are two general approaches to infrastructure management, proactive and reactive, and, in general, only the proactive approach can be recommended in the case of a bridge's expansion joints. Inspection and maintenance work is an essential part of the proper management of any bridge, and even more so in the case of its expansion joints, which as noted previously are subjected to greater movements and more dynamic loading than the bridge as a whole. NCHRP Synthesis 319 [5], for instance, states: "All currently available joints require preventive maintenance to keep joints functioning and avoid costly structural damage", noting in particular that "it is important to minimize the leakage to avoid serious damage to the bridge structural support system". In the case of modular joints, NCHRP Report 467 [2] found that "failures are often a chain reaction (i.e., the failure of one component leads to the destruction of other components). Eventually, this chain reaction leads to a failure or loss of serviceability or functioning" – highlighting the importance of early detection of problems and taking of corrective or preventative action. In spite of this, NCHRP Synthesis 319 [5] notes that some "agencies indicated that they tend not to respond to joint problems unless there is a safety hazard or the deck is being rehabilitated or replaced". A change of mind-set is therefore required of many of those who are responsible for inspection and maintenance activities; it should be recognised that the costs of a sensibly planned inspection and maintenance regime are well invested, and will likely result in much greater long-term savings by reducing the need for expensive reactive repairs and by delaying or avoiding the need for joint replacement work.

4.3 Direct replacement cost

As noted above, an expansion joint of any type has a shorter life expectancy than the main structure on which it is installed. The direct cost to the owner, or agency, of the replacement works that become necessary at the end of the service life of a particular joint can be very significant. At any rate, due to the costs of site mobilisation and traffic management, and the limitations on progress imposed by the need to keep traffic flowing on the bridge, the costs are likely to be much higher than the initial supply and installation works that were carried out when the bridge was under construction. The costs of replacing an expansion joint on an existing bridge are estimated by Braun [3] to be approximately three times higher than the initial installation costs, when the work is scheduled with pavement renovation activities, or between five and six times higher when the work is carried out on its own.

Data from an actual bridge gives a further indication of the magnitude of such costs; in 2006, the direct cost to the owner of the replacement of a single 9-gap modular joint on the Anzac Bridge in Sydney Harbour was “conservatively estimated at 5 million Australian dollars” [6], or approximately USD 5,300,000. While it is unsafe to compare this estimate with the actual cost of initial supply and installation of the (somewhat larger) joints of the Lacey V. Murrow floating bridge in Seattle as recorded above, the difference in magnitude between the figures is remarkable.

Therefore, in order to minimise the life-cycle costs of a bridge’s expansion joints, during the life of the bridge, it is clearly necessary to minimise the number of joint replacement exercises required during that life – by the use of joints of suitable quality and durability, and appropriate attention to inspection and maintenance activities.

4.4 User cost

The user costs associated with a bridge’s expansion joints result primarily from the disruption to traffic that is caused by joint maintenance or replacement works. The assessment of these costs requires the estimation of such factors as the number of vehicles and occupants which will suffer delays, the average length of delays, the cost per hour per vehicle or occupant, and increased fuel consumption. User costs will therefore vary greatly from one structure to another, but an indication of their magnitude is again given by data relating to the Anzac Bridge in Sydney, where it was estimated that, in addition to the above-mentioned direct costs to the owner, “community savings (associated with traffic disruption, increased travel times, increased pollution, etc) of 10 million Australian dollars” [6], or approximately USD 10,600,000, could be realised by avoiding replacement.

This emphasises once again the importance of minimising the frequency at which the expansion joints of a bridge will have to be replaced; by the use of joints of high quality and high durability, and proper attention to inspection and maintenance activities, overall life-cycle costs can be minimised.

5. How the life-cycle costs of a bridge’s expansion joints can be minimised

The results of the above analysis of the life-cycle costs of a bridge’s expansion joints, as presented in Equation 2, might be summarised as follows:

> *In order to minimise the overall life-cycle costs of a bridge’s expansion joints, it must be ensured that adequate resources are devoted to maximising the suitability, durability and quality of the joints selected for use, and enabling them to perform as well as can be expected, for as long as can be expected, by ensuring the quality of their installation and the adequacy of subsequent inspection and maintenance activities.*

This overall strategy is broken down and discussed in the following sections – in some cases illustrated with reference to joints of the modular type, which are the most versatile available today and which can be designed to satisfy the requirements of almost any structure.

5.1 Maximising the suitability, durability and quality of the joints selected for use

The bridge designer can play an important role in optimising the overall costs of a structure's expansion joints, by paying due attention to the issues described below. Many such issues require proper understanding of the capabilities of particular joint types and awareness of the capabilities of the supplier that will design and manufacture them, so proper support from an experienced and qualified supplier can be of great value, even in the early stages of a bridge design and construction project.

5.1.1 Specification of demands which must be satisfied by the expansion joint

It is of course important to define the demands to which the expansion joint will be subjected, and to ensure that this will not present major difficulties for supply. This assessment should not be limited to just the bridge's longitudinal movements and designer or owner preferences, but should consider all other relevant factors such as: transverse and vertical movements; rotations about every axis; the frequency of such movements and rotations; the cumulative movement during the lifetime of the joint (including micro-movements which can occur due to wind or traffic, and due to thermal changes when the sun's warmth is temporarily blocked by a cloud); and the nature of the movements (whether they are sudden and irregular, or gradual and predictable). When these factors have been assessed, such issues as choice of sliding material can be properly considered, and it can be confirmed whether the best materials available can be expected to satisfy durability requirements. If they cannot, then this should be recognised and accepted, and suitable allowance made for maintenance and replacement, or another solution should be sought – issues which should certainly be considered early in the design process.

5.1.2 Evaluation of the needs of the preferred joint type

Once the type of joint which can optimally satisfy the structure's needs has been identified, and allowance made for the costs of supply and installation of this type, it is important to ensure that the bridge deck is designed to receive the selected joint, with proper access and correctly sized block-outs and bridge gap. Inadequate access to the underside of the joint may cause difficulties with inspection and maintenance at a later stage, and incorrectly dimensioned recesses and bridge gap may necessitate changes to approved plans, or even adaptations to the constructed bridge deck on site. Failing this, a less optimal, and perhaps inappropriate joint type may have to be selected to suit the deck design, or the optimal joint type may be used but in a sub-optimal way – for example, with inadequate access to the joint from beneath to allow proper and uninhibited inspection and maintenance.

5.1.3 Verification of joint performance

It is most important that the ability of the selected joint, as designed and fabricated by the selected manufacturer, to withstand the loads and movements to which it will be subjected during a long life on a structure, should be verified in advance of its use.

The best verification of this is a strong track record on the part of the expansion joint supplier, with evidence of satisfactory performance of the joint over many years on comparable structures which place similar demands on the joint.

Laboratory testing also serves a useful purpose, and can be very extensive (for instance, the testing which is required by American standards, as described by Spuler et al [7]), but it must be recognised that the degree to which it can replicate actual service conditions is limited by the need to make testing practical, affordable and possible to complete in a reasonable timeframe. This dictates that any particular test can only assess certain defined performance characteristics, and that such assessments will be based on various simplifications and assumptions. No combination of practical, affordable laboratory tests can accurately assimilate the full range of demands experienced by a joint in service. Nonetheless, laboratory testing is often necessary, even if only to give new or improving suppliers an opportunity to demonstrate the quality of their products. The specification of standard testing requirements by road authorities / agencies also ensures that a certain level of quality, which is necessary in minimising life-cycle costs, will be demanded in the procurement of the joints which will be installed on their structures.

5.1.4 Design measures which can protect the joint and extend its lifespan

The bridge designer may consider measures, separate from the expansion joint, which have the effect of protecting the joint and enabling it to serve a longer life. For example:

- the fitting of hydraulic dampers to a bridge deck which would otherwise experience fast, erratic movements at its expansion joints, could reduce the movements and their detrimental effect on the joints; or
- the use of an automated monitoring system may provide ongoing confidence in the performance of the structure's expansion joints, especially where the magnitude, frequency or nature of the deck's movements, or other influences, cannot be predicted with great confidence (see also Section 5.3 below).

5.1.5 Suitable corrosion protection

The corrosion protection applied to any exposed steel on the expansion joint should be appropriate to the bridge's environment – meaning that an appropriate system, (e.g. painted, galvanised etc) and appropriate level of protection must be specified, and properly applied, with adequate verification of quality and particularly layer thickness and adhesion. It must also be considered that such joints will require re-application of corrosion protection (generally by painting) some time after the joint has been installed, so access to the susceptible parts of the joint should allow this work to be done well and without great difficulty.

5.1.6 Quality of design and manufacture

A comprehensive QA/QC system, for example in accordance with ISO 9001, and approval of design and manufacturing processes in association with the issuing to suppliers of national general approvals to supply the product in a certain country without further evaluation, can also provide confidence in the ability of a particular supplier to provide a product of the required quality.

5.2 Ensuring the quality of installation

The importance of proper installation to the correct functioning and durability of an expansion joint should be fully appreciated. For example, a joint should be installed in such a way that all its parts are properly supported and will not be subjected to any unnecessary forces. Its gap width at the time of installation must be appropriate for the gap width of the structure at that time, considering the prevailing structure temperature, with allowance for the future opening and closing movements that the joint must accommodate. And any designed pre-tensioning within the joint should be as designed, without increase or decrease due to lack of proper levelling. Many other factors must also be considered and checked. But all too often, expansion joints are installed with insufficient care or expertise, as recognised by NCHRP Report 467 [2], for example, which broadly groups durability problems with modular expansion joints into four categories, one of which is "Problems that can be traced to improper installation". It is thus important that the installation of a bridge's expansion joints is supervised by a competent person who is familiar with the design and needs of the particular joint type. Supervision provided by the joint manufacturer may be the best solution and is generally to be recommended.

It should also be noted that expansion joint designs can have a serious impact on constructability. For example, a joint whose design (e.g. with orthogonal shape) allows easy placing of reinforcement and concrete around it on a bridge deck will be less likely to suffer from poor quality installation than a joint whose design makes this site work complicated and difficult.

5.3 Ensuring the adequacy of inspection and maintenance activities

As noted in Section 4.2 above, proper inspection and maintenance are essential for the long-term functioning of an expansion joint. NCHRP Report 467 [2], for instance, states in relation to modular joints: “It is recommended that they be inspected at least every 2 years or when the bridge has its regular inspection”.

As also noted above, these activities often do not get the attention or resources they deserve, resulting in durability and other problems. NCHRP Report 467 [2] goes on to note:

“The three major factors inhibiting good inspection and maintenance practice are as follows:

- High expense;
- Access limitations; and
- Lack of technical understanding … among engineers and maintenance personnel”.

In commentary on each of these points, it should be noted:

- Avoiding inspection and maintenance work to save money is generally counter-productive, as this is liable to lead to far higher repair costs in the future, and earlier joint replacement;
- Access limitations should certainly be avoided during the bridge design and joint selection phase, as noted in Section 5.1.2 above; and
- Technical understanding is certainly important, so that the potential consequences of any issues observed can be investigated, and so that the correct course of action to address such issues can be selected.

An enhanced recognition of these facts among those who are responsible for funding and arranging maintenance of expansion joints will play an important role in improving the performance of the joints and thus minimising their life-cycle costs and that of the bridge in which they are located.

<u>The role of modern structural health monitoring</u>

Of course, inspections, and the investigations associated with required remedial works, are no longer limited to purely manual efforts; great benefits, in terms of both ability and expense, may be offered by automated remote monitoring systems [8]. The formidable data measuring power of today’s structural health monitoring (SHM) technology can be used to measure and report on any chosen variables in the bridge’s condition (saving manual inspection visits), or to precisely define a maintenance or repair challenge and thus refine and optimise the selected solution. Such systems can even be programmed to send alarm messages to the bridge engineer, by email or SMS, should any measured variable exceed a predefined boundary value – thus ensuring that any potential problem can be dealt with before it develops into a costly repair project. The use of such systems can thus, in many cases, enable the life-cycle costs of a bridge’s expansion joints to be optimised.

6. Further considerations

Although a great improvement on the “traditional” approach, it should be recognised that even Life-Cycle Cost Analysis, as defined and explored above, does not encompass all considerations that should be included in an analysis of the total costs related to bridge expansion joints. For example:

- Since it only considers the costs to the bridge’s owner (or responsible agency) and its users, an important omission is the costs to the environment and society in general. Maintenance and repair work on a bridge’s expansion joints, and especially replacement work, can have a great environmental impact, due, for example, to the use of new materials to replace old ones and the exhaust fumes and fuel wastage that results from traffic congestion.
- Another significant omission (which has not been included in Equation 2) is the impact on the main structure. A higher quality expansion joint can better protect the main structure, for example by absorbing impact loads from traffic, or by eliminating water ingress into the structure, which can result in serious damage to the structure (as noted in Section 4.2 above).

These additional impacts strengthen yet further the case for the use of only high quality expansion joints in bridges, and their proper installation and maintenance.

7. Conclusions

Consideration of the costs of a bridge's expansion joints, during the complete life-cycle of the bridge, shows that the cost of procuring a suitable, high-quality joint and installing and maintaining it properly, will be repaid many times by minimising the need for costly repair and replacement works. A properly selected and designed joint may provide good service for 40 years or more, while a cheaper alternative, selected primarily with a view to minimising short-term construction costs, is likely to require replacement much earlier. Maintenance and repair effort during the shorter service life of a low-quality joint are also likely to be higher, not only for the joint itself but also for the parts of the bridge beneath that it has failed to protect. And the cost of maintenance and replacement works, considering both the direct costs to the owner and the indirect costs to society of disruption to traffic etc, are likely to amount to many times the cost of the original expansion joint.

Recognition of this must, however, translate into practice in the construction and maintenance of bridges. In spite of the "insignificance" of the costs of expansion joint supply in relation to replacement and user costs, supply costs unfortunately still often play a dominant role in the selection process, because a lower-cost, low end product may fulfil short-term needs. It is therefore important that bridge construction contracts are so devised, that the company that chooses the joints and their supplier has a real incentive to ensure their long-term quality and performance.

Consideration of life-cycle issues also demonstrates the importance of good technical information at every stage throughout the life of a bridge's expansion joints, starting of course with selection of the most suitable type and detailing the joints to satisfy all needs (as well as detailing the bridge deck to satisfy the needs of the expansion joints). Proper understanding of the joint type and its requirements is also needed to ensure that inspection and maintenance efforts are well directed and have the desired effect. And the supply and installation challenges only become greater when the joints are being replaced in an existing bridge. The involvement of well qualified joint suppliers, who are specialised in these particular issues, should always be considered.

Of course, life cycle considerations should not consider only financial and user costs, but also the wider impacts on society and the environment. It seems likely that the future generations who will be responsible for the management of structures built today will be yet more concerned with environmental protection and conservation of natural resources than we are today, and the provision of joints which achieve longer life with less maintenance and repair effort, and which can be replaced or partially renewed with less effort and waste, will be highly appreciated.

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