Long Life Bridges

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ABSTRACT: Bridges, like many Civil Engineering structures, are designed quite conservatively – the probability of dying due to collapse of a new bridge is about 1 in 10 million. Part of the reason for this conservatism is that adding extra strength to a bridge when it is being built is not expensive. For older bridges however, the situation is quite different. There is a huge difference between the cost of strengthening an existing bridge and not doing so. It is frequently possible to prove that a bridge is perfectly safe despite having deteriorated since it was first built. Sometimes the deterioration is in a non-critical element of the bridge and often the bridge has significant reserve capacity due to conservatism in the initial design process. Long Life Bridges investigates the use of probabilistic techniques in analysing the performance of bridges. This approach reduces the conservatism present in current deterministic methods, particularly in the Dynamic Amplification Factor (DAF) employed in the code. This will allow bridges to be kept in service that would otherwise have been deemed unsafe preventing unnecessary repair or replacement works and resulting in significant savings for the bridge owner.

KEY WORDS: Bridges, probabilistic analysis, dynamics, life cycle evaluation.

1 INTRODUCTION

Transportation infrastructure is a foundation stone for any developed economy. For Europe in particular, the single market depends on an effective transportation system to bring together people and to facilitate trade across the entire eurozone. With a huge stock of ageing bridges present on the European transport network, many of these structures will soon need maintenance/intervention strategies to optimize their remaining service life. Across Europe there are a significant number of bridges that are vital to the economies they serve, and which, if taken out of commission would have a devastating impact on local, national, and international economies. Take for example, the Firth of Forth Bridge in Scotland which connects Edinburgh to Fife (Figure 1).

Figure 1: Forth Road Bridge, Scotland

This bridge, which opened in 1964, is a vital element of Scotland’s transportation infrastructure and is of prime importance for the local and national economies. Due to inadequate maintenance strategies, the bridge, which was designed to be serviceable up to 2084 was found to be undergoing significant deterioration, with the result that by 2017 it was predicted that it would no longer be able to safely carry vehicular loading. As a result a new bridge is currently under design.

Traditionally, this replacement of infrastructure, usually at the end of its design life, has been the adopted strategy. However, advanced analysis techniques, which Long Life Bridges aims to exploit, now exist to accurately assess and identify, on an ongoing basis, maintenance and repair strategies that would prevent a recurrence of the Forth Road bridge scenario. Normally, due to conservatism in their initial design, many bridges may have sufficient reserve capacity to remain in service for an extended period of time beyond their initial design life. The goal of the Long Life Bridges project is to develop techniques to extend the lives of these bridges. It will allow identification of old bridges that are safe to remain in service and those that need maintenance plans to optimise their remaining life. In times of economic recession this is particularly important, ensuring the maximum return possible from the existing bridge infrastructure as opposed to undertaking expensive new design and build projects. Long Life Bridges aims to deliver:

- More road and rail bridges being proven to be in a safe state.
- Higher speeds on our (non-high-speed) railway lines.
- Less demand for non-renewable and carbon intensive resources.
- Less cost associated with achieving these goals.
The project is a collaboration between two Small/Medium Enterprise (SMEs); Roughan and O’Donovan consulting engineers in Ireland (the consortium leaders), and Phimeca in France, and two university partners; The Royal Institute of Technology, KTH, in Stockholm, Sweden, and Aalborg University in Denmark. The partnership brings together experts in the fields of structural assessment, probabilistic analysis and risk quantification from both academic and industrial backgrounds. Three main research threads are studied in the project: Bridge Dynamics, Life Cycle Evaluation and Fatigue. These topics are discussed in the following sections.

2 BRIDGE LOADING AND DYNAMICS

A bridge is safe if the stresses due to the applied loads are less than its capacity to resist those stresses (load < resistance). Many assessments of bridge safety – with or without dynamics – come back to this basic point and calculate some indicator of the probability that load is less than resistance. It can be argued that both sides of this equation – load and resistance – are equally important. Site-specific measurement of traffic load and quantification of the associated uncertainty [1] has great potential as there are many bridges where the actual load is much less than that for which the bridge was designed. Recent improvements in Weigh-In-Motion (WIM) technology [2] have made this possible, by providing road authorities with large databases of vehicle weights, axle configurations and inter-vehicle gaps. Even with years of WIM data, combinations of vehicles can occur in the lifetime of a bridge that were not recorded. To comprehensively explore the complete design space of loading scenarios, most researchers simulate many more loading scenarios than measurement would allow and apply statistical approaches to the results. The peaks over threshold approach [3], Rice level-crossing technique [4] and extreme value probability distribution fits [5] have been used to extrapolate from simulated results to find characteristic maximum loading effects. The variability in results can be significant – all of these processes are essentially extrapolations from data collected over a relatively small time to a very large return period.

This branch of the Long Life Bridges Project deals with bridge dynamics. There is a substantial body of literature on vehicle/bridge dynamic interaction [6, 7, 8] but most of it is deterministic in nature. Even in the derivation of the Eurocode, a probabilistic model was used to represent the uncertainty in static loading and simple Dynamic Amplification Factors (DAFs) were applied to the result. A small number of researchers, including the authors, have been developing probabilistic approaches to the dynamic interaction between traffic and bridges [9, 10]. There is great potential in this as the Eurocode factors range from 20% to 70% (see Figure 2) whereas the true dynamic amplification is generally less than 10%. By finding the true dynamic allowance, bridges can be safely retained in service that would otherwise be replaced or strengthened. Equally, for railway bridges, trains can be allowed to travel at higher speeds than would otherwise be allowed.

The evaluation of bridge dynamics is most often studied using the DAF. This is the ratio of the total load effect to the static load effect for a particular loading scenario, expressed in equation 1. Values of DAF as high as 4 have been recorded by Prat [11].

\[
DAF = \frac{LE_{\text{Total}}}{LE_{\text{Static}}} \tag{1}
\]

However, this method makes the assumption that the maximum total load event also results in the maximum static load event which may or may not be the case. An alternative measure of dynamics, known as the Assessment Dynamic Ratio (ADR), recognizes the reduced probability of both the static and total load effect occurring simultaneously [5]. This measure of dynamics is defined as the ratio of the characteristic total load effect, to the characteristic static load effect, described by equation 2.

\[
ADR = \frac{\sim LE_{\text{Total}}}{\sim LE_{\text{Static}}} \tag{2}
\]

The characteristic value is the maximum expected load effect for all loading scenarios for the specified return period, typically 1000 years. The ADR method provides a less conservative approach than the more traditional DAF, whilst ensuring an adequate allowance for bridge-vehicle interaction. In Long Life Bridges a greater understanding of how to quantify the uncertainty associated with bridge dynamics will be developed. The theory outlined in this section has been applied successfully to road bridges. In the Long Life Bridges project it will be extended to assess the dynamic behaviour of railway bridges which have important differences such as absence of road surface roughness, presence of ballast and less variability in vehicle properties and in speeds. A semi-active damping system will also be developed to reduce the risk of dynamic excitation.

3 LIFE CYCLE EVALUATION

Life Cycle Analysis (LCA) has been developed on the basis of statistical decision theory and applications of the general theory to infrastructure systems, especially bridges, which have been described by, for example, Frangopol et al. [12], Ang & De Leon [13] and Ellingwood [14]. All uncertainties, and all costs and benefits in the life cycle are
accounted for. The main objective is to minimize the total expected costs by optimising the maintenance actions taken during the design lifetime of the structure. Figure 3a shows the life cycle performance of a structure with no intervention measures, with Figure 3b illustrating the effect of preventative and corrective actions.

Figure 3. Optimisation of life cycle performance

Sustainability aspects can be included using the principles in the risk assessment guideline of the Joint Committee on Structural Safety [15]. Probabilistic life cycle evaluations have also been applied for fixed offshore structures by, for example, Sørensen & Faber [16]. The results show that the total life cycle costs related to these structures can be reduced significantly if strategic planning of inspection, maintenance and repair is performed. Reduction of the total life cycle costs will reduce the total project costs but will also reduce the use of limited non-renewable material resources.

As part of Long Life Bridges, LCA techniques will be applied to calculate the probability of a bridge failure. Generally, this is a calculation at one specific point in time indicating as to whether or not the bridge in question, in its current condition, is safe to remain in service. More recently, consideration of the complete remaining life of the bridge, allowing for its deterioration through time, is the state of the art approach. Long Life Bridges will investigate the use of probabilistic measures in the assessment of bridges and implement them in a case study. Focus will be given to development of a probabilistic framework for the whole life assessment of new cable stay bridges, such as the Boyne Bridge shown in Figure 4, designed by Long Life Bridges consortium leader Roughan and O’Donovan.

Figure 4: Boyne Bridge, M1 Dublin – Belfast

4 FATIGUE EVALUATION

The evaluation of fatigue in civil engineering structures (including bridges) often involves significant uncertainties as investigated by, for example, Sorensen et al. [17]. These uncertainties should be taken into account in the design process by using a probabilistic approach from which the reliability of the structure can be estimated.

Sørensen & Toft [18] divide the uncertainties related to fatigue design into physical, model and statistical uncertainty which can be estimated from tests using classical statistical methods. During the structure’s service life, information from monitoring can be used to update the reliability using Bayesian methods as described by Faber et al [19].

This branch of Long Life Bridges will develop a probabilistic framework for fatigue design of steel bridges building on the fatigue model described by Paris’ Law (Figure 5) which relates the crack growth to the number of stress cycles. The graph is split up into three distinct regions. Region 1 is the threshold zone where below the value of $\Delta K_{th}$ cracks do not propagate, while the linear behaviour in region 2 represents Paris’ Law (note the logarithmic scale on both axes), which is expressed as:

$$\frac{da}{dN} = C \Delta K^m$$

where $a$ is the crack length, $N$ is the number of cycles, $\Delta K$ is the range of the stress intensity factor and $C$ and $M$ are material factors. Finally region 3 represents the zone where failure occurs.
Further to the development of a fracture mechanics model, the work will include a probabilistic description of both the fracture parameters and the time-variant loading.

The structural reliability assessment will be incorporated into a maintenance planning approach, whereby measurements of crack length are monitored in time. This will lead to an optimal maintenance planning framework (such as that shown in Figure 3) that combines fracture models and monitoring data.

5 CONSORTIUM OVERVIEW

*Long Life Bridges* is a Marie Curie Industry Academia Partnerships and Pathways project. The consortium involves four partners; two SMEs, and two leading European Universities, each with particular expertise key to the success of the project.

Roughan and O’Donovan (ROD) consulting engineers are a SME based in Dublin, and are the project coordinators of *Long Life Bridges*. They are recognised as one of the leading civil engineering consultancies in Ireland with particular expertise in bridge structures. They are developing an increasing reputation on a European level, having recently designed the New Wear Bridge in the United Kingdom which will be the tallest bridge in the British Isles when completed (Figure 6). A subsidiary company, Roughan and O’Donovan Innovative Solutions (RODIS) is a partnership with staff of Trinity College Dublin and University College Dublin. The subsidiary focuses on the application of recent research developments in advanced structural design and assessment. Staff have developed software and published extensively on probabilistic approaches to bridge safety assessment, bridge dynamics, bridge traffic loading and Bridge Weigh-In-Motion.

Phimeca is an SME in France with expertise in uncertainty, particularly in the nuclear industry in the quantification of extremely remote risks. Their expertise will allow development of a probabilistic approach to the analysis and design of fatigue critical details in cable stay bridges.

The two university partners, Aalborg University (AAU) in Denmark and The Royal Institute of Technology (KTH) in Stockholm both conduct world class research in areas key to the success of the Project. AAU perform research in structural reliability and risk analysis with experience in application to industrial sectors such as offshore structures, bridges and wind turbines. This also includes development of reliability and risk based methods for life-cycle assessment and optimal planning of inspection, operation and maintenance of structures. KTH conduct research into the analysis and design of bridges, with particular expertise in dynamic behaviour including the instrumentation and monitoring of several bridges across Sweden.

The project involves the secondment of staff between the partners as shown in Figure 7 to enhance knowledge transfer and exploitation of the results on a European wide basis. The three research objectives of the project, Railway Bridge Dynamics, Life Cycle Evaluation and Fatigue Evaluation are illustrated in the schematic with each arrow representing an exchange of staff between the partners concerned.
CONCLUSIONS

The goal of Long Life Bridges is to extend the lives of the existing bridge stock in Europe. ‘Europe 2020, A European Strategy for Smart, Sustainable and Inclusive growth’, is the EU’s policy which sets out an economic growth strategy for the coming decade. Long Life Bridges will make a significant contribution to the goals set out in this plan by:

(i) Integrating sensor information with computer software. This will promote smart growth, thus delivering market-leading assessment tools giving much better information about the safety of bridges. This is a growth market, especially during recession, when infrastructure budgets are under tight constraints.

(ii) Extending the safe working lives of bridges. This improves the sustainability of the transport infrastructure and reduces the demand for new construction involving non-renewable resources.

(iii) Promoting bridge monitoring. This will encourage long term sustainable and local employment of semi-skilled workers promoting the 3rd strand of the Europe 2020 strategy of inclusiveness.

The project has three main research areas: (i) Bridge Dynamics, (ii) Life Cycle Assessment, and (iii) Fatigue Evaluation, involving partners from Ireland, France, Denmark and Sweden. The collaboration brings together experts in the fields of structural assessment, probabilistic analysis and risk evaluation.

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