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<td>Authors(s)</td>
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<td>Publication date</td>
<td>2014-04-17</td>
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<tr>
<td>Conference details</td>
<td>TRA 2014 Transport Research Arena 2014, Transport Solutions: from Research to Deployment - Innovate Mobility, Mobilise Innovation, Paris, France, 14 - 17 April, 2014</td>
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<td>Link to online version</td>
<td><a href="http://tra2014.sciencesconf.org/">http://tra2014.sciencesconf.org/</a></td>
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Long life bridges

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Abstract

The single market is at the core of what the European Union (EU) represents and for Europe in particular, the single market depends on an effective transportation system. However, much of the EU's stock of an estimated 1 million bridges are old and have deteriorated over time. Many of these structures will soon need replacement or maintenance/intervention strategies to optimize their remaining service life. The Long Life Bridges project is a European 7\textsuperscript{th} Framework-funded project that is using advanced analysis techniques to extend the lives of bridges, allowing them to be kept in service longer than would otherwise be possible. Research is centred on the specific considerations of bridge loading and dynamics, life cycle evaluation and fatigue evaluation. It is being carried out by a consortium consisting of two small/medium enterprises and two universities that bring together expertise in the fields of structural assessment, probabilistic analysis and risk quantification from both academic and industrial backgrounds.

Keywords: Bridge; loading; dynamics; Life Cycle Evaluation; fatigue; long-span; cable stayed; probabilistic; risk; reliability.

Résumé

Le marché unique est au cœur de ce que représente l'Union européenne et pour l'Europe en particulier, le marché unique dépend d'un système de transport efficace. Cependant, beaucoup de stock de environ 1 million de ponts de l'UE sont vieux et se sont détériorés au fil du temps et beaucoup de ces structures auront bientôt besoin de stratégies de remplacement ou d'entretien / d'intervention afin d'optimiser leur durée de vie restante. Le projet "Long Life Bridges" est un projet financé par le 7\textsuperscript{ème} PCRD européen qui vise à utiliser des techniques d'analyse avancées pour prolonger la durée de vie des ponts, leur permettant d'être maintenus en service plus longtemps que jugé possible. La recherche est centrée sur les aspects spécifiques de chargements des ponts et des dynamiques, l'évaluation du cycle de vie et de la fatigue. Le projet est mené par un consortium composé de deux PME et deux universités qui rassemblent l'expertise dans les domaines de l'évaluation structurale, analyse probabiliste et la quantification des risques de deux milieux académiques et industriels.

Mots-clés: Pont; chargement; dynamique; évaluation de cycle de vie et de fatigue; haubans; probabiliste; risque; fiabilité

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1. Introduction

An effective transportation infrastructure network is vital to facilitate trade and the transfer of people within the single economic and political area that is the European Union. However a significant number of the bridges on this network are ageing – over 36% of rail bridges are more than 100 years old – and have deteriorated considerably in their lifetimes to date. Coupled with this is the fact that the traffic on these structures is consistently growing, placing increasing demands on these bridges. At the same time, the budgets available for their maintenance/upgrade and/or replacement are consistently reducing, especially in the current economic climate. For example, the Connecting Europe Facility has cut the allocated budget over the next seven years for major transportation projects from approximately €31.7 billion to €23 billion.

Traditionally replacement, usually at the end of a structure’s design life, has been the adopted strategy in dealing with the issues of ageing infrastructure. However, advanced analysis techniques, which Long Life Bridges exploits, now exist to accurately assess and identify, on an ongoing basis, maintenance and repair strategies that could minimise the need for replacement. Due to conservatism in their initial design, many bridges 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 and the research is focused around three central themes: Bridge Loading and Dynamics, Life Cycle Evaluation and Fatigue Evaluation. Work performed in the project will facilitate identification of old bridges that are safe to remain in service and those that need maintenance plans, incorporating structural control and health monitoring, to optimise their remaining life. Coupled with reduced spending on infrastructure, this is particularly important, ensuring the maximum return possible from the existing bridge infrastructure as opposed to undertaking expensive and carbon-intensive new projects. Long Life Bridges will deliver:

- More road and rail bridges being proven to be in a safe state;
- Higher speeds on our (non-high-speed) railway lines;
- With less demand for non-renewable and carbon intensive resources and
- For less cost.

Long Life Bridges is a European 7th Framework research project funded under the Marie Curie Industry Academia Partnerships and Pathways programme (IAPP). It commenced in August 2011 and is of four years duration. The consortium consists of two Small/Medium Enterprises (SME’s) and two universities. It is led by Roughan and O’Donovan (ROD), one of Ireland’s largest civil and structural engineering consultancies. Phimeca, a French SME, are experts in uncertainty quantification, primarily developed in the Nuclear Industry. Aalborg University (AAU) in Denmark is a world leader in the development of reliability and risk-based methods for lifecycle assessment and optimal planning of inspection, operation and maintenance of structures. The Royal Institute of Technology (KTH) in Sweden have a particular expertise in assessing the dynamic behaviour of railway bridges, including the instrumentation and monitoring of several bridges across Sweden.

2. Industry-Academia Partnerships and Pathways (IAPP) and Long Life Bridges

The IAPP programme seeks to promote knowledge transfer between the industry and academic sectors and exploits the results on a Europe-wide basis by embedding the research results in industry. In the Long Life Bridges project, this is achieved through the secondment of staff between the partners as shown in Figure 1. The secondments are centred around the research themes of Railway Bridge Dynamics, Life Cycle Evaluation and Fatigue Evaluation, and in the schematic, each arrow represents a transfer of staff between the partners concerned.

Each of the four partners brings a particular expertise to the consortium which is key to the success of the project. ROD, in conjunction with AAU and KTH, are developing state-of-the-art probabilistic approaches to accurately assess the loads on long-span cable stayed bridges and rail bridges which will be incorporated into a framework for the probabilistic life cycle evaluation of such structures. Phimeca, in conjunction with AAU and KTH, have developed a probabilistic approach to the analysis and design of fatigue-critical details in cable stay bridges, leading to an optimal maintenance planning framework that combines fracture models and monitoring data. This paper presents the aforementioned approaches, proposing them as a partial solution to the problem of
reduced maintenance budgets and ever increasing demand on ageing bridges. Ultimately the project seeks to identify old steel and concrete bridges that are safe to remain in service and those that need maintenance plans to optimise their remaining life.

3. Research focus and results

3.1. Bridge loading and dynamics

This element of the Long Life Bridges project deals with railway bridge dynamics and has two main objectives:

1. to accurately quantify the ‘true’ dynamic allowance for railway bridges with an acceptably low probability of exceedance, using a probabilistic evaluation and
2. to develop a semi-active damping system to reduce the risk of dynamic excitation.

3.1.1 True Dynamic Allowance

Many assessments of bridge safety, irrespective of whether dynamics is considered or not, come back to the basic point that a bridge is safe if the applied load effect is less than the resistance. In particular, engineers are concerned with ensuring that the probability that the load exceeds resistance is acceptably low. Examining the load side of the equation using site-specific measurement of traffic load and quantification of the associated uncertainty, has great potential (O'Connor & Eichinger 2007), 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 have made this possible, by providing authorities with large databases of vehicle information and the techniques to calculate bridge loading probabilities (Caprani et al 2008, Caprani & O'Brien 2010, O'Brien & Enright 2011, Enright & O'Brien 2012). 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 (Crespo-Minguillon & Casas 1997), Rice level-crossing technique (Cremona, 2001), and extreme value probability distribution fits (O'Brien et. al. 2009) 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.

There is a substantial body of literature on vehicle/bridge dynamic interaction but most of it is deterministic in nature (Cantieni 1983, Green & Cebon 1995, Kim et. al. 2007). Probabilistic models have been applied in the Eurocode to represent the uncertainty in static loading but 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 road bridges (Kim et. al. 2007, O'Brien et. al. 2010). This leads to DAFs of significantly larger value than those that occur in reality. Particularly for railway bridges, the DAF does not account for resonant behaviour and for bridges on higher-speed lines, separate dynamic calculations are required. By finding the true dynamic allowance, bridges susceptible to dynamics at the Ultimate or Fatigue Limit States (ULS or FLS) can be better maintained through their required service lives and can be safely retained in service that would otherwise be replaced or strengthened. For this purpose, a measure of...
dynamics known as the Assessment Dynamic Ratio (ADR), recognizes the reduced probability of both the static and total load effect occurring simultaneously (OBrien et al. 2009):

\[ ADR = \frac{\overline{LE_{tot}}}{\overline{LE_{stat}}} \]  

(1)

where \( \overline{LE_{tot}} \) is the characteristic maximum total load effect, including dynamics, and \( \overline{LE_{stat}} \) is the characteristic maximum static load effect. While this concept has been applied successfully to road bridges, in the Long Life Bridges project it is being extended to assess the dynamic behaviour of railway bridges which have important differences such as (i) the absence of large road profile roughness considerations, (ii) the presence of ballast and (iii) less variability in vehicle properties and speeds. These variables are modelled in complex vehicle-bridge dynamic interaction models (Yang et al. 2004).

### 3.1.2 Damping System

In some cases, it is necessary to reduce the dynamic effects on railway bridges by external means, i.e. structural control strategies. These control strategies are seen by the project consortium, as a means to relieve the pressure on rail authorities to increase both the allowable axle loads and the allowable speed on existing railway lines, critical points for which are bridges susceptible to dynamics. These dynamic effects may result in exceedance of dynamic design criteria, reduced service life due to fatigue effects, or even failure. Through better quantification of risk, it is often possible to prove that speeds can be increased with no adverse effect. However, for bridges where the level of risk is too high, a cost-effective means of reducing dynamic effects are active and semi-active control systems which have the ability to change in either stiffness or viscous damping due to a control input, usually voltage, depending on the functioning condition. Conversely, a passive damping system has fixed properties that cannot be altered, often has a narrow efficient bandwidth and may be highly inefficient outside that range, e.g. due to changed frequency of either the structure, the forced vibrations or the damper itself. A bi-directional tuned mass damping system has been developed within the project to reduce the risk of dynamic excitation and thereby extend fatigue service life. This damper (Figure 2), developed by KTH and ROD, was tested on a real bridge in Sweden, Figure 3, the hangers of which are susceptible to damage due to fatigue. The results indicate the benefits of the adaptive damper device in the mitigation of potentially harmful vibrations, Figure 4.

![Fig. 2. Tuned Mass Damper](image)

![Fig. 3. Case Study: (a) Photograph of Bridge; (b) Damper Layout](image)
3.2. 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. 2001, Ang & De Leon (2005) and Ellingwood (2005). 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 optimizing the maintenance actions taken during the design lifetime of the structure. Probabilistic life cycle evaluations have been applied for fixed offshore structures and total life cycle costs related to these structures have been shown to reduce significantly if strategic planning of inspection, maintenance and repair is performed (Sørensen & Faber 2002).

As part of Long Life Bridges, LCA techniques are being applied to calculate the probability of a bridge failure, considering the complete remaining life of the bridge and allowing for its deterioration through time. 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 Probabilistic load modelling and Structural health monitoring techniques.

3.2.1 Probabilistic Load Modelling

This study aims to contribute to the development of the lifetime performance evaluation of long span bridges through the application of more accurate load modelling. Probabilistic load modelling, for traffic loading and traffic plus wind load interaction, is being examined in detail by considering the actual traffic and wind as a coupled system, the importance of which has been stressed by previous authors (Chen & Cai 2007, Petrini & Bontempi 2010). More appropriate bridge load models are being developed by integrating the bridge structure, wind load and traffic micro-simulation models. In the micro-simulation approach, traffic on a bridge is presented as a multi-vehicle system, where each vehicle has its own set of geometrical characteristics (i.e. length, height and width) and driver behaviour characteristics of acceleration, overtaking and lane changing. A general framework is being studied for a scenario-based cable-stayed bridge under normal (free flowing, Figure 5(a)) and extreme load events (congestion, Figure 5(b)). A generated history of load effects is being used to perform probabilistic extrapolation of the traffic and wind loading extremes for the definition of the characteristic values of interest and their comparison with the corresponding values calculated in accordance with the Eurocode.
3.2.2 Structural Health Monitoring

For high speed railway bridges in particular, where dynamics plays an important role in the behaviour of the bridge, a monitoring system was implemented on the Skidträsk Bridge in Sweden to assess the influence of temperature effects on ballast stiffness which in turn affects the natural frequencies of the bridge. Data was collected over a period of one year and the data gathered during that period was used in conjunction with a finite element model and a meta model, to estimate the stiffness properties of the ballast, and hence the natural frequency of the bridge deck, during both cold and warm seasons. A Bayesian updating scheme was used to update the distribution of the stiffness properties of the ballast, using the meta model to calculate the likelihood of any given input. Measured first and second eigenfrequencies for a number of train passages are shown in Figure 6 – their dependence on temperature is apparent. For example the first eigenfrequency was clustered around a value of 3.8 Hz for temperatures above 10°C and a value of 4.5 Hz for temperatures below -10°C.

3.3. Fatigue Evaluation

The evaluation of fatigue in bridges often involves significant uncertainties as investigated by, for example, Sorenson et al. (2001) These uncertainties are best accounted for in the design process by using a probabilistic approach from which the reliability of the structure can be estimated. This branch of Long Life Bridges has developed a probabilistic framework for fatigue design of cable stayed steel bridges, which includes allowance for the effects of corrosion and cracking in the cables and welded plate details respectively.

3.3.1 Reliability Assessment of a cable stayed bridge

Stay cables are subjected to a combined action of fatigue load and corrosion and these two processes must be modelled appropriately to assess reliability. A cable consists of many wires and must be modelled as a parallel system. Li et al. (2011) proposed a methodology to assess the reliability of stay cable, but the effect of a parallel system was not taken into account. A global methodology, considering the system as parallel, was developed to assess the system reliability.
The first step in the process was to determine loads induced by the traffic flow on the bridge. The WIM data considered in this study are measurements at a highway in the Netherlands with three lanes in each direction and WIM data is available for the 2 slow lanes in one direction. The measurements are used as a basis for simulating the traffic flow on the bridge, assuming that each truck travels with a constant speed. The rainflow counting method is used to transform the load time history to a number of elementary stress cycles. A distribution of stress amplitudes over a period of ten weeks is obtained, Figure 7. The second step was to assess the cable strength, where the influence of the number of wires, cable length and corrosion were considered. The load and resistance of the cable can then be used to obtain the cable reliability. When one or more wires fail, then the cross section of the cable decreases and the stress range on the unbroken wires increases. It is assumed that if a wire breaks, then the wire loses completely the load carrying capacity over the entire length of the cable. The load is assumed to be equally shared by all the unbroken wires in the cable. Two effects of corrosion are taken into account in this study: the reduction of the cross section of each wire due to corrosion depth and the reduction of the lifetime on the S-N curve. Pitting corrosion is modelled in order to obtain the evolution of corrosion depths. Some test data is fitted to assess the effect of corrosion on the lifetime of the cable.

![Fig. 7. Distribution of fatigue load amplitude](image)

The fatigue behaviour of a material is subject to uncertainty. If different fatigue tests are performed at the same stress level, the number of cycles to failure will be different for each test. This strength variability has to be considered to assess the fatigue life. The bilinear S-N curve, provided by the Eurocode (Eurocode 3, part 1-11, 2007) for parallel wire strands, is assumed to correspond to a probability of failure equal to 2.3%. A standard deviation, in Log-space, is assumed equal to 0.3 on the number of cycles to failure (DNV, 1995) for both parts of the S-N curve. The reliability is estimated using Monte Carlo simulation. For each simulation, times to failure of the whole cable and each wire are recorded. The cumulative and annual reliability indices are shown, with confidence intervals, in Figure 8.

![Fig. 8. Cumulative and Annual reliability](image)
3.3.2 Probabilistic Fatigue Model using Fracture Mechanics

In the second strand of this work, a probabilistic fracture mechanics model for welded steel details was formulated based on the models presented by Righiniotis & Chryssanthopoulos (2003), Timothy et al. (2004) and Maljaars et al. (2012), Figure 8. However, this model takes the influence of misalignment and bending stresses in the welded connection into account. The fatigue design builds on the fatigue model described by Paris’ Law, Figure 9, which relates the crack growth to the number of stress cycles.

![Fig. 9. Semi-elliptical crack in steel plate.](image)

Weigh-in-motion measurements from a highway in the Netherlands have been used to estimate the fatigue stress ranges for a generic bridge structure. The fatigue stress ranges shows a bi-modal tendency, Figure 10, which is due to a bi-modal gross vehicle weight. In reliability assessment of welded steel details the fatigue stress range is normally approximated by a Weibull or Rayleigh distribution (Righiniotis & Chryssanthopoulos 2003; Maljaars et al. 2012). However, these distributions do not capture the bi-modal tendency as shown and, as such, Kernel smoothing was applied.

![Fig. 10. Distribution of fatigue stress range.](image)

A probabilistic model was formulated based on the fracture mechanics model and traffic data. From the probabilistic model the annual probability of failure $\Delta P_F$ is estimated along with the annual reliability index $\Delta \beta$ which is defined by:

$$\Delta \beta = - \Phi^{-1}(\Delta P_F)$$

where $\Phi$ is the standard normal distribution function. The annual reliability index is estimated using Monte Carlo simulation and shown in Figure 11 as a function of the bridge’s design lifetime. In order to update the reliability level during the design lifetime, inspections can be applied in order to check if cracks have developed. The probability of detecting a crack with a given size is modelled stochastic by a probability of detection curve from which the reliability level can be updated using Bayesian statistics. In the figure the updated reliability level dependent on time is shown when four inspections are applied during the design lifetime. It is seen that the reliability level can be significantly updated by applying inspections.

4. Discussion & 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:

![Annual reliability index](image)

**Figure 11.** Annual reliability of butt-welded joint. Planned inspection applied at year $T_i=20,40,60,80$ years.

(a) Integrating sensor information (Structural Health Monitoring) 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.

(b) 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.

(c) 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) Loading and 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.

**Acknowledgements**

*Long Life Bridges* is a Marie Curie Industry and Academia Partnerships and Pathways project and is funded by the European Commission 7th Framework Programme (IAPP-GA-2011-286276).

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