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Reliability Analysis of a Bridge Network in Ireland

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Abstract

This paper presents the reliability analysis of a network of six bridges in Ireland, with a focus on the sensitivity analysis and the analysis of parameter importance measures. The basis of the analysis stems from the possibility of investigating similarities in various parameters, leading to the establishment of network-level indicators based on fully probabilistic assessments. Initially, deterministic assessments are carried out on these bridges to verify the limit-states, and a detailed probabilistic analysis is conducted, taking uncertainty in relation to the available information into account. Parametric importance measures are established across the network, and patterns identified from these studies suggest the potential for reliability-based network calibrations of bridge structures. This paper is expected to encourage a greater sharing of network-level information of the owners and managers of bridges.

Keywords: bridges, maintenance & inspection, risk & probability analysis

List of Notation:

CoV	Coefficient of variation
P_f	Probability of failure
$\mathbf{u}^*$	Design point
x_i	Basic variable
α_i	Mean-value sensitivity factor
α_i^2	Parameter importance factors
β	Reliability index
γ_i	Omission sensitivity factor
θ	Parameter
μ_i	Mean-value of basic random variable
Φ	Standard normal cumulative distribution function

1 Introduction

As bridge infrastructure networks age, it is often necessary to employ advanced techniques in the assessment of intervention options for deteriorating network assets to maintain an adequate level of safety throughout the network (Žnidaric et al., 2011). Probability concepts have been shown to have significant advantages in the design and assessment of engineering structures, specifically structural reliability methods (Ang and Tang, 2007). A reliability-based approach for quantifying the safety of structures enables a lifetime evaluation of both individual and networks of structures (Akgül and Frangopol, 2004a,b; Frangopol and Das, 1999; Liu and Frangopol, 2006a,b; Frangopol and Liu, 2007a,b; Frangopol, 2011; Bocchini and Frangopol, 2011a,b,c; Saydam et al., 2013). While this method is commonly implemented at both a component and system level for an individual bridge in isolation (O'Connor and Enevoldsen, 2008; Estes and Frangopol, 2001), there are advantages to conducting a reliability analysis for a network of bridges (Frangopol and Bocchini, 2012); highlighting critical components and providing the stakeholders of bridge stock with comparable safety indices and sensitivity measures (O'Connor and Enevoldsen, 2007; Dong et al., 2014).

The effective allocation of capital resources seeks to minimise the inherent risks associated with investments through the use of advanced methods (Mueller and Stewart, 2011). Reliability methods are an effective tool for the monitoring of the asset base and, thus, allowing the prioritisation of intervention and investment requirements in a more careful and rational manner. Intervention can be focused to address the most important parameters that govern the safety of the bridges, as highlighted by the parametric sensitivity and parameter importance factors, which are beneficial by-products of reliability assessments. Conducting this analysis over a network allows for the comparison of different parameters and uncertainties in each bridge type, and investigates correlations that arise between them (Hanley and Pakrashi, 2014). This emphasizes the need of a network based calibration of the importance of certain critical parameters, and provides a framework for future assessments of the structures.

The objective of this paper is to investigate how uncertainty in the parameters involved can affect this proposed framework and to assess the existence of a minimum level of confidence that is required in order to make a rational intervention decision. A brief introduction to reliability analysis is provided first. A network of bridges is described and results of a deterministic analysis are presented in order to identify the limit-states. The results of the reliability analysis are shown over the network and the parametric sensitivity studies are detailed, highlighting critical parameters that contribute to the violation of the established limit-states. Investigations are carried out to obtain common markers or patterns of information present in the bridge network described by the sensitivity studies and parameter importance measures.

2 Reliability Analysis: A Brief Review

The reliability index β is defined as a probabilistic measure of safety which can be interpreted as the least distance to a limit-state failure surface in a probability preserving standard normal space (Shinozuka, 1983). The location of the point corresponding to this least distance on the failure surface is considered to be the design point **u***, which is also the point in the space with the highest probability density or the most likely point of failure (Ditlevsen and Madsen, 1996; Melchers, 1999). The probability of failure P_f is defined as the probability of violation of a limit state. It is related to β through the standard normal cumulative distribution function Φ, after converting all involved parameters into a multidimensional space typically through a Rosenblatt transformation (Rosenblatt, 1952) as:

$$\beta = -\Phi^{-1}\left(P_f\right) \tag{1}$$

where the generalised limit-state can be expressed as:

$$P_f = P\left(R - S \leq 0\right) = P\left[G\left(R, S\right) \leq 0\right] = P\left[G\left(X\right) \leq 0\right] \tag{2}$$

where R corresponds to the resistance variables and S to the load effect variables. First-Order Reliability Methods (FORM) and Second-Order Reliability Methods (SORM) are popular in terms of establishing or estimating β (Sarveswaran and Roberts, 1999); FORM calculates failure probabilities and reliability indices without correction for curvature of the limit state surface at the most central point, while SORM calculations include this correction (Breitung, 1984). These methods were favoured above simulation methods as they allow the computation of parametric sensitivities and importance factors.

Sensitivity studies can be carried out within the framework of reliability analysis and it is helpful in identifying and quantifying errors in design, modelling and construction (Frangopol, 1985; Nowak and Carr, 1985). The importance of a variable to β is defined as the alpha-value α_i, which measures the sensitivity of β to a small variation in the mean-value μ_i of a basic random variable (Hohenbichler and Rackwitz, 1986):

$$\alpha_i = \frac{\partial \beta}{\partial \mu_i} \tag{3}$$

This parametric sensitivity factor α_i for the reliability index β with respect to a parameter θ is defined (Madsen et al., 1986) and developed (Bjerager and Krenk, 1989) as the derivative $\partial\beta/\partial\theta$. This factor measures the relative change in β due to a variation in a parameter $\Delta\theta$. For a specified or known value of $\Delta\theta$, the adjusted reliability index β' can now be expressed as:

$$\beta' = \beta + \frac{\partial \beta}{\partial \theta}\Delta\theta \tag{4}$$

With this expression, the magnitude of how much each parameter must change in order to satisfy a specified level of safety can be evaluated. For design, the parameters can be adjusted to obtain a target reliability index β_T, and for assessment, the parameters can be monitored such that they do not degrade to a critical reliability index β_{Min}.

$$\Delta\theta = \frac{\beta' - \beta}{\partial\beta / \partial\theta} \tag{5}$$

It should be noted that the terms β_T and β_{Min} are often used interchangeably, and that the rest of this paper will use the term β_T.

As part of a sensitivity analysis, parameter importance factors α_i^2 can be determined, identifying which of the modelled parameters have the greatest impact on the reliability index, and thus, the safety of the structure.

$$\sum_{i=1}^{n} \alpha_i^2 = 1 \tag{6}$$

These factors indicate through their ranking, expressed as a percentage, what parameters are important for monitoring within a system and to what extent they contribute to the probability of safety or failure. Also, for varying limit states or uncertainties, the ranking of these parameters within a system can change; emphasizing the fact that the contribution of a certain factor to a failure defined by a limit state is a function of the information available about the system and the associated confidence or accuracy of that information.

The parameter importance factors allow for the computation of the omission sensitivity factor γ_i, which is the relative error of β when a stochastic variable is modelled as a deterministic parameter (Madsen, 1988). This factor for a basic variable x_i is measured as the inverse ratio of β and an adjusted reliability index β' when the random variable x_i is replaced by a deterministic parameter, typically its median (Ditlevsen and Madsen, 1996).

$$\gamma_i = \frac{1}{\sqrt{1-\alpha_i^2}} \tag{7}$$

3 Description of Network and Assessment Methodology

An Irish bridge network consisting of both reinforced and prestressed concrete structures, of varying age and exposure conditions, was used for this assessment (Table 1). The bridges in the network were highlighted, through routine visual inspections, as being in various states of damage, and consequently the network underwent an extensive assessment campaign; including non-destructive testing and deterministic computational assessments, and intervention activities were conducted, accordingly, to restore the network to an acceptable level of safety. The bridges in the network were assessed for the ultimate limit-states of bending and shear at the critical locations on the primary structural elements. The limit-states and locations of assessment were established and verified through deterministic assessments using finite element methods (FEM) and load & resistance factor design (LRFD) calculations. These limit states were analysed for combinations of dead and traffic loading; the traffic load models considered were normal (HA) and abnormal (HB), in accordance with *BD 21* (Highways Agency, 2001), the assessment loading code. Normal (HA) loading is said to represent the worst-case occurrence of typical traffic loading over the lifetime of the bridge, and is specified by a standard loading curve derived from the bunching of trucks in a notional lane (Henderson, 1954). This is most onerous for shorter spans as this bunching can more reasonably be expected to occur, and is less onerous for longer spans where such an occurrence is less likely. It is modelled as a uniformly distributed load, along with a knife-edge load for shear effects, and has a 5% probability of occurring during the design life (120 years) of a bridge, for a return period of 200,000 years (Dawe, 2003). Abnormal (HB) loading is used to design and assess for the effects of untypical traffic loading, in the guise of multi-axle special vehicles carrying heavy loads. It has its foundation in post- war reconstruction to account for the transportation of heavy infrastructure, such as electricity generators (Dawe, 2003). It is modelled as a series of point loads to represent the application of the multiple axles. The section capacities for the resistance of bending moment and shear force were determined in accordance with *BD 44* (Highways Agency, 1995) and *BS 5400-4* (BSI, 1990).

Probabilistic traffic-load models have been developed for the application of the reliability method to bridge structures (Nowak, 1993; O'Connor and Enevoldsen, 2009; O'Connor and O'Brien, 2005), which focus on the modelling of multiple presence or meeting events for ordinary and heavy transport trucks in both design and assessment. However, in the absence of site-specific data, the application of these methods was deemed inappropriate for this assessment. Thus, the applied traffic loads were derived from the deterministic worst-case HA and HB loading. However, as these values are functions of the bridge geometry and deterministic, code-defined axle loading, the load-effects were modelled functions of the basic variables. The overall effect of the traffic loading was represented by the coefficient j in the probabilistic model. The sensitivity of β to a change in the total applied traffic load is shown in the results for this coefficient, which was modelled as being equal to unity in the following assessment. Without site-specific probabilistic traffic load models, the reliability indices must be seen as a relative measure; however, sensitivity measures remain unaffected, in this regard.

The effects of bending moment and shear force were evaluated for the critical superstructure elements in each bridge in the network, as identified in the deterministic assessment. In each case, the primary load-carrying beams were identified as the critical elements. The applied loads S and the characteristic resistance R were established, and a performance index was defined as the ratio S/R. A performance index less than or equal to one indicates compliance with safety standards and a performance index exceeding one indicates non-compliance with the standards. While a commonly used method in the design and assessment of structures, this method can only give a generalised indication of the level of safety present, and does not necessarily correspond to the true safety level of a structure (Allen, 1975; Ellingwood, 1996). Marginal violation does not immediately imply failure, but rather emphasizes the importance of a reliability analysis to be carried out since the normative standards often tend to be conservative (O'Connor and Enevoldsen, 2007).

It can be seen that the performance index has exceeded unity in a number of cases (Table 4). For PS2, it can be seen that bending and shear are both critical under normal traffic loading, while the limit-state is satisfied under abnormal loading. This is due to the bridge's short span, from which normal loading is most onerous for shorter spans becomes less so as the span approaches 50m (Dawe, 2003). This is also seen for the short span of RC1. For RC2, the abnormal traffic load is most critical, as span is large enough to experience the full effect of an abnormal traffic load vehicle. For all the RC bridges in the network, shear was observed to be a critical limit-state.

Following the deterministic analysis, a probabilistic analysis framework was developed. The load and resistance variables, *S* and *R* respectively, are expressed as:

$$S = M_{App}, V_{App} \tag{8}$$

$$R = M_{Cap}, V_{Cap} \tag{9}$$

$$M_{App} = M_{DL} + M_{SDL} + M_{LL} \tag{10}$$

$$V_{App} = V_{DL} + V_{SDL} + V_{LL} \tag{11}$$

where *M* and *V* represent the bending and shear limit-states, and the subscripts *App* and *Cap* represent the load applies and the section capacities at these limit-states, respectively. The subscripts *DL, SDL,* and *LL* refer to dead load, superimposed dead load, and traffic (live) load, respectively, and are functions of the basic variables described in Tables 2 & 3.

4 Probabilistic Assessment

4.1 Reliability Indices of Bridges within the Network

The reliability indices β for the bridges within the network were determined using FORM and were then checked for non-linearity using SORM. The high correlation between β_{FORM} and β_{SORM} suggested that the failure surfaces were highly linear. The results for prestressed concrete (PS) structures and the reinforced concrete (RC) structures were grouped together to determine if a relationship existed for β between common bridge materials, and to what degree uncertainty, with regard to the random variables, affected the results of a safety classification based on β. The uncertainty in the random variables is represented by the coefficient of variation (CoV), which is a relative measure of dispersion within the probability density function (PDF). It is proposed that a high level of certainty for the value of a random variable would, as much as practicable, manifest itself as a PDF with a narrow dispersion. For bridge structures, this can be seen to occur in material strengths where a variation is present, and the level of variation across the structure can be known or unknown, based on the level of information obtained from, say, non-destructive testing (NDT) or structural health monitoring (SHM) (Frangopol, 2011; Frangopol and Bocchini, 2012). As they can be measured with a high degree of accuracy, the basic variables related to the bridge geometry are considered deterministic (Table 3), and those related to material properties were modelled stochastically (Table 2).

A target reliability index β_T of 3.8 was established as being the lowest acceptable index, as specified in the *Eurocodes* (CEN, 2002; González et al., 2005). For the prestressed concrete bridges in the network (Figure 1), it can be seen that this β_T is satisfied in most cases for a CoV of 0.1. This target is not satisfied in the bridge PS2 for the bending limit-state under both normal and abnormal traffic loading. This result correlates with those presented for the deterministic performance indices (Table 4), which showed that PS2 also violated the limit-state for bending in both load cases.

The remaining initial values for β were seen to be bunched in the $\beta \approx 6 \rightarrow 8$ range, with the results for the shear limit-state showing the smallest variation across bridges and load cases. This bunching of β was not as apparent in the results for the reinforced concrete bridges in the network (Figure 2), with a much higher variation being present. A possible explanation for this is the general disparate nature of the three RC bridges, as opposed to the somewhat homogeneous nature of the PS bridges, which all possess the same basic form. The RC bridges, on the other hand, comprise a slab bridge (RC1) and two slab/girder bridges; one in the longitudinal direction (RC2), the other in the transverse direction (RC3). Additionally, the variation in the effective span L_{Eff} will govern significant changes in the applied traffic loading; with short spans being critical for normal loading, and long spans being critical under abnormal loading.

It is expected and observed that β decreases with increasing CoV. It can be seen that this decrease occurs almost asymptotically from a CoV of 0.1 to 0.2, 0.3, and 0.4 at an approximate rate of $^1/_2$, $^1/_3$, and $^1/_4$, respectively. This demonstrates the importance of limiting uncertainty within the probabilistic model, as the greatest decrease occurs in the CoV increase from 0.1 to 0.2, after which it is observed that β has fallen below β_T in most cases. In fact, it can be seen that for β_T at a CoV of 0.2, the initial β at CoV of 0.1 must be greater than twice that of β_T. In this case, only those cases where initial $\beta > 7.6$ will still satisfy minimum requirements for a CoV of 0.2. Consequently, for higher levels of uncertainty, the lack of information governs the estimated risk of failure and this also explains the lack of variability of different bridges at higher levels of uncertainty. This builds the basis for assessing the relative importance of the basic variables in the failure surface.

4.2 Sensitivity Studies

Sensitivity assessments were carried out by considering a 10% perturbation in the various parameters involved in the assessment, which demonstrate the relative contribution each basic variable makes to β. The results are presented by grouping prestressed concrete bridges (Figure 3) and reinforced concrete bridges (Figure 4) for each failure mode for a CoV of 0.1. The relationship of the sensitivities between the increasing CoV is the same as that for β, and thus only sensitivities for CoV of 0.1 are presented.

For the PS bridges in the network (Figure 3), it can be seen that the basic variables that have the greatest positive contribution to the reliability index for bending moment β_M are the: mean value μ of the area of prestressing tendons A_{ps}, notional lane width b_L, effective depth d, and μ of the prestressing tendon strength f_{pu}. The positive contribution of $A_{ps}(\mu)$, d, and $f_{pu}(\mu)$ are expected due to their inherent nature as resistance variables; however the positive contribution of b_L is borne by its effect on the applied normal traffic loading, with a wider notional lane resulting in a lower effective applied uniformly distributed load (UDL) and knife-edge load (KEL) (Highways Agency, 2001). The upper and lower bounds (represented by the 'whiskers' extending away from the mean) display the variation in these values across the three bridges. The close proximity of these bounds to the mean values indicate a high degree of correlation amongst the different network assets. These basic variables remain favourable for the reliability index for the shear limit-state β_V, with the exclusion of A_{ps} and the inclusion of overall depth of the section h. The larger spread between the upper and lower bound values for h can be attributed to the variable's individual contribution to the normal and abnormal traffic loading; the variable has very little effect for normal loading, whereas it is prominent in abnormal loading, due to the individual wheel loads being dispersed through the depth of the section to the neutral-axis. Thus, for a greater section depth, the wheel load experiences a larger dispersion, and individual beam elements are subjected to reduced loading from the individual wheels.

For β_M, the variables that are most unfavourable are: the width of the section b, the effective span L_{Eff}, as well as the CoV for the favourable variables A_{ps} and f_{pu}. For the deterministic parameters b and L_{Eff}, there is very little variation across the network, while there exists some variation between $A_{ps}(CoV)$ and $f_{pu}(CoV)$. However, this can be expected based on the in basic variables, with upper and lower bounds. relationships observed in Figures 1 & 2. It can also be seen that the deterministic parameter h has a mean unfavourable effect on β_M, but exhibits a significant spread between its upper and lower bound values; even behaving as a favourable variable at its upper-bound value. This is explained as before, with h being unfavourable for normal traffic loading, and favourable for abnormal traffic loading; with the unfavourable effect outweighing the favourable effect. The same is observed to be true in β_V for the deterministic parameter L_{Eff}. It can also be seen from the results for the coefficient of traffic loading j, that a 10% increase in the overall applied traffic load would result in a reduction in $\beta_{M,V}$ of approximately 0.5.

For the RC bridges in the network, a much higher variation is present in the upper and lower bound values for the basic variables (Figure 4). This is expected based on the results obtained for β_{RC} (Figure 2), and the disparate nature of the geometric forms, as compared to those for the PS bridges in the network. Thus, a relatively clear pattern emerges for each basic variable when similar bridge types of closely related geometry and structural material are considered together, and such a pattern is less apparent when the geometry is less closely related, even with the same structural material.

However, while a 10% increase in the basic variables has been examined to identify those most critical, their overall effect on the violation of the limit-state has not been shown. For existing structures, a change in the deterministic parameters is not expected, and so it must be examined how much a random variable must deviate from its mean value to constitute limit-state violation. This can be evaluated at the design point $\mathbf{u}^*$, the most likely point of failure, to see the extent to which random variables have moved from their mean values μ into the tail of their distributions (O'Brien et al., 2015). This has the practical application of establishing how much a material property must deteriorate to reach a critical point. It can be seen (Figures 5 & 6) that the mean values and the upper and lower bounds of the relative change in the random variables exhibit a similar relationship to the initial spread of β (Figures 1 & 2), whereby the greatest level of bunching was observed for β_V for the PS bridges, and the most significant spread occurred for the RC bridges, as is reflected by the wide bounds for the design point **u***.

4.3 Importance Factors

Importance factors α_i^2 were determined to allow the relative ranking of random variables to aid the assessment process. These factors highlight those random variables which have the greatest influence on β, and thus which variables it would be beneficial to reduce the level of uncertainty. Random variables with low importance factors can afford to be modelled as deterministic parameters, without significant change in the computed β. Those with high importance factors should be prioritised when more detailed material assessments are deemed necessary.

For the PS bridges in the network, it is apparent that the combination of A_{ps} and f_{pu} represent more than 90% of the stochastic importance for β_M, while f_{pu} alone represents approximately 90% of the stochastic importance for β_V (Figure 7). For both β_M and β_V, f_{cu} has very little importance, and can afford to modelled deterministically without any significant loss to the probabilistic model. This would suggest that any chemical inspections or non-destructive testing of these bridge types should focus entirely on evaluating an accurate model for the PDF of A_{ps} and f_{pu}, and it would be considered unnecessary to establish anything more than basic knowledge of the properties of f_{cu}, or the bulk densities of concrete or road surfacing, ρ_C and ρ_S, respectively. Again, little variation was observed between the upper and lower bounds of the results for the PS bridges in the network.

Similarly to β_M for the PS bridges in the network, the most stochastically important variables in the RC bridges in the network those that relate to the reinforcement in the section; in this case the area and the yield strength of the reinforcement A_s and f_y, respectively (Figure 8). These two variables account for approx. 98% of the stochastic importance for β_M, and highlight the relative unimportance of the contribution of the compressive strength of concrete f_{cu} to flexural resistance. For β_V, f_y is seen to be unimportant while f_{cu} now accounts for approximately 39% of the stochastic importance. This increased significance of f_{cu} in β_V is expected given its understood contribution to shear resistance, and its absence as an important variable for RC structures would question the accuracy of the limit-state models. It should also be noted that the bulk density of concrete ρ_C, the principal variable accounting for dead load, has a mean importance of 22%, with a wide spread between the upper and lower bound values. This can be explained by the greater geometric variance in the RC bridges than is present in the PS bridges in the network as, in practice, the typical value for ρ_C is observed to be 24-25 kN/m^3.

The effect on β of modelling these variables as deterministic parameters rather than stochastic variables can be determined from the omission sensitivity factor γ_i which is a function of α_i^2 (Eqn. 7). This factor ratio of the β' and β, and shows the relative error of replacing a stochastic variable with a deterministic parameter a probabilistic assessment (Table 5).

It should be noted that due to the asymptotic nature of γ_i, there will be rapid increases in this ratio for any importance factor $\alpha_i^2 \gtrsim 85\%$.

5 Conclusions

A structural reliability analysis was conducted on six bridges in a network in Ireland. These bridges were assessed for the limit-states of bending and shear, under code-defined normal and abnormal traffic loading. A deterministic analysis was conducted in advance of the reliability analysis, in order to identify the limit-states and the associated input parameters. The computed estimates of the reliability indices were presented, along with associated parametric sensitivity and importance measures. It was observed that bridges of similar structural material and form are clustered in terms of sensitivity or parametric importance studies. The levels of existing correlations for the parameters across the bridge types, and how their influences on the reliability under varying degrees of uncertainty indicates the importance of a calibrated framework for the assessment of bridges at a network level. The network-level calibration is observed to be strongly dependent on the availability and the quality of information of the bridges within the network and, consequently, it can be stated that structural reliability analysis refers more to our state of knowledge of the structure than to the actual state of the structure itself. This emphasizes the need for data-sharing for such structures by the managers and owners of bridge networks for the most reasonable and cost-effective interventions to be carried out. Further work is encouraged on a wider range of bridges under improved probabilistic information, in order to establish if baseline safety classifications can be established for specific bridge types.

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