INNOVATIVE BRIDGE ASSESSMENT FOR DEVELOPING COUNTRIES

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ABSTRACT

Reliability based bridge assessment has become a standard way of assessing bridges in developed countries across Europe, North America and Australia. Through clever collection of load and resistance data, design parameters can be quantified with greater accuracy. By applying the principles of structural reliability, bridges can be assessed less conservatively, implying that more bridges can be treated at the same cost of a conservative code-based assessment. This paper presents some innovative assessment methods which have been developed elsewhere with the aim to expose local bridge engineers to the available techniques and to motivate how they can be applied locally.

1. INTRODUCTION

The design life of bridges is typically set at 100 years according to ISO2394 (ISO, 2015), EN1990 (CEN, 2002) and TMH7. Many bridges across the world are nearing the end of their service lives and either need to be rehabilitated and/or strengthened or demolished and replaced. It is widely accepted that replacement, strengthening and rehabilitation are expensive (Savor & Novak, 2015), and the associated cost must be minimised. Canada, USA, UK, Denmark and Switzerland have all developed guidelines for bridge assessment (Wisniewski, Casas & Ghosn, 2018).

For countries without assessment guidelines, it is typical to perform assessments similar to the design of new structures as if the structures need to resist another 100 years. Structures are assessed using the current codified traffic loads which could be significantly greater than the actual traffic loading on a bridge. This approach is conservative and often leads to costly repair and/or strengthening measures or even demolition. By assessing a bridge for its remaining service life, a much less conservative solution can be developed. Conservatism can be reduced by:

- Reduction of target reliability index values for existing bridges.
- Use of advanced calculation procedures like non-linear finite element analysis.
- Measuring the actual traffic loads for a bridge.
- Testing of in-situ material properties for increased certainty.
- Load testing of a structure.

The above measures are typically applied in a tiered approach to assessment which is described further in this paper. The tiered approach is mostly focused on reducing partial factors for existing bridges by applying the principles of structural reliability.

2. THE RELIABILITY INDEX FORMULATION AND DERIVATION OF PARTIAL FACTORS

The reliability index, denoted by β, is a measure of the probability of failure of a structure in a given reference period.

$$\beta = -\Phi_U(P_f) \quad (1)$$

Φ_U in Equation 1 refers to the standard normal distribution with a mean of 0 and a standard deviation of 1. The definition of a partial factor (PF) is the design value of an action, or a resistance, divided by the characteristic value according to Equation 2.

$$PF = \frac{X_d}{X_k} \quad (2)$$

The design value of an action (X_d) or resistance is a function of β according to Equation 3.

$$X_d = F_x^{-1}[\Phi(\alpha\beta)] \quad (3)$$

For new structures in South Africa β_{50} = 3.5 which translates to a return period of 5040 years for ultimate failure. For Europe β_{50} = 3.8 which translates to a return period of 16 000 years. It is worth noting that the safety margin for new bridges in Europe is an order of magnitude larger than that for South Africa (van der Spuy, 2020; van der Spuy & Lenner, 2021). For a comprehensive discussion on this topic the reader is referred to van der Spuy (2020). The α factors are the First Order Reliability Method (FORM) sensitivity factors for load and resistance given in Konig & Hosser (1982) which weigh the importance of different load components to the reliability of the system.

By accepting a lower reliability index for assessment directly reduces the PF and leads to a more favorable assessment for an existing bridge.

3. STANDARDS AND GUIDELINES FOR REDUCED RELIABILITY FOR ASSESSMENT

The standards presented in this section are the Canadian Standard CSA-S6-06, American Standard MBE and the Dutch Standard NEN 8700. These standards allow for a reduced reliability level for assessment of existing bridges.

3.1 Canadian Standard

The reliability index for assessment is given by Equation 4 and refers to an annual reference period.

$$\beta = 3.75 - (\Delta_C + \Delta_S + \Delta_I + \Delta_R) \geq 2.0 \quad (4)$$

where:

Δ_C is an adjustment factor for the failure mode (sudden or with warning)

Δ_S is an adjustment factor for the redundancy in the system

Δ_I is an adjustment for the inspection level of a structure

Δ_R is an adjustment factor for risk category

The standard gives most credit if a structure fails with warning (ductile failures), is redundant or statically indeterminate, can be inspected and has a low risk of unsupervised overload. For the values of the adjustment factors refer to CSA-S6-06. Note that the minimum β allowed for assessment at Ultimate Limit State is 2.0.

3.2 American Standard

Two levels of reliability are applied in assessment. The standard target reliability of 3.5 in 75 years for new structures is used as a first line of assessment. This results in a PF of 1.75 for traffic loading. If a structure fails this test, the reliability index can be reduced to 2.5 for a remaining service life of 5 years, with a reduced PF of 1.35. This does imply that a structure must be inspected regularly, at least once every five years.

3.3 Dutch Standard

The reliability index for assessment of bridges to the Dutch Standard can be reduced according to Equation 5.

$$\beta_U = \beta_{new} - \Delta\beta_U \quad (5)$$

where β_{new} is the reliability index for the design of new bridges. An economic optimization exercise resulted in a $\Delta\beta_U$ value of 1.5 for assessment. Below this level of reliability, a structure is considered unfit for use. A reliability index for repair was introduced according to Equation 6.

$$\beta_{repair} = \beta_{new} - \Delta\beta_{repair} \quad (6)$$

This allows for structures that do not meet assessment standards in current form to be repaired, rather than replaced. The value for $\Delta\beta_{repair}$ is given as 0.5.

4. STANDARDS BASED ON RETAINED RELIBILITY INDICES

In the Austrian, Swiss and German standards existing bridges are first assessed as if new (Savor & Novak, 2015). If a structure does not conform to the required reliability for new structures, then the PF for permanent loads is reduced to 1.20 and in-situ measurements are taken for self-weight to reduce uncertainty. The partial factors for imposed loads remain unchanged.

As a third tier of assessment the deformation of a structure can be measured under service loads to give an accurate representation of the load deformation behavior. The fourth tier of assessment concerns research methods for the capacity calculation of a structure using non-linear methods.

5. OTHER METHODS TO REDUCE CONSERVATISM IN ASSESSMENT

Further levels of assessment would be to measure the actual traffic loads on a bridge and describe the load effects probabilistically and calibrate PFs in alignment with the assessment reliability level. Apart from measuring the weight of in-situ materials the strength of the materials can be determined through testing to reduce uncertainty in the structural resistance. This forms part of probability-based bridge assessment where a FORM analysis is performed to assess the reliability of the total system.

As a last level of assessment, a structure can be subjected to proof loading to determine the real load carrying capacity of a structure.

6. OTHER UNCERTAINTIES

PFs for resistance and loading both include allowance for model uncertainty. Model uncertainty is defined as the uncertainty inherent in the models employed for quantifying capacity and load effects (Melhem & Caprani, 2020). An example of model uncertainty is the difference between assumed and real support conditions of a structure. Models often assume pin supports, where in reality the supports are somewhat distributed.

When measured traffic is used to reduce the intensity of codified traffic models, an allowance must still be made for dynamic amplification (Caprani, 2017; van der Spuy, Lenner & Meyer, 2019). Guidelines for dynamic amplification are both deterministic and probabilistic. The German expression for the dynamic amplification factor (DAF) is as per Equation 7 where *l* is the span length.

$$DAF = 1.4 - 0.008l \tag{7}$$

Research shows that the span length is only one parameter that influences the DAF and a representation such as this fails to capture the full phenomena (Boros, Lenner, O'Connor, Orcesi, Schmidt, van der Spuy & Sykora, 2021). For probabilistic assessments, a model has been proposed for the DAF which follows a Gumbel distribution with a mean of 1.10 and a standard deviation of 0.10.

7. CASE STUDY

A case study where a nuclear turbine must be transported across a bridge is considered. The vehicle mass is 380 t including the payload and the trailer. The load, shown in Figure 1, is uniformly spread over 18 axles spaced at 1.5 m.

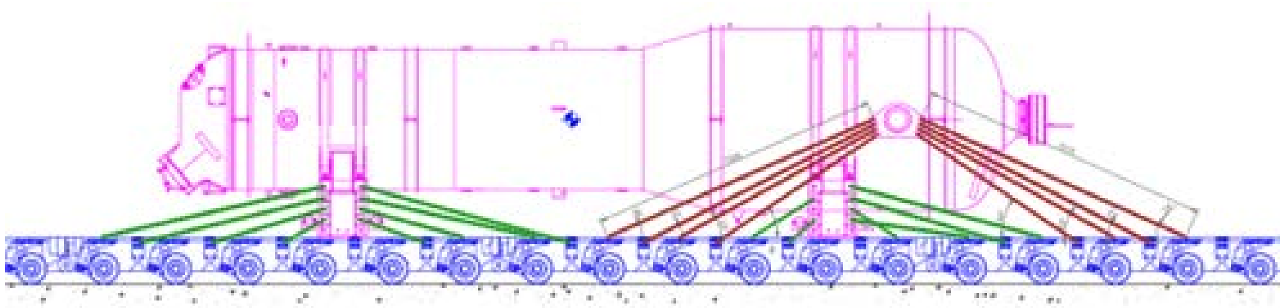

Figure 1: Abnormal vehicle

The bridge investigated by Skokandić & Mandić Ivanković (2022) is considered in the case study. The bridge is a three-span structure with spans of 9 m, 15 m and 9 m respectively. The cross section is a solid slab with a trafficable width of 7 m and a total depth of 0.6 m. The concrete class is C30/37 and the characteristic reinforcement strength is 500 MPa. The deck is reinforced with 2450 mm^2/m in the bottom layer with a cover to reinforcement of 50 mm.

The sagging moment in the centre span is considered as a critical scenario, with the permanent action due to self-weight Gk = 171 kNm/m and the load effect due to the specified abnormal vehicle Qk = 265 kNm/m. If the design load is considered using PFs of 1.35 for both G and Q according to EN 1990, Ed = 589 kNm/m is obtained.

The design resistance, using PFs of 1.15 for reinforcement and 1.5 for concrete is obtained as R_d = 568 kNm/m. Therefore, by using the design values for assessment $E_d > R_d$ and the transport cannot be authorised to cross the bridge. The utilisation ratio is E_d / R_d = 1.04.

By using the PFs for assessment, the assessment load effect is calculated as E_{assess} = 488 kNm/m and the assessment resistance as R_{assess} = 608 kNm/m. From $E_{assess} < R_{assess}$ it can be concluded that the abnormal load can safely cross the bridge if probability-based assessment is applied, rather than using design values. In comparison to the latter, the utilisation ratio decreases by about 23% to E_{assess} / R_{assess} = 0.80.

For more information about the case study, the reader is referred to Van der Spuy, Lenner, Schmidt & Sykora (2023).

8. CONCLUSION

Bridge assessment in South Africa is currently performed using a tier 1 approach. This means that structures are assessed as if they are new, even though some concrete bridges were constructed in the 1950's or perhaps even earlier. This is a conservative approach which often leads to costly strengthening and repair measures, or even reconstruction. For a country with such limited resources for rehabilitation of existing structures, this is a practice which can hardly be afforded.

This paper highlights some common international practices for the assessment of existing bridges. These methodologies are mostly based on the reduction of PFs by collecting more accurate data for the resistance of structures and the actions acting on them and allowing a reduced level of reliability. Credit is given to the reduced remaining service life of structures which have already served some of the original 100-year design life. By employing these advanced assessment methodologies, it has been shown that a significant reduction in cost can be achieved for strengthening, and in some cases strengthening or demolition have been avoided completely.

The methodologies described in this paper can readily be applied to the local market. However, a study is needed to determine an acceptable reduced reliability level for South Africa based on the principles of structural reliability. A recent paper by Way, de Koker & Viljoen (2022) provides a starting point by suggesting target reliability for new road bridges in South Africa. A lower consequence class can possibly be adopted for assessment (Viljoen, Retief & Holicky, 2019).

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