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Lantsoght, Eva; Yang, Yuguang; Hendriks, Max

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Extending the service life of existing concrete bridges using improved assessment methods

Eva Lantsoght

Delft University of Technology, Delft, the Netherlands

Universidad San Francisco de Quito, Quito, Ecuador

Yuguang Yang

Delft University of Technology, Delft, the Netherlands

Max Hendriks

Delft University of Technology, Delft, the Netherlands

Norwegian University of Science and Technology, Trondheim, Norway

Contact: <mailto:john.doe@goodmail.com> e.o.l.lantsoght@tudelft.nl

Abstract

As the existing bridge stock is ageing in various parts of the world, the topic of how to assess, maintain and/or improve, and manage existing bridges becomes increasingly important. Existing bridges may be designed according to outdated codes with requirements that may be considered unsafe nowadays, and for loads that are significantly different than those used nowadays. For those bridges, an accurate assessment leads to more efficient management of the bridge stock. This paper outlines various strategies that lead to an improvement of the assessment, and potentially to the extension of the service life of existing concrete bridges. This paper provides a selected examples that engineers who are faced with the assessment of ageing bridge can use. Ultimately, the presented insights can serve to support countries with a younger bridge stock in the development of an assessment strategy.

Keywords: shear; distribution width; monitoring; non-destructive evaluation; modelling strategies; nonlinear finite element modelling; probabilistic methods; field testing

1 Introduction

In Europe, a major portion of the bridge stock was built during the decades after World War II, as a result of reconstruction paired with road expansion. Similarly, in the United States, a large number of bridges were built during the development of the Interstate network. In the major developed countries, a large portion of the existing bridge stock has been in service for 60 - 80

years. As such, we can say that in various parts of the world, the existing bridge stock is ageing, and many bridges are reaching the end of their originally intended service life of 75 years [1].

Bridges reaching their service life will not lead to replacement in any part of world, but will trigger actions for the asset owners to assess the safety of the existing bridges. Existing bridges can present us with design details that are not used nowadays

anymore, either because they have been replaced by new technology or because we now know that these details can result in poor performance under certain conditions. Existing bridges may also be designed according to codes that are not used anymore, with capacity models that can indicate higher capacities under certain conditions than when using modern codes, and with lower traffic loads. As a result, such bridges will rate insufficiently when checked using the currently governing codes. This outcome does not mean that the bridge does not fulfil the underlying safety requirements of the code, but it indicates that we will need to use more advanced methods to better evaluate the bridges, to then evaluate if the safety requirements are fulfilled.

Replacing all the bridges that are reaching the end of their originally devised service life is not feasible, not economic, would create an unwanted large ecological impact, and lead to various indirect and social impacts, such as driver delays. Therefore, engineers now are faced with the task of evaluating these existing bridges. In particular, the topics of assessing, maintaining and/or improving, and managing existing bridges is becoming increasingly important.

Engineers who work with existing bridges will recognize that the tools they use are different from the tools needed for the design of new bridges. In Europe, engineers have developed a set of tools that can reveal the residual capacity of the bridges. This paper outlines various strategies available that may lead to an improvement of the assessment, with a focus on existing concrete bridges. A better assessment in turn could lead to an extension of the service life. In particular, better capacity models, methods to work with field data, and advanced modelling strategies are discussed. Then, a framework for combining these insights together with the Levels of Approximation approach from the *fib* Model Code [2] (Figure 1) is presented, with lessons learned for knowledge transfer.

Finally, in Latin America, several countries, such as Ecuador, have seen a more recent development of the road network. As a result, the bridge stock of these countries is relatively younger. Asset owners and engineers in these countries are recently starting to search for optimal methods for

operating, maintaining and managing their bridge stock. As such, transfer of lessons learned is important.

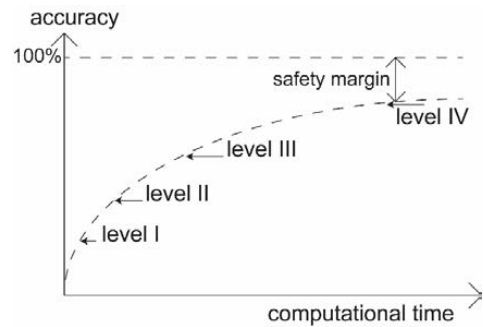


Figure 1. Levels of Approximation approach

2 Strategies for improved assessment

2.1 Introduction to assessment

A general assessment procedure typically consists of three steps: 1) obtaining input data, 2) modelling the load effect and 3) evaluating the structural safety using a resistance model. In correspondence to the three assessment steps, we address these strategies: field data; advanced modelling methods and tailored resistance models.

2.2 Field data

2.2.1 Necessity for field data

Assessment of existing bridges often has to rely on assumptions of material properties and boundary conditions based on the original design of the structure. Over time, the structure undergoes changes that introduce additional uncertainty and that should be considered in the assessment. Field measurements give an insight in the actual material properties and overall performance of the bridges, therefore reducing uncertainty of the input of the assessment and potentially increase the capacity of the structure.

2.2.2 Structural monitoring

For critical infrastructure, structural monitoring can be used to follow the behaviour over time and to observe the effect of ongoing degradation, or to follow behaviour about which bridge engineers are not certain, such as new repair strategies [3]. Measurements are typically taken over a longer period of time to be able to observe such effects, and are taken and analysed periodically. One structural monitoring strategy that is the topic of current research at Delft University of Technology is the use of smart aggregates, which are piezoelectric elements that can be cast into new structures (see Figure 2) or embedded into existing structures and that give insights in the cracking in concrete at early stage. The information can be used in pro-active maintenance of concrete bridges.

For assessment, often threshold values of the measurements are identified that can be used together with the monitoring data. If a certain threshold is exceeded, often a more in-depth analysis needs to be carried out for the assessment and to identify if the structure is still safe for the traveling public to use.



Figure 2. Smart aggregates in rebar cage.

2.2.3 Non-destructive testing and evaluation

Within the realm of non-destructive testing and evaluation, a large number of techniques exists, and we could consider bridge load testing as a non-destructive testing technique as well. Typically, however, non-destructive testing techniques refer to methods used to obtain information about

material properties and existing deterioration and degradation in the structure, for which no damage is inflicted on the structure. For existing bridges, non-destructive testing techniques allow us to see inside the bridge, and beyond what we can identify with a visual inspection. As such, the combination of non-destructive testing methods with visual inspections, and often by using a combination of non-destructive techniques is a powerful method. The information on the material properties and state of degradation can then be included into the capacity models to obtain a better assessment of the existing bridge.

For example, due to the ongoing hydration of cement, the concrete compressive strength typically increases over time. Using the compressive strength obtained from field data, which is usually higher than the specified strength, will result in higher calculated capacities and will improve the assessment.

2.2.4 Load testing

Bridge load testing directly gives information on the overall performance of the structure [4]. Diagnostic load testing, for which relatively low load levels are applied, can be used together with an analytical model, often a linear finite element model, to update properties regarding the overall behaviour of the bridge, such as unintended composite action, transverse load distribution, stiffness of the structure, or the effect of frozen bearings. In a proof load test (Figure 3), on the other hand, a load representative of the factored live load is applied to the bridge. If the bridge can carry this load without signs of distress, then it is shown experimentally that the bridge fulfils the code requirements. From this point of view, diagnostic load testing is used to improve the analytical model used for the assessment, whereas proof load testing can replace the assessment calculations.

2.3 Modelling strategies

2.3.1 Necessity for advanced modelling strategies

As shown in Figure 1, simplified hand calculations are often only possible with strong assumptions,

more advanced modelling strategies, on the other hand consider structural behaviour in a more realistic manner, and therefore can give more accurate estimation of the structural behaviour in terms of load effect. Typical additional effects that cannot be considered in simple hand calculations are: the complex stress (re)distribution, the effect of nonlinear material properties to the structural behaviour, etc.



Figure 3. Proof load testing of viaduct Zijlweg [5]

When a traditional assessment based on spreadsheets that replace hand calculations shows that a bridge section does not fulfil the code requirements, it does not automatically mean that the section is unsafe. Typically, the interpretation is that further assessment calculations are needed, and that these calculations should be carried out with a more advanced modelling strategy. While the use of linear finite element models is standard engineering practice nowadays, more advanced modelling techniques for the assessment of existing concrete bridges may be less commonly used.

2.3.2 Nonlinear finite element models

With a nonlinear finite element model, additional sources of capacity and additional load paths can be unearthed (such as compressive membrane action, see Figure 4), and the expected behaviour of the structure can be closely modelled, together with the critical failure mode. For such models, often sufficient information is necessary, such as reinforcement drawings, material properties, and detailed information about the occurring deterioration or damage. When the required input information is available, a large number of

modelling choices are available to the engineer, which can sometimes be considered as a rather daunting task. To provide guidance on the modelling choices, in the Netherlands guidelines are available for the nonlinear analysis of concrete structures [6].

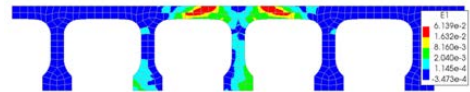


Figure 4. Nonlinear finite element model of Vecht Bridge, showing compressive membrane action developing [7].

2.4 Tailored resistance models

2.4.1 Necessity for tailored resistance models

Design codes aim at providing engineers with capacity models that are generally applicable. Consequently, they cannot provide the same level of accuracy for all structural types that the model can cover. This is especially true for the models that are based on empirical formulas. Often, a tailored model that can explicitly consider the specific considerations of the structure and that is calibrated by dedicated experiments can more accurately predict the resistance of these structures.

A typical example is the shear capacity of structural concrete members without transverse reinforcement. The expressions given in most design codes internationally were calibrated using shear tests of beams without transverse reinforcement failing in flexural shear. However, they are mostly applied to evaluate the shear capacity of slabs under concentrated loads. In this paper, we present three examples that have been used in the Netherlands to demonstrate ultimate shear capacity of concrete slab structures.

2.4.2 Physical based modelling approach

In the current Eurocode 2 [8], the shear capacity is described using a semi-empirical formula. In recent years, however, mechanical models have been able to better predict the shear behavior and capacity under a range of different types of applied loading. Therefore, the new generation of codes for design includes mechanics-based models for shear, such

as the Critical Shear Crack Theory [9], which lies at the basis of the next generation of Eurocode provisions. Moreover, other mechanical models are available to give us insight in the contributions of the different shear-carrying mechanisms, such as the Critical Shear Displacement Theory [10]. Because the clearer physical background, such mechanics-based expressions can be more easily tailored for the special conditions of the structure to be assessed. Thus, they can be used for assessment after agreement with the bridge owner, as not all these approaches are yet represented in the existing codes for assessment.

2.4.3 Load distribution in slabs

In concrete slabs under concentrated loads, transverse distribution results in a wider region contributing to the capacity, and, after cracking, increasing redistribution of internal forces reduces the peak forces in the slab, resulting in a larger capacity.

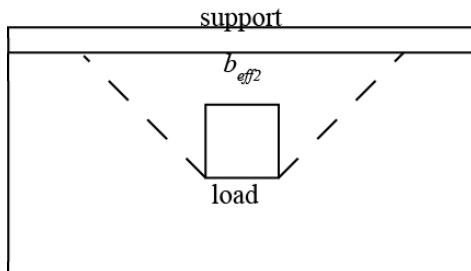


Figure 5. Plan view of slab with a single concentrated load, showing horizontal load distribution under 45° and resulting effective width.

At this moment, in the Dutch guidelines for assessment of existing concrete highway bridges (RTD) [11], two approaches are used. The first approach is the use of a horizontal load spreading method to determine an effective width (Figure 5), which can be combined with the capacity model using a hand calculation. The second approach requires the use of a linear finite element model, in which the governing shear stress is found by distributing the peak shear stress over $4d$ (with d the effective depth to the longitudinal reinforcement of the slab) and in which the governing moment is found by distributing the peak moment over $2d$. Considering the distribution

width can result in an improved assessment for concrete slab bridges.

2.4.4 Arching action

When the load path in a structure is carried by an arch in compression, the resulting arching action will lead to an increase in capacity. Such arching action occurs as compressive membrane action in bridge decks (both for cases with the load in between two girders [12] as well as for the case with the load above a girder [7]), as well as compressive arching action in prestressed girders [7] and arching action from direct load transfer in reinforced concrete girders [13]. Considering arching action can result in an improvement assessment for various bridge types, such as slab-between-girder bridges.

Arching action is sustained under repeated cycles of loading and does not break down under fatigue [14]. As such it is indeed safe and permitted to use compressive membrane action for an improved assessment of existing slab-between-girder bridges, including for the fatigue assessment [15].

2.5 Probabilistic analyses

In a probabilistic analysis, the goal is to demonstrate directly that the underlying safety requirements from the code are met by calculating the probability of failure of the section or structure, or by determining the reliability index. In the Netherlands, research is geared towards the use of concepts of structural reliability together with proof load testing, to develop a probabilistic substantiation of the practice [16]. In other countries, probabilistic-based assessment techniques are available in guidelines and recommendations [17].

3 Assessment framework

3.1 Levels of Approximation approach

As can be seen in the previous sections, an engineer can have various options to better assess an existing concrete structure. To assist the selection of the required approaches, an assessment framework based on the Levels of Approximation from Figure 1 can be considered (see Table 1), and this strategy can be called a



Levels of Assessment approach. Such an approach has been developed in the Netherlands for the assessment of shear-critical reinforced concrete slab bridges [18], and has been extended in recent years to cover both shear and flexure [19]. A higher Level of Assessment requires more investment, but at the same time leads to more accurate estimation on the actual safety of the structure. Depending on the importance of the structure, the available resources of the asset owner, and the state of information, a choice can be made accordingly.

In the first Level of Assessment, hand calculations (programmed into a spreadsheet) are used to compare the factored load effect to the factored capacity (by calculating the Unity Check, the ratio of factored load effect to factored capacity) at a number of predetermined cross-sections for a number of predetermined critical positions of the design tandem. For shear, the load spreading method from Figure 5 is used. If the Unity Check is equal to or less than one, the bridge fulfils the assessment requirements. If the Unity Check is larger than one, the assessment continues to the second Level of Assessment.

In the second level, the load effect is calculated by using a linear finite element model, whereas the capacity is still determined with a spreadsheet-based calculation. The load effect can now be more accurately quantified, and for shear a load

distribution of the peak of $4d$ is used, whereas for bending moment a distribution of $2d$ is used. If the resulting Unity Check is equal to or less than one, it has been shown that the assessment requirements are fulfilled. If the Unity Check is larger than one, the next level is explored.

In the third Level of Assessment, probabilistic analyses or nonlinear finite element models can be used, provided that sufficient information is available. If necessary, data can be obtained using non-destructive testing or core sampling in the field to better determine the material properties or the extent of deterioration or degradation. In these calculations, no separate analysis of the capacity and load effect are used – the nonlinear finite element model is combined with a safety format [20] to directly carry out the assessment, and the probabilistic analysis results in the probability of failure of the section, member, or entire bridge, depending on the selected approach.

The final Level of Assessment is proof load testing of the bridge to directly check if the code requirements can be met. Moreover, the data obtained during the proof load test can be used to develop a field-validated model of the bridge, which can be used for future assessments.

Table 1. Levels of Assessment

LoA	Load effect	Capacity	Application
LoA 1	Hand calculation, using horizontal distribution for determining effective width for point loads	Hand calculation with code formula	Sectional check of shear in RC slab bridges
LoA 2	Determined using linear finite element analysis and distributing the peak value	Hand calculation with code formula	Check of shear in RC slab bridges, more positions can be covered
LoA 3	Nonlinear finite element analysis or probabilistic analysis. Load effect and capacity are considered together		Find maximum load factor in NLFEA or determine probability of failure
LoA 4	Proof load testing: assessment is carried out directly		Proof load test shear-critical and flexure-critical position in RC slab bridge



3.2 Lessons learned

The approach using Levels of Approximation is a framework that can be used by engineers who are faced with the assessment of ageing bridges. Ultimately, the aim is that these insights can be used for a better assessment of existing bridges, leading to a better management of the existing bridge stock and a potential extension of their service life, where appropriate.

Countries with a relatively young bridge stock should not wait until they are faced with major problems caused by the ageing of their bridges to prepare for the future assessment of their assets. In fact, a proactive attitude can reduce the long-term costs, and can help engineers and asset owners plan ahead. For countries with a relatively young bridge stock, such as Ecuador and other Latin American countries that have seen recent expansions of their road and/or railroad network, thinking ahead is important. As such, the best practices for these countries include: proper storage of the data (plans, designs, material properties, and, where available, finite element models used for the design) of the recently constructed bridges, development of an inspection scheme with particular attention to bridges at critical locations (for example, regions with high risks of scour due to the topography, or bridges at locations where no redundancy in the road network exist, such as various locations along the Pan-American highway in the Andean highlands), planning of preventive maintenance actions to ensure the optimal operation of the bridges, and creating a bridge management strategy for or by the asset owner (public or private party).

4 Discussion

More and more, bridge and structural engineers are shifting their efforts from the design of new structures to the assessment of existing structures. While the mechanical principles at the basis of the problem are the same, the approach of assessment is different from design, and requires the engineer to use different skills and tools. Some tools that may be unfamiliar are important for assessment: use of advanced modelling strategies, obtaining field data through non-destructive evaluation

methods, and load testing. While each of these tools have quite a learning curve, it is important for the assessment engineer to be aware of the various strategies that are available, so that the appropriate methods can be used for each particular case, and as a function of the available information and condition of the bridge. Where particular skills are necessary, a specialized engineer can be subcontracted. In addition, it is important for educators to pass this knowledge on to the new generation of engineers, as they will see larger portions of their time spent on assessing existing bridges rather than designing new ones.

5 Conclusions

This paper gives an overview on how recent research insights can be combined into strategies for the assessment of existing concrete bridges. In particular, improved methods for obtaining field data (structural monitoring, non-destructive evaluation, and load testing), advanced modelling strategies (in particular, nonlinear finite element models), tailored resistance models (physical based modelling approach for shear, methods for determining load distribution in slabs, and including arching action), and probabilistic analysis methods are highlighted. These methods are then combined into a Levels of Assessment framework, and ultimately lessons learned from the assessment of existing concrete bridges are summarized for countries that have a relatively young bridge stock, as is the case for various countries in Latin America where the road or railway network has recently been expanded.

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