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DOI
10.1201/9781003322641-54

Publication date
2022

Document Version
Final published version

Published in
Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability - Proceedings of the 11th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2022

Citation (APA)
de Vries, R., Lantsoght, E. O. L., Steenbergen, R. D. J. M., & Fennis, S. A. A. M. (2022). Reliability assessment of existing reinforced concrete bridges and viaducts through proof load testing. In J.-R. Casas, D. M. Frangopol, & J. Turmo (Eds.), *Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability - Proceedings of the 11th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2022: Mini-symposium: [MS05] Assessment of existing infrastructure assisted by field data* (pp. 467-475). (Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability - Proceedings of the 11th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2022). https://doi.org/10.1201/9781003322641-54

Reliability assessment of existing reinforced concrete bridges and viaducts through proof load testing

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Mini-symposium: [MS05] Assessment of existing infrastructure assisted by field data

ABSTRACT: In the assessment of existing infrastructure performing only a desk study is often not sufficient to determine the structural reliability of a bridge or viaduct. For concrete structures gathering field data by performing a proof load test offers detailed information about the structural performance. However, the relation between the magnitude of the load and the structural reliability is not immediately clear. In the present study the challenges in determining the target load and the uncertainties that require attention are described. An approach is presented that addresses the time-dependent character of the structural reliability, the need for accurate stop-criteria, the knowledge level and spatial uncertainty. It is shown how both past traffic loads and a proof load test may contribute to the proven strength of a structure. The described methodology provides a starting point towards a flexible approach for proof load testing in which structure-specific information and requirements are considered.

Keywords: Deterioration, existing structures, load testing, proof loading, reliability, time-dependence

1 INTRODUCTION

Due to the constant aging of infrastructure, increased traffic load and traffic intensities, methods are explored by which the reliability of existing road bridges and viaducts can be assessed. In case limited information of the structure is available or its condition is of concern, load testing may be used to prove that the structure can still satisfactorily carry the live loads. A test conducted with this aim is referred to as a 'proof load test'. Historically, before complex structural analysis was commonplace, proof load testing was regularly performed prior to opening a bridge to the public. In a number of countries performing a proof load test before use is still required (Lantsoght et al. 2017).

The magnitude of the load to be applied, or target load, is of particular importance. If the, relatively large, target load is successfully carried by the structure then it has proven to be sufficiently structurally reliable for future use. The test can be performed using regular trucks, a special vehicle (Figure 1) or other methods such as a loading frame including ballast.

Often, for existing structures less stringent reliability requirements hold. Therefore, a design load used for new structures is not necessarily useful in the assessment of existing structures. In addition, the condition of the structure may be of particular concern due to the effect of deterioration or other time-dependent processes (Ellingwood 1996).

This article describes the challenges in determining the target load in relation to structural reliability and the associated uncertainties. In particular, the following aspects will be discussed: the evolution of the structural reliability with time, the reliability of stop-criteria, the level of knowledge about the structure and assessment at the system-level.

2 LITERATURE

2.1 *International standards*

Proof load testing is not a standardized assessment procedure in many countries. If national guidance is lacking, standards or guidelines from other countries can provide useful insight into accepted practices.

Figure 1: Pilot proof load test being performed on the Vechtbrug in the Netherlands (October 2016).

In the USA, the Manual for Bridge Evaluation (MBE) (AASHTO 2018) is used as a guideline for proof load testing. The target proof load is expressed in terms of the regular load model and is magnified by a proof load factor (X_p). Its default value (1.4) was derived in a basic probabilistic analysis (Lichtenstein 1993) that did not address the challenges described in this article. Another relevant American standard is the ACI 437.2M (ACI 2013) which describes the requirements for load testing of existing concrete buildings including loading protocols and acceptance criteria.

Recently the German committee for reinforced concrete has published a new version of its guideline for proof load tests on concrete structures (DAfStb 2020). The guideline is mainly intended for buildings, but speaks in more general terms such as structures and components. The magnitude of the proof load is expressed in a format that resembles the load effect in Equation (6.10) of EN 1990 (CEN 2019). An interesting aspect of the guideline is the consideration of multiple similar components. When a limited number of similar components are tested, the remaining uncertainty associated with their slight differences is accounted for by increasing the magnitude of the test load (Marx 2019).

2.2 *Research*

2.2.1 *General*

Proof load testing is still an active field of research and continues to gain attention due to the growing need for versatile assessment methods for existing structures (Lantsoght 2019).

It is desirable that the assessment of infrastructure is not overly conservative because that may lead to the replacement or upgrading of bridges that are actually satisfactory. Proof load magnitudes can vary depending on the load rating, dead/live load ratios, degradation, bridge age, reference period and prior service loads (Faber, Val & Stewart 2000).

In Casas & Gómez (2013) proof load factors are presented that were developed as part of the large scale ARCHES (Assessment and Rehabilitation of Central European Highway Structures) project. The factors are applied to the characteristic (or nominal) live-load obtained from a traffic load model (e.g. Eurocode LM1). A distinction is made between the case where bridge documentation is available and the case where it is not. Depending on the target reliability and estimated strength, different factors apply. Weigh-in-motion (WIM) data from five European countries, including the Netherlands, is used to describe the traffic load. Their study presents a step forward from current code-based approaches by making use of recent traffic load data and the option to include bridge documentation.

For existing structures flexibility is needed regarding the reference period, therefore the time-dependent nature of the structural reliability is of particular interest. An early description of the time-dependence in relation to proof load testing is found in Spaethe (1994). It is shown that during the proof load test the reliability of the structure is low, due to the relatively large load that is applied, but afterwards the reliability is increased – if the test was successful. In the more recent work by Schacht, Bolle & Marx (2019) and Frangopol et al. (2019) the decrease of reliability with time in case of deterioration is also recognized.

2.2.2 *System reliability*

One of the main aspects in which the assessment by load testing is different from the design of new structures is the influence of system action on the performance of an existing structure. Therefore, system reliability is of particular interest to proof load testing.

A system may be thought to be comprised of multiple components; the performance of all components needs to be combined according to a certain scheme to result in the system reliability. In this scheme the components may act in parallel or in series. In addition, the combined performance of a group of elements may interact with one component, or another group. In the context of system failure a diagram of the interaction is called a fault tree (Fussel 1975).

Various methods may be used to calculate the failure probability of a system. The Monte Carlo Simulation (MCS) is a straightforward method that is always applicable, but it is computationally expensive (Metropolis & Ulam 1949). For better computational efficiency the equivalent planes method (Roscoe, Diermanse & Vrouwenvelder 2015) is used in this article. The method is based on the equivalent component method (Gollwitzer & Rackwitz 1983) and the first-order system reliability method described by Hohenbichler & Rackwitz (1983). The reliability of the individual components may be determined using the first order reliability method (FORM) (Hasofer & Lind 1974) or any other method that also provides the influence coefficients of the random variables.

The equivalent planes method works on the basis of two components. The (linearized) limit state functions Z_i of two components may be written using the reliability index (β_i) of the component and the influence coefficients (α_{ij}) of all random variables present in the system:

$$Z_1 = \beta_1 + \alpha_{11} U_{11} + \alpha_{12} U_{12} + \cdots + \alpha_{1n} U_{1n} \tag{1a}$$

$$Z_2 = \beta_2 + \alpha_{21} U_{21} + \alpha_{21} U_{21} + \cdots + \alpha_{2n} U_{2n} \tag{1b}$$

In this equation U_{ij} are standard normally distributed random variables that are statistically independent (i.e. uncorrelated) within the component. However, auto-correlation $\rho_j = \rho(U_{1j}, U_{2j})$ may exist.

In case of more components, the combination process needs to be repeated several times until just one component remains. Each time two components are combined to give a new component that replaces the two original components. The most accurate results are obtained when the components with the highest correlation between the limit state functions are combined first in every step (Gong & Zhou 2017).

2.2.3 *Reliability updating*

Proof load testing is starting to be considered in the light of maintenance and durability. In particular, the so-called ‘updating’ of structural reliability as performed on the basis of Bayesian theory provides the opportunity to incorporate various sources of information. The theory can provide a mathematical basis for the updated distributions of the reliability (Yuefei, Dagang & Xueping 2014).

The more generally applicable Bayesian decision theory is also used in the context of proof load testing. It can provide decision support and the identification of information to aid in modelling and monitoring of structures (Schmidt et al. 2020). In Bayesian decision theory, today often mentioned in the context of value of information (Zhang et al. 2021), the state of information about an object results in three possible types of analysis: prior analysis, posterior analysis and pre-posterior analysis (see Figure 2). Each stage in the analysis has its own set of possibilities (E, X, A, Θ), dependent on earlier choices or outcomes. All possible paths lead to certain consequences or costs (C), which may also include the risk of losing human life.

In a prior analysis, the decision alternatives are directly associated with possible outcomes and the associated consequences. In a posterior analysis, additional information is added to update the probabilistic model. The added value of additional data may be quantified, even when it has not been collected yet – i.e. the *value of information* is studied. This gives rise to the pre-posterior analysis, where the extra costs of acquiring additional data is evaluated against possible gains. Proof load testing itself may also be viewed as an additional source of information about the structure and a pre-posterior analysis may be employed to determine if it is beneficial (Nishijima & Faber 2007).

3 CHALLENGES AND SUGGESTED APPROACH

Because of the long history of proof load testing, methods applied in practice possess a strong deterministic character or are based on basic probabilistic calculations that do not consider the aspects described in the following sections.

3.1 *Time-dependence*

In case a variable load acts on a structure, e.g. traffic load, the structural reliability is time-dependent. Additional time-dependent processes such as load trends

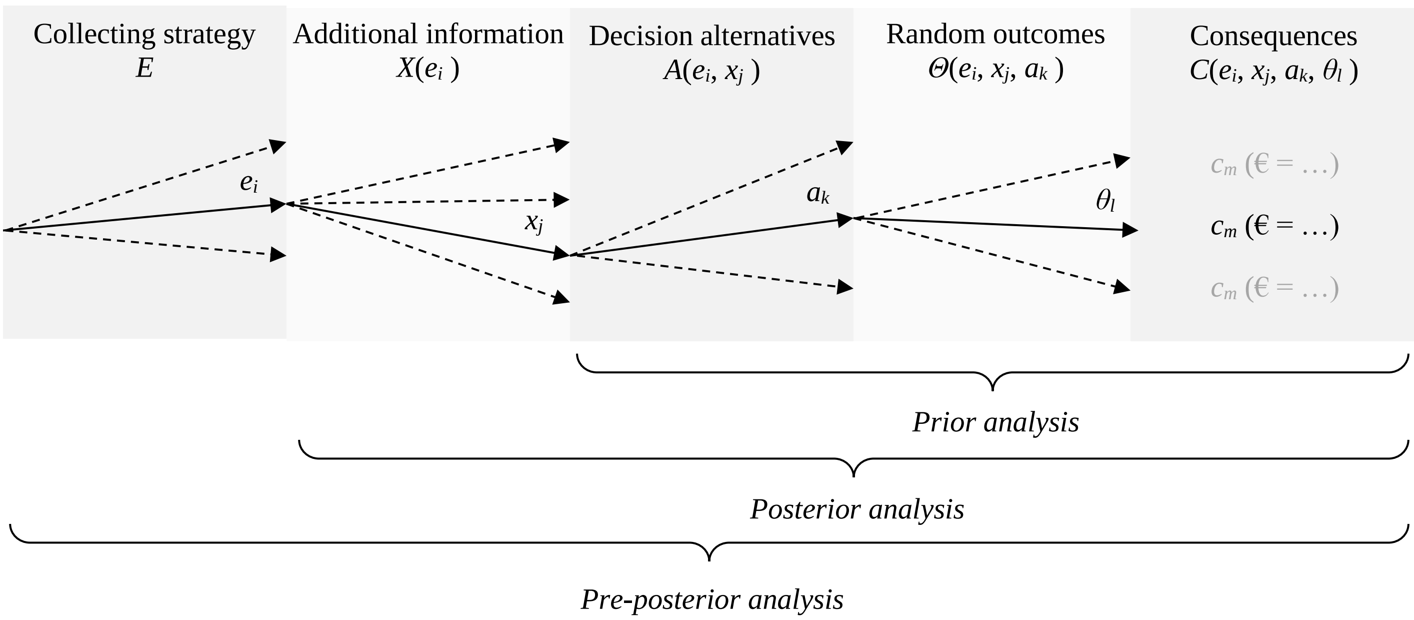

Figure 2: Analysis type depending on the state of information.

and material deterioration add to this effect. Also, during a proof load test the structural reliability is markedly lower than in normal operation. In relation to the desired reliability level, a fixed design reference period (e.g. 50 years) lacks the flexibility to accommodate the remaining functional life span of an existing structure. Moreover, the reliability level for new structures is larger than strictly required for human safety because of economic benefit. A structure that lasts longer may be profited from for a longer period of time (Steenbergen & Vrouwenvelder 2010).

To judge if the structural reliability is satisfactory after a successful proof load test, an assessment on the basis of annual reliability is suggested, but any small time period suffices. In this way the framework is also flexible regarding the remaining life span of an existing structure. Considering the time-dependence is also beneficial in relation to the proven strength by past traffic loads. In a sense, every truck passing a bridge may be viewed as a sort of proof load test, contributing to the proven strength of the bridge. Standard texts on reliability theory describe the proven strength from past loading via the ‘bathtub curve’ of the failure probability (Jonkman et al. 2015).

3.2 *Reliability of stop-criteria*

Although various stop-criteria have been developed (Zarate Garnica & Lantsoght 2021), little attention is paid to the link between structural reliability during the load test and the magnitude of the load. Reaching the target load, as calculated before the execution of the load test, may not always be feasible due to signs of distress appearing when the load is gradually applied. If the reliability of the stop-criteria is low, the proof load test may be aborted before the structure is actually near is maximum capacity.

Collapse or partial collapse of a structure during the proof load test is undesired. Considering the reliability during testing can mitigate the risk of collapse of the structure and provide decision support in the selection of sensors and measurement plans. In addition, if enough evidence of proof load tests reaching the target load successfully with some signs of distress is incorporated in the analysis, the risk at damage may be quantified instead of avoided (risk aversion).

3.3 *Knowledge level*

The knowledge level (available information in drawings, material tests, etc.) varies between structures, especially because of their age. Therefore, a flexible method is needed that can utilize various types of information. To assess the bending moment capacity the cross-sectional area of the reinforcement is of main interest. However, to assess the shear capacity the concrete quality is more valuable. Various data sources and their influence on the state of information are collected in Figure 3. In addition, a balance is sought between how much information is collected and analyzed before performing the proof load test and regarding the proof load test itself as the primary source of information about the structural performance (Medha et al. 2019).

In the suggested approach the state of information plays a key role in the reliability analysis preceding a proof load test. The basic information in a prior analysis is complemented by additional information in a

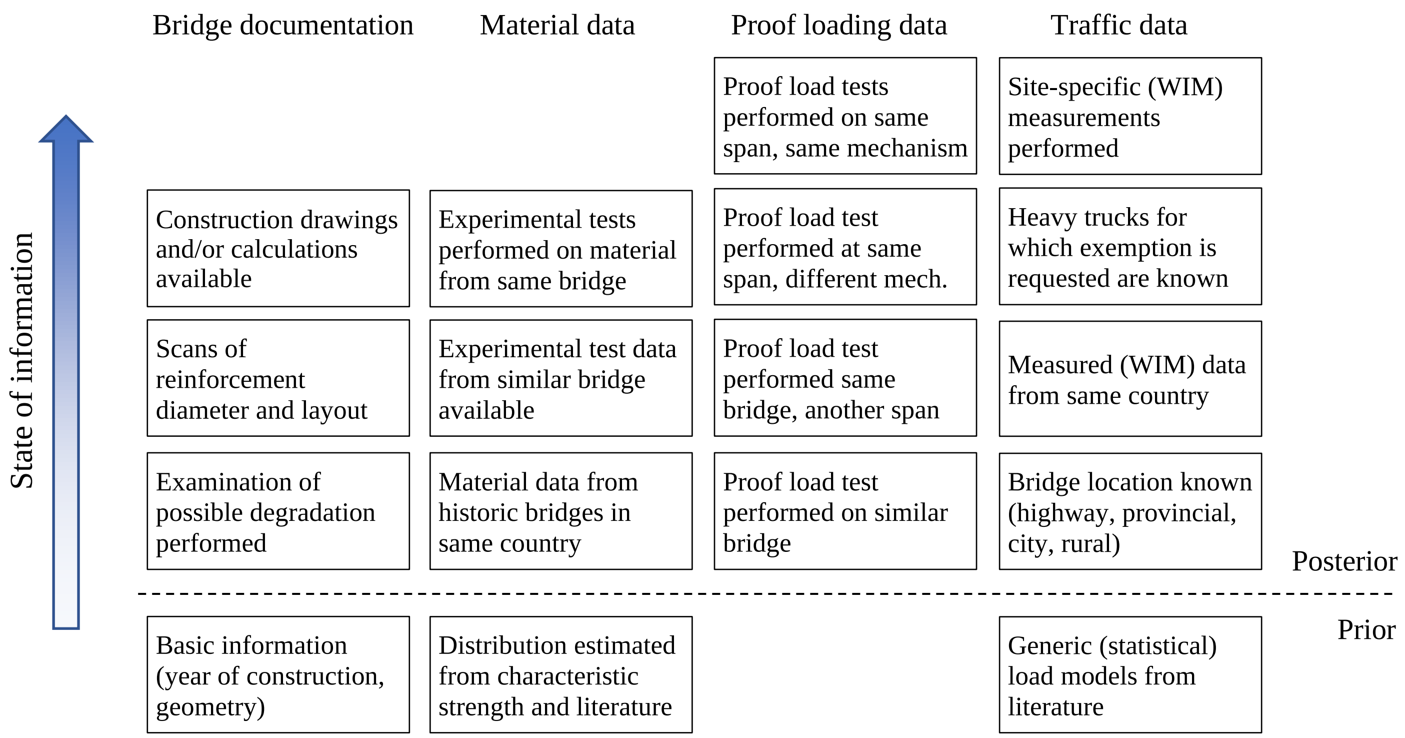

Figure 3: State of information considering various information sources.

posterior analysis (see Figure 2 and Figure 3). By introducing additional uncertainty into the probabilistic model it may subsequently be updated (reduced) through the application of Bayes' theorem:

$$\mathrm{P}(H \mid D) = \frac{\mathrm{P}(D \mid H)\,\mathrm{P}(H)}{\mathrm{P}(D)} \tag{2}$$

where H is the hypothesis (e.g. assume that parameter x of the model takes on value y, etc.) and D is the additional data that has become available. The data is a possible outcome of the model observed in real life and may take on many forms (e.g. a numeric value, a flag indicating failure, etc.). Because of this, various kinds of data (or evidence) can be combined.

Uncertainty in the resistance may be split into an objective (natural) and subjective part (model), often written as a multiplication ($\theta_R R$). In this formulation the model uncertainty (θ_R) is the parameter that is updated in a Bayesian approach (Lin & Nowak 1984). Very large uncertainties may be introduced purposely as 'objective' low informative priors (Ditlevsen & Vrouwenvelder 1994). If available, other broad prior distributions following from basic information such as the bridge span and traffic type are also suitable.

3.4 *System-level assessment*

A bridge or viaduct consists of physical components such as the bridge deck, supports, etc. However, also cross-sections and connections may be regarded as components. In addition, the same component may take part in different failure mechanisms. In a design all components are typically verified to achieve the desired structural reliability at element-level. It may subsequently be assumed that the reliability of the structure, i.e. the system, is at least equal to the reliability at the element level. Assessing the reliability of just one component, cross-section, or failure mechanism by proof load testing does not provide the reliability of the structure. Usually practical limitations apply with regard to the number of tests because of the hindrance caused to traffic and the costs of testing.

In a system-level assessment the performance of multiple components and spatial variability is incorporated. Also here Bayesian analysis can be utilized to update the reliability of the system (joint PDF) with incomplete and uncertain information about a limited number of parameters (Schneider 2020). An example of a simplified bridge with two spans is provided in Figure 4. In this case only load and spatial variation in the longitudinal direction is considered (and not over the width of the bridge). The structural schematization with a distributed load indicates three common design checks: bending moment at midspan (blue), support moment (green) and shear force near the support (orange). The corresponding cross-sections are indicated in the lower part of the figure. Because of spatially varying material properties and execution details other cross-sections may be critical. In Figure 4 these cross-sections have been drawn with same color, but transparently.

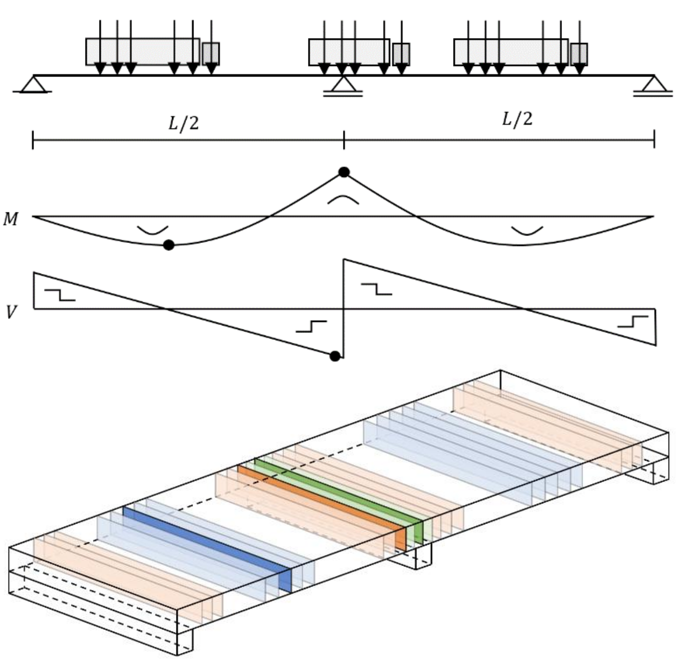

Figure 4: Visualization of the cross-sections to be assessed in a system-level assessment.

4 EXAMPLE TIME-DEPENDENT ANALYSIS

4.1 *Description*

To illustrate the effect of proof load testing in a time-dependent reliability analysis an example calculation is presented (De Vries, Lantsoght & Steenbergen 2021). Under consideration is a simply supported slab bridge located in one of the highways in the Netherlands. The structure was built in 1960 and designed according to the prevailing standards of that time (KIVI 1938, 1950). The traffic load used in its dated design is inappropriate when compared to today's high traffic intensity. But, the design values of material properties (e.g. steel and concrete strength) were quite conservative. As a result, old bridges and viaducts can still possess adequate structural strength to resist today's higher loads.

In case the original bridge documentation such as drawings and calculations are still available, they may be used to infer the (prior) probabilistic description of the resistance of the structure. In this case the bridge documentation is not available. Therefore its design was 'reverse engineered' by using historic standards (Harrewijn, Vergoossen & Lantsoght 2021).

In this example only the bending moment at midspan will be considered. In reality, the shear capacity of the slab near the supports and the capacity of other bridge components will require assessment as well.

4.2 *Conditional annual reliability*

The annual reliability is calculated under the condition that no failure occurs in any of the years before the year under consideration. Using the following events:

A failure in the year i;
B failure in the years 1 to $i-1$;
B' no failure in the years 1 to $i-1$ (complement).

the conditional annual probability of failure can be written as:

$$\mathrm{P}(A\,|\,B') = \frac{\mathrm{P}(A \cap B')}{\mathrm{P}(B')} = \frac{\mathrm{P}(A \cup B) - \mathrm{P}(B)}{1 - \mathrm{P}(B)} \tag{3}$$

The probability $\mathrm{P}(A \cup B)$ may be read as the cumulative failure probability up to and including the year i, whereas $\mathrm{P}(B)$ is the cumulative failure probability up to, but not including, the year i.

To calculate the conditional annual reliability using the system reliability method, first the reliability index and influence coefficients of each year need to be calculated, e.g. using FORM. The individual years are the system components in this calculation. Next, the cumulative probability of failure can be calculated using the equivalent planes method (OR-combination). Then, the conditional probability of failure in year i is:

$$P_{\mathrm{f,cond},i} = \frac{P_{\mathrm{f},i} - P_{\mathrm{f},i-1}}{1 - P_{\mathrm{f},i-1}} \tag{4}$$

where $P_{\mathrm{f},i}$ is the cumulative failure probability up to and including the year i. In the first year no conditionality holds and thus $P_{\mathrm{f,cond},1} = P_{\mathrm{f},1}$.

Table 1: Random variables used in the limit state function.

Var.	Description	Dist.*	Mean	COV
θ_R	Model uncertainty of the resistance	LN	1	0.05
R	Bending moment resistance at midspan	LN	4100 kNm	0.05
θ_E	Model uncertainty of the load effect	LN	1	0.11
G_{DL}	Load effect of the dead load	N	721 kNm	0.05
G_{SDL}	Load effect of the superimposed dead load	N	101 kNm	0.1
C_{0Q}	Time-independent uncertainty of the variable load, including bias for dynamic load effect	LN	1.1	0.1
Q	Load effect of the annual traffic load	G	1150 kNm	0.025
t_{R0}	Initiation time to deterioration	LN	20 yr	0.1
Δ_{cR}	Degradation per year	LN	0.0025	0.1
c_{Q0}	Starting value of the trend	LN	0.78	0.1
Δ_{cQ}	Increase of traffic load per year	LN	0.004	0.1
Q_{PL}	Load effect of the proof load, including uncertainty	N	(varies)	0.05

*Distribution LN is lognormal, N is normal and G is Gumbel.

4.3 *Probabilistic model*

The limit state function for the probabilistic calculation is formulated in line with fib (2016):

$$Z = \theta_R c_R R - \theta_E (G_{\mathrm{DL}} + G_{\mathrm{SDL}} + c_Q C_{0Q} Q) \tag{5}$$

where the properties of the random variables are provided in Table 1. Each variable is characterized by a distribution, the mean value and coefficient of variation (COV).

To include the deterioration of the resistance and a trend in the traffic load, the limit state function makes use of the following time-dependent coefficients:

$$c_R(t) = \begin{cases} 1 & t \le t_{R0} \\ 1 - \Delta c_R (t - t_{R0}) & t > t_{R0} \end{cases} \tag{6a}$$

$$c_Q(t) = c_{Q0} + \Delta c_Q t \tag{6b}$$

where the parameters are random variables, listed as well in Table 1. This degradation model includes a time to initiation (t_{R0}), followed by a linear reduction of strength (Enright & Frangopol 1998). Corrosion leading to a reduction of the effective steel area in a cross-section was modelled by a quadratic function in Vu & Stewart (2000). In case of deterioration, a large degree of uncertainty exists with respect to the current capacity of the bridge. In this example only a limited amount of uncertainty is considered for simplicity. It thus represents the rather uncommon scenario where the deterioration process is well-known.

The system reliability method (Section 2.2.2) is applied to combine the failure probability in time. All random variables are fully auto-correlated except the annual traffic load which is assumed to be independent (i.e. a new realization each year).

WIM data from 2015 was analyzed to determine the load effect on the bridge, expressed as the largest bending moment at midspan within a certain period of time. Only the traffic in the right-most lane, where the trucks drive, has been analyzed.

4.4 *Results*

Using the presented probabilistic description, a time-dependent reliability analysis can be performed. The result is displayed in Figure 5. The base case displays the reliability without traffic trend and degradation. In this case the annual reliability increases gradually due to proven strength of past traffic loads. The traffic trend and degradation are incorporated subsequently to display their detrimental effect on the evolution of the annual reliability. A higher reliability is attained in the first years when including the traffic trend because the adopted linear trend expresses a reduction before the year 2015 and an increase afterwards.

Note that in this example the parameters of the degradation and traffic load trend have been tuned to

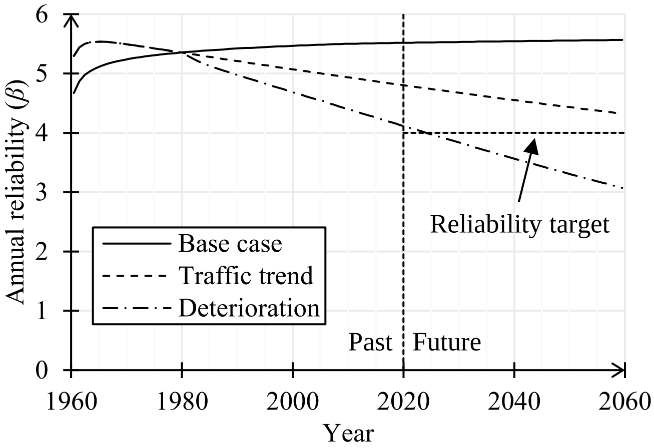

Figure 5: Development of the conditional annual reliability with time, incorporating a traffic load trend and deterioration.

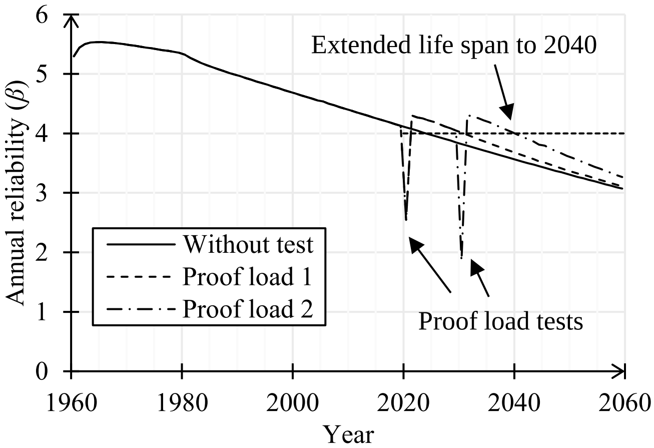

Figure 6: Effect of proof load testing on the annual reliability.

yield a reliability index that drops below the acceptable annual reliability β = 4 for CC3 (Steenbergen & Vrouwenvelder 2010) around 2020. In a real-life situation the parameters will need to be determined by studying the effect of all possible degradation mechanisms and the actual trend in traffic loads.

Proof load testing is adopted to ensure the bridge meets the required structural reliability. When a proof load test is performed an additional term is included for the proof load effect in the limit state function:

$$Z = \theta_R c_R R - \theta_E [G_{\mathrm{DL}} + G_{\mathrm{SDL}} + \max(c_Q C_{0Q} Q, Q_{\mathrm{PL}})] \quad (7)$$

The first proof load test is performed in the year 2020 and has a target (mean) value of 1800 kNm. Then, in the year 2030 the second proof load test is performed with a higher target load effect of 2000 kNm (Figure 6). In the year the test is performed, the annual reliability is markedly lower, but as a reward the reliability in the following years is higher. The target loads have been determined such that the annual reliability remains above the target in the next 10 years. Alternatively, the higher target load could have been applied directly in 2020, also leading to sufficient reliability until 2040. But, then the probability of failure in the first test in 2020 would be larger.

5 DISCUSSION

In this article, a hypothetical slab bridge was analyzed to show the development of the reliability with time. With regard to the knowledge level, in this example a scenario was depicted where the structural properties of the bridge, the traffic trend and deterioration process are known to large degree. Normally, this will not be the case. Especially the rate by which deterioration occurs will be difficult to establish. Suitable treatment of these uncertainties is critical.

The mathematical form of the limit state function is not definitive, other formulations are possible as well. In the presented formulation the model uncertainty of the load effect (θ_E) acts on both the traffic load effect and the load effect produced during the proof load test. In practice, the methods to calculate both effects will likely be similar (e.g. finite element analysis), but it does not guarantee full correlation.

In addition, it was investigated to what extent the historic traffic load influences the reliability at the moment of proof load testing. If the traffic load before the year 2015 (date of measurements) is ignored, comparable outcomes are produced. In this way insensitivity to the (difficulty to estimate) historic traffic load was established.

A future framework for proof load testing should be flexible, in such way that it could also consider the method by which a proof load test is performed. For example, when driving over a bridge less spatial uncertainty remains than when a single position is loaded.

6 CONCLUSIONS

With the suggested approach to the reliability assessment of existing reinforced structures through proof load testing a new framework can be developed that addresses existing challenges. An assessment based on annual reliability highlights the evolution of the structural reliability before, during and after the proof load test. A clear need for stop-criteria and an evaluation of their reliability, emerges from the relatively large probability of failure during the proof load test.

By adopting a flexible method, various types of information can be combined to assess the structural reliability through proof load testing. How much benefit is obtained when considering various kinds of information should be quantified in future research.

By judging the reliability on the system-level, uncertainty with regard to multiple failure mechanisms and spatial variability can be addressed. In this way, reservations regarding the assessment of shear capacity through proof load testing may be lifted.

ACKNOWLEDGEMENT

The authors wish to express their gratitude and sincere appreciation to the Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat) for financing the research work. In addition, the fruitful discussions with M. Naaktgeboren of Rijkswaterstaat and M.A.N. Hendriks of Delft University of Technology have been of great help.

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