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Evaluation of test loads on existing concrete structures by means of Bayes' Theorem

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ABSTRACT: For existing structures, load tests are often carried out to demonstrate the load-bearing capacity. Reasons for this can be found in a number of unknowns regarding the design loads, the materials used, their current condition, the design assumptions, and even effects linked to system behaviour. An analysis of existing standards shows that codes or guidance is lacking as to what load level such a test should be carried out for. In this contribution, using the Bayes theorem, the reliability of a structure is examined when passing a load test of a given load level. To define the posterior probability of a structure that passed a load test, knowledge is needed about the likelihood that a structure survives a test load given a certain structural reliability. Prior knowledge about the latter might be based on structural assessment, expert judgement and the load history. Most difficult aspect to assess, in the denominator of Bayes rule, is the marginal probability related to the condition assessment. Results in this paper show the benefits of test loads up to high load levels to estimate the reliability of existing structures. In that way, the approach is of great practical importance to enable a valorisation of the existing (historical) building stock.

1. INTRODUCTION

In the perspective of sustainability, the reuse of existing structures is a topic of interest. When looking into the assessment of their bearing capacity, multiple questions arise concerning reliability. ISO 13822 (2010) specifies the adjustment of the target reliability for existing structures. (fib Bulletin No. 80 2016) provides a guideline to modify partial safety factors for the adjusted reliability index. However, a challenge in the assessment of existing structures is the amount of unknowns related to structural modelling and load arrangements. The number of knowns may increase by surveying techniques and material characterization with mechanical testing.

Using a load test to verify the structure has been of interest in the past (Ellingwood 2000; Stewart 2001), but seems of lesser interest during the last decades. It is preferable to execute a load test on a part of the structure that is thoroughly investigated. Certain parts can be more difficult to examine due to inaccessibility, causing them to possibly behave differently because of unknowns such as degradation and corrosion. Figure 1 shows an example of a load test on an existing building by the aid of pools. This paper studies the knowledge gained on the reliability of the structure after performing such load tests.

Figure 1: Load Test - Leopold II building

Eurocode 0 (EN 1990 2002) allows for a design to be based on a combination of tests and calculations. Annex D, called "*design assisted by testing*", elaborates further on this matter. Load tests on existing structures can be considered as a control test to check the behaviour of an actual structure or of structural members after completion. This type of test, however, is indicated as acceptance test of which no further methodology is described since no broad range of statistically processable test data is available.

The European technical specification (CEN/TS 17440 2020) is dedicated to the assessment of existing structures. Load testing is prescribed as a manner of investigation with the definition: *"Test of a structure or part thereof to evaluate its behaviour or properties, to predict or determine its load-bearing capacity."* The specification acknowledges that the structural behaviour and the boundary conditions can be different for different load levels. However, at the same time suggesting that the load level of the test is lower than the design load in ultimate limit state. The methodology prescribed herein, is limited to the interpretation of a surviving load test stating that solely the minimum resistance equal to the applied test load can be concluded from the test and not the resistance of the structure. Yet again, no load level is recommended.

When looking broader to performance tests of structural elements, multiple guidelines are available prescribing requirements for testing. (EN 1997-1 2005), for example, describes load tests on piles. The minimum load level of the test is the design load. In case of tensile pile foundations and/or trial piles, the test should be carried out to failure. Another example is the performance test of hollow core slabs according to EN 1168 (EN 1168 2011). The sample is loaded in two cycles: first to 70% of the ultimate load and then to the ultimate load and failure.

(EN 1363-1 2020) prescribes fire resistance tests. Annex D of this guideline is dedicated to the selection of test loads. Nevertheless, no definite load level is specified. A distinction in fire tests between different structural elements is made in separate standards. (EN 1365-2 2014) is dedicated to floors, where the required load level is prescribed as what is to be expected in practice.

Lastly, guidelines (Standaardbestek 260 2021) in Belgium are provided for load tests on bridges by the aid of predefined trucks. The guideline dictates that the load level and load plan should result in the characteristic values of the calculated load effects for concrete and steel bridges. The loads need to decrease to frequent values when testing a prestressed concrete bridge.

Considering the previously mentioned European guidelines (EN 1168 2011; EN 1997-1 2005), there is a tendency to test in a final stage till failure when trial samples are available. Obviously this cannot be the goal of load tests on existing structures. However, it is difficult to determine the necessary load level when performing a load test on actual structures, that will be used afterwards.

In the American code (ACI 437.1R-07 2016; ACI 437.2-13 2016), a procedure is provided for test loading of an existing concrete structure. When only a part of the structure will be tested, the Test Load Magnitude (TLM) is given by Eq.(1a) if no roof loads should be taken into account. This is compared to the design load (ULS) (ACI 318-14 2016) in Eq.(2), symbols are explained in the following paragraph.

$$TLM = 1{,}3(D_w + D_s) \quad (1a)$$
$$TLM = 1{,}0D_w + 1{,}1D_s + 1{,}6L \quad (1b)$$

$$ULS = 1{,}2(D_w + D_s) + 1{,}6L \quad (2)$$

According to ACI, the *TLM* to necessary strength ratio should be between 90 and 95 percent in order to provide an appropriate level of safety validation without causing too much damage. The TLM is comparable to the design load except for the safety factor of the dead loads. The self-weight (D_w) is a known feature of an existing structure, hence safety factor 1. In comparison to the design load, The safety factor for superimposed dead loads (D_s) is smaller in TLM. However, this safety factor must increase if the loads are not yet in place on the structure. On the other hand the safety factor on the live loads (L) remains the same.

(CEN/TS 17440, 2020) provides an argument for using ultimate design loads by stating that the structural behaviour and the boundary conditions can differ depending on the load level. However, in ULS, non-reversible damage (cracking) is allowed, as also acknowledged by ACI, which then again opposes testing up to this load level.

By presenting case studies, literature can provide a different perspective on conducting load tests. (Arangjelovski et al. 2015) used two case studies to compare Macedonian to European standards. In Macedonia, a load test is obligated if a wooden structure is damaged. For both case studies, the load was limited to characteristic values. +In a more recent paper (Poutanen et al. 2021), load tests are considered as a method for determining the structure's reliability. The test load reduces uncertainties associated with codes, design and execution. This principle, in combination with measuring the structure, can be interpreted as a method for reducing model and geometric uncertainties of the material.

The uncertainty of degradation also presents a challenge when evaluating load testing levels on existing structures. Numerous destructive, semi-destructive, and non-destructive concrete compressive strength testing techniques are known (Vona 2022; Wróblewska and Kowalski 2020; Yue Choong Kog 2018). For steel reinforcement, in situ estimating the corrosion risk or rate is possible (Andrade and Alonso 1996; Colozza et al. 2020; Tang et al. 2021; Verstrynge et al. 2022) . However, estimating the corrosion level and pitting factor is not readily done. In addition, testing the rebar yield strength is nearly impossible without critically damaging the structure, as also stated by (Croce et al. 2020).

In current paper, two difficulties are considered concerning load tests on existing structures namely the unclear load level in current guidelines and the unknown degradation of the structure. With the aid of the theorem of Bayes, the reliability of existing structures in view of load tests is analysed using the framework of the European standards (EN 1990 2002),

2. THE THEOREM OF BAYES APPLIED ON LOAD TESTS

Annex B of (CEN/TS 17440 2020) provides a conditional formula for updating the failure probability after obtaining data through inspection, according to the conditional probability, see Eq.(3).

$$P(F|I) = \frac{P(F \cap I)}{P(I)} \quad (3)$$

F denotes a local or global structural failure and I is the inspection data. P(I) is the probability of obtaining certain inspection data. $P(F \cap I)$ is the intersection between the failure probability and P(I). The probability of failure given the inspection data P(F|I) is equal to 1-P(S|I), the probability of survival given the inspection data.

The theorem of Bayes is a derivative of the conditional formula, describing the probability of an event A given an event B, see Eq.(4).

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \quad (4)$$

P(A|B) is called the posterior probability. P(B|A) is the probability of event B when A is given or the likelihood of A given a fixed B. P(A) is the

prior knowledge based on a substantiated estimate. The Bayes Theorem knows many application among which Engineering (Feng et al. 2022). The latter work applies the Bayes Theorem to the failure probability of engineering structures. The paper is an elaborate and generalized application of the theory, where this contribution aims to provide a more practical approach.
The goal is to predict the reliability of a structure when performing a load test for both SLS and ULS test load levels. In first instance, this might seem straightforward: P(A) is the probability of an appropriate structural safety level of the structure and P(B|A) is the likelihood of structural safety compliance of the structure given a successful load test. However, multiple difficulties arise in the form of unwanted dependencies, an excess of unknowns and difficulties in defining the probabilities.

When the target reliability is reached, the structure is assumed to be safe, referred to as healthy. Any probability function that does not reach this reliability target is therefore deemed unsafe or unhealthy. The indications healthy and unhealthy are applied since the unsafe structure can become redefined as safe after succeeding a load test.

To clarify following formulas, Table 1 explains the abbreviations that will be used.

Table 1: Abbreviations

Abb.	Explanation
P(A)	Probability of A
A^c	Complementary probability of A $P(A^c) = 1\text{-}P(A)$
FT	Failure at test load
ST	Survival at test load
FS	Failure of the structure - deteriorated structure not reaching the target reliability
SS	Safety of the structure – healthy structure reaching the target reliability

The posterior probability is P(SS|ST), the probability of a reliable structure given a successful load test. The desired outcome is the failure probability of the structure after a successful load test P(FS|ST), which can be directly derived through 1-P(SS|ST).
The numerator of the Bayes formula contains P(ST|SS), the probability of a succeeding load test given a healthy structure, and P(SS), the prior knowledge.
Defining the denominator, two options are possible. The first option uses the probabilities, see Eq.(5). The second option looks into the likelihood instead of the probability, resulting in an integral, see Eq.(6).

$$P(ST) = P(ST|SS) \cdot P(SS) + P(ST|FS) \cdot P(FS) \tag{5}$$

$$P(ST) = \int p(ST|SS) \times p(SS) \times dSS \tag{6}$$

The first option, Eq.(5), is used to define P(ST). Herein is P(ST|FS) the probability of a successful load test given an unhealthy structure. P(FS) is then the probability of failure equal to 1 - P(SS). The final composition of the formula is shown in Eq.(7). The probabilities will be defined in Section 3.

$$P(SS|ST) = \frac{P(ST|SS) \cdot P(SS)}{P(ST|SS) \cdot P(SS) + P(ST|FS) \cdot P(FS)} \tag{7}$$

3. APPLICATION EXAMPLE

The concept is summarised in Eq.(7), though the probabilities need to be defined. The difficulty herein lies in the lack of knowledge about the unsafe or unhealthy structure. This results in the inability to define the probability of surviving a load test given an unhealthy structure P(ST|FS) Therefore, it is necessary to model hidden defects, typically present in existing structures, in order to characterise the unhealthy structure. This is where this contribution deviates from generalisation and needs to consider a specific case with known parameters. The resulting probabilities will therefore only apply in this case. However, this case can provide insight into the impact of the load level of a load test. The load test is assumed to be executed on a RC floor slab with a thickness of 200 mm, reinforcement Ø12 every 150 mm or 754 mm²/m and concrete strength class C30/37. It is a simply supported one-way bearing slab with span length 5,4m.

A Monte Carlo simulation is performed using 15 000 samples to obtain a probability distribution of the slabs' bearing capacity. The bending theory with a rectangular stress-strain relation is used since this represents the failure mechanism. Shear failure is shown to be not critical. Table 2 shows the parameters, their probability features and the source of these data. To simplify, only permanent loads are presumed to act on the slab. Therefore, all parameters have normal probability density functions except for the lognormal probability of the yield strength of reinforcement and the compressive strength of concrete. The CoV of permanent loads is taken 0,10 as can be found in (Ellingwood 2000). The source FORM of the diameter stands for the first order derivation of this CoV from the section A_s. The mean standardized values of each parameter are set to one. The execution of the Monte Carlo simulation will multiply the random value within this probability distribution with the realistic mean value of the parameter.

Table 2: Characteristics of the parameters of a new RC building - (Ellingwood 2000*; EN 13670 2010; JCSS Part 2 2001; JCSS Part 3 2000)

	unit	value	μ	CoV	source
Load	kN/m²	10	1	0,100	*
Length	m	5,4	1	0,004	EN 13670
Height	mm	200	1	0,015	JCSS
Width	mm	1000	1	0,010	JCSS
Cover	mm	30	1	0,167	JCSS
Ø	mm	12	1	0,083	Taylor
A_s	mm²	754	1	0,020	JCSS
f_y	N/mm²	560	1	0,060	JCSS
f_c	N/mm²	38	1	0,060	JCSS

A distinction is made between the healthy and unhealthy existing structure by adjusting the yield strength of steel and the compressive strength of concrete according to (Croce et al. 2020). Assuming concrete material class 3 (31,8 N/mm² mean compressive strength), the coefficient of variation (CoV) is equal to 13%. For the reinforcement, the current yield strength is adopted, but with an increase in CoV to 13% that matches the class 3 reinforcement as proposed by (Croce et al. 2020). Taking into account the degradation of the structure, the section of the reinforcement is reduced by 3% as suggested for a 70 year old building with a low degradation rate. This reduction in section is applied to the mean value, adjusting 1 to 0,97. Table 3 shows the adapted parameters for the existing (unhealthy) structure.

Table 3: Characteristics of the parameters of an existing RC building - (Croce et al. 2020)*

	unit	value	μ	CoV	source
A_s	mm²	754	0,97	0,020	JCSS *
f_y	N/mm²	560	1	0,130	*
f_c	N/mm²	31,8	1	0,130	*

Although the concrete strength generally increases over time, the reduced value used here assumes damage (cracks) due to degradation.

The bearing capacity of the slab is approached by a normal probability density function to calculate the standard deviation resulting from the Monte Carlo simulation. The validity of this approach is checked in Figure 2. In this figure, the Monte Carlo simulations for the new (blue) and the old (orange) slab are shown indicated by the graphs with markers. These graphs are then compared to the normal probability density function based on the calculated standard deviation indicated without markers. Though the right tail of the graph is somewhat longer, the normal distribution seems to approach the results quite well. Only a slight shift of graphs can be detected due to the application of range sets of 0,5 for the Monte Carlo simulation results.

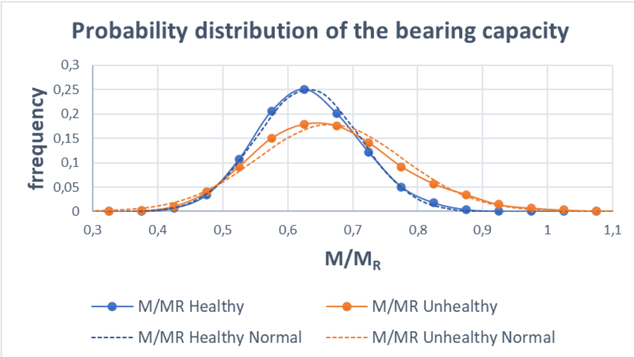

Figure 2: Validation of the normal distribution for the bearing capacity of the slab - SLS

4. NUMERICAL RESULTS

In practice, the partial safety factor method is used to obtain an adequate structural reliability. (EN 1990 2002) provides the background of these safety factors by defining a reliability index β depending on the reliability class (RC). This paper will assume RC2 for which β is equal to 3,8 for a reference period of 50 years. This value of β corresponds with a failure probability P(FS) of 7,32 x 10^{-5},

The safety factor is equal to 1,35 for permanent loads, since no live loads are considered. The load test in ULS is simulated by multiplying the mean value of the load with 1,35. This results in shifting the probability density function. The permanent load itself is equal to 10 kN/m² (5kN/m² self-weight of the slab).

In practice, the structure would be calculated in a simplified manner using the known values of the healthy structure. This results in a limited shortage of reinforcement. The required reinforcement is 772 mm²/m, while 754 mm²/m is provided in the existing RC slab. This could be an argument for performing a load test. The Monte Carlo simulations provide failure probabilities under certain load levels, which can be interpreted as failure probabilities of the load test. These are summarised in Table 4 for SLS and ULS load levels, where P(FT|SS) stands for the failure probability of the load test given the healthy structure and P(FT|FS) for the unhealthy structure. In the Eqs. (8) and (9), the probability of survival of the test is necessary, which is the compliment of the failure given by column 1-Pf.

Table 4: Summarised reliability index for span 5,4m

Situation	Pf	1-Pf	β
$P(FT\|SS)_{SLS}$	$1{,}30 \times 10^{-6}$	1,000	4,70
$P(FT\|SS)_{ULS}$	$5{,}48 \times 10^{-2}$	0,945	1,60
$P(FT\|FS)_{SLS}$	$1{,}26 \times 10^{-3}$	0,999	3,02
$P(FT\|FS)_{ULS}$	$2{,}23 \times 10^{-1}$	0,773	0,75

P(FS) is the failure probability of the unhealthy structure, which is assumed equal to the Monte Carlo simulation with the mean value of the load. Eqs. (8) and (9) show how the values from Table 4 are implemented in the formula.

$$P(SS|ST)_{SLS} = \frac{1{,}000 \cdot (1 - 1{,}26 \times 10^{-3})}{1{,}000 \cdot (1 - 1{,}26 \times 10^{-3}) + 0{,}999 \cdot 1{,}26 \times 10^{-3}} \quad (8)$$

$$P(SS|ST)_{ULS} = \frac{0{,}945 \cdot (1 - 1{,}26 \times 10^{-3})}{0{,}945 \cdot (1 - 1{,}26 \times 10^{-3}) + 0{,}773 \cdot 1{,}26 \times 10^{-3}} \quad (9)$$

The posterior probability P(SS|ST) results in 0,9987 for SLS and 0,9900 for ULS. The result of the Bayes theory P(SS|ST) is the complement of P(FS|ST), which is the value of interest. Therefore, P(FS|ST) is equal to 1-P(SS|ST) or 0,0013 for SLS and 0,0010 for ULS. The corresponding reliability indexes for test load magnitude TLM SLS and TLM ULS are of respectively 3,02 and 3,08. The outcome is very dependent on the estimated failure probability P(FS).

To compare, a second case is examined with similar properties however a larger span of 5,7m. This span is chosen so the reliability index of the healthy structure approaches 3,8. Table 5 shows the results of the Monte Carlo simulation.

Table 5: Summarised reliability index for different span 5,7m

Situation	Pf	1-Pf	β
$P(FT\|SS)_{SLS}$	$5{,}91 \times 10^{-5}$	1,000	3,85
$P(FT\|SS)_{ULS}$	$3{,}09 \times 10^{-1}$	0,691	0,50
$P(FT\|FS)_{SLS}$	$1{,}79 \times 10^{-2}$	0,982	2,10
$P(FT\|FS)_{ULS}$	$5{,}04 \times 10^{-1}$	0,496	-0,01

The probabilities are implemented similarly to previous Eqs.(8) and (9). The reliability index after performing a load test is equal to 2,11 for SLS and 2,23 for ULS. The impact of the load test on the reliability of the structure seems to increase when the reliability of the structure itself decreases.

It should be noted that common practise in load tests is the monitoring of the deformations. The results of this monitoring procedure need to comply with the acceptance criteria and limit values. By measuring the deformations during the test, the behaviour of the slab can be examined for different load levels and compared to the calculation models. Excessive deformations can be a reason to stop the test. These can be compared to the expectation and thereby detecting any anomalies beforehand.

5. DISCUSSION OF THE RESULTS

The reliability index is recalculated for an existing structure after the load tests. (EN 1990 2002) suggests target β values for SLS and ULS respectively 1,5 and 3,8. (ISO 13822 2010) allows for a reduction of β from 3,8 to 3,3 in case of existing buildings. The reliability of the first considered existing structure is 3,02, which is insufficient. After performing a load test with the design load, the index increases to 3,08. The second case results in 2,11 for SLS and 2,23 for ULS.

The influence of the test load suggests that the ratio load effect to resistance is significantly affected by the load. This can be examined through a First Order Reliability Method (FORM) by calculating the ratio of the CoV of the parameter to the total CoV of the structure (M/M_R). For the new structure, the load is responsible for 69% of the CoV of the structure. The second important parameter is the yield strength of steel which contributes only 16%. The balance is different for the existing structures due to higher CoV for steel and concrete strength. The load and the yield strength of steel each contribute 45%.

6. CONCLUSIONS

This paper aims to formulate the reliability of an existing structure after surviving a load test, where two load levels are compared: SLS and ULS. The main difficulties lie in defining the probabilities of various situations. Current perspective leads to no increase in the reliability index for TLM SLS and only a limited increase for TLM ULS.

These results are only valid for the bending theory. Other structural mechanisms like shear failure, compression membrane action or tensile membrane action will need to be defined as well in further research.

A theoretical example is elaborated to answer the problem statement, assuming the execution of the test itself does not fail. This approach shows the benefit of a testing till ULS, where testing to SLS does not make a significant difference.

The contribution of this paper is not to provide an all-in answer. The conclusions are solely based on the considered examples, with the bending theory as failure mechanism. However, a practical framework is proposed out of which a certain mindset and perspective on the necessary load level emerges. The focus is testing the characteristics of the slab rather than its structural behaviour.

Further research will include the influence of measuring deformations during the test to shift the focus to the structural behaviour.

7. ACKNOWLEDGEMENTS

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