Structure and Infrastructure Engineering
Maintenance, Management, Life-Cycle Design and Performance

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/nsie20

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To cite this article: Numa J. Bertola & Eugen Brühwiler (2021): Risk-based methodology to assess bridge condition based on visual inspection, Structure and Infrastructure Engineering, DOI: 10.1080/15732479.2021.1959621

To link to this article: https://doi.org/10.1080/15732479.2021.1959621

Published online: 03 Aug 2021.

STRUCTURE AND INFRASTRUCTURE ENGINEERING
https://doi.org/10.1080/15732479.2021.1959621

Risk-based methodology to assess bridge condition based on visual inspection

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ABSTRACT

The visual inspection of existing infrastructure is a critical step for asset management, as the detection and quantification of damage must be useful to prioritise maintenance. In Switzerland, main inspections are made every five years for all road bridges. For each bridge, a condition value ranging from 1 to 5 is given. As only element-based degradations are currently taken into account in bridge-condition evaluations, inaccurate assessments of global structural safety are often provided by bridge inspectors. In this paper, a risk-based methodology is introduced to evaluate bridge conditions based on visual-inspection data. Degradation states of bridge elements are coupled with element-failure consequences on the global structural safety in risk analysis to accurately assess the bridge condition. A case study of a strategic road involving sixty bridges is used to assess bridge-condition evaluations using the risk-based methodology based on recent visual inspections. The study reveals that including element-failure consequences in bridge-condition assessments supports more accurate evaluations of the impacts of damage on the global structural safety, leading to more objective decisions on asset management actions. Analyses of four damaged bridges show that inspection reports are often over-pessimistic in terms of structural damage, and this can lead to unnecessary rehabilitation interventions.

ARTICLE HISTORY
Received 25 February 2021
Revised 20 April 2021
Accepted 25 May 2021

KEYWORDS
Bridges; condition evaluations; visual inspection; infrastructure management; concrete structures; risk assessment; damage detection

1. Introduction

The management of existing civil infrastructure is challenging because of evolving functional requirements, insufficient durability of reinforced concrete and steel, availability of novel in-situ testing methods, and modification of standards. To select optimal maintenance strategies, the infrastructure network is typically managed using a bridge management system (BMS), where bridge conditions are often evaluated based on visual inspection in order to define the optimal maintenance strategy that minimises the cost of interventions over time (Mirzaei & Adey, 2015).

The information collected during the visual inspection is critical as it allows to update the current degradation states of elements in the BMS (Hearn & Program, 2007). This information is typically collected every five years by engineers of or mandated by road agencies. Several limitations of these inspections exist (Agdas, Rice, Martinez, & Lasa, 2016). First, inspections are typically made every five years, meaning that important degradations, such as rebar corrosion of severely exposed reinforced-concrete (RC) elements, may happen between them. Then, these inspections are subjective. An experiment where thirty inspectors were asked to detect cracks on bridge steel members shows a large variability between inspector performance (Campbell, Connor, Whitehead, & Washer, 2020). Eventually, some structural elements may not be accessible and thus cannot be inspected such as prestressed tendons in concrete.

Studies have shown the potential of drones for visual inspection (Seo, Duque, & Wacker, 2018) or artificial neuron networks to detect and quantify damage such as concrete cracks and steel corrosion (Cha, Choi, Suh, Mahmoudkhani, & Büyüköztürk, 2018). However, these new technologies are currently expensive compared to human visual inspection and are still experimental to be implemented by road agencies. Research interests have focused on the deployment of structural-health monitoring systems, where the structural behaviour, as well as the environmental conditions, are monitored using sensors (Catbas, Susoy, & Frangopol, 2008; Cross, Koo, Brownjohn, & Worden, 2013). Typically, damage-detection techniques involve measuring the variations in time of structural dynamic properties (Farrar & Worden, 2010) and are coupled with reliability analysis to evaluate structural performance (Frangopol, Strauss, & Kim, 2008; Loraux & Brühwiler, 2016). Recently, the cost of sensor technologies has been significantly reduced. Consequently, a significant amount of sensors have been installed on bridges (Cunha, Caetano, & Delgado, 2001; Runcie, Mustapha, & Rakotoarivelo, 2014). For example, up to 1500 sensors on the Stonecutters Bridge (Hong-Kong) (Wong, 2007), resulting in challenges in data interpretation and data storage (Brownjohn, De Stefano, Xu, Wenzel, & Aktan, 2011).

Once information is collected on-site either during the visual inspection or using sensor measurements, bridge-element conditions are usually assessed (Ellingwood, 2005).

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The structural reliability is typically expressed in probabilistic terms and is time-dependent (Wang, Li, & Ellingwood, 2016) due to material degradation processes, such as steel corrosion and disintegration of concrete due to alkali-aggregate reaction, freeze-thaw cycles, and other chemical/physical phenomena. Target reliability levels are varying between structural elements as the element failure mode and the importance of the individual member to overall system integrity differ (Ghosn, Frangopol, et al., 2016). When only qualitative information is provided, the element condition is usually assessed using a condition value that varies from 1 to 5 (Pellegrino, Pipinato, & Modena, 2011).

Based on element-condition assessments, the structural performance of the bridge is evaluated using system-level metrics such as the reduction of capacity due to degradations (Ghosn, Dueñas-Osorio, et al., 2016). However, estimations of global structural safety are difficult due to the uncertainty levels associated with material properties and structural-behaviour modelling (Smith, 2016). These estimations may thus require significant computational effort (Frangopol, 2011). Consequently, a strategy for optimal infrastructure management is developed at the network level based on structural-performance indicators, deterioration processes, and intervention costs (Sánchez-Silva, Frangopol, Padgett, & Soliman, 2016). A bridge management system is a software used by road agencies, such as PONTIS in USA (Thompson, Small, Johnson, & Marshall, 1998), that aims to minimise maintenance costs within structural-safety, social and environmental constraints (Lounis & McAllister, 2016). In order to minimise the intervention costs in the long term, deterioration processes must be predicted (Adey, Hajdin, & Brühwiler, 2003). One main limitation is that interventions are mostly driven based on durability issues on equipment components rather than global structural safety (Frangopol & Liu, 2007).

The Swiss national roads cover around 1850 km with more than 4500 bridges mostly built between 1960 and 1985. A bridge management system, called KUBA-BD (Hajdin, 2008, 2001) is used to optimise and predict maintenance costs of this infrastructure. This software accounts for visual inspection data to evaluate bridge-element conditions and uses Markov Chains to obtain condition forecasts. Then, maintenance and rehabilitation interventions are designed for each element using a cost-benefit analysis and project costs are evaluated as the sum of costs on the element level. KUBA-DB is updated using information collected during a visual inspection of bridges every five years. In these inspections, the deterioration of each observable bridge element is assessed using a 5-level condition value, from elements in good conditions (score of 1) to alarming states (score of 5) (Schellenberg, Vogel, Chèvre, & Alvarez, 2013).

To evaluate bridge conditions based on element-condition assessments, two methods are typically used in Switzerland. In each inspection report, results from these methods are presented on the front page. For each bridge, the first methodology assesses the bridge condition using the worst score of element condition values, while the second method is a global evaluation made during the inspection. In a recent report (in French) by the Federal Road Office (FEDRO), the average bridge condition is 1.9 with only 2% of bridges in bad or alarming states (Federal Road Office (FEDRO), 2018). In these methodologies, bridge conditions are assessed based on the degradation states of elements. However, the loss of load-bearing capacity of the bridge due to element degradations may differ significantly depending on the damaged elements. Structural elements, such as girders, piers and abutments, should be differentiated to equipment components (pavement, railings) that only affect operational safety in order to accurately evaluate the effect of element degradation on global structural safety.

This paper presents a methodology to evaluate bridge conditions that accounts for degradation states of elements and the element failure consequences on the global bridge safety, following a risk analysis. This risk-based methodology, designed based on the Swiss standards for existing structures (Brühwiler, Vogel, Lang, & Lüchinger, 2012; Swiss Society of Engineers & Architects, 2011) uses visual-inspection data from inspection reports to assess bridge-element conditions. The bridge condition is assessed based on element conditions but also using the element-failure consequences on the structural safety. This methodology is intended to remain simple and does not require advanced computational or statistical backgrounds in order to be easy-to-use for road agencies. A case study of a road in the Swiss Alps comprising 60 bridges, is used to compare bridge condition evaluations from this risk-based methodology with traditional methods currently used in Switzerland. Results show that the proposed risk-based methodology leads to more accurate evaluations of bridge conditions.

The paper is structured as follows. Section 2 introduces the current state-of-the-art of bridge condition assessments based on visual inspection in Switzerland. Then, the risk-based methodology is presented in Section 3, following four main steps, and applied to the population of 60 bridges in Section 4. Based, on a recent visual inspection, assessments of element degradation states are updated and detailed analyses of bridge conditions are presented for selected bridges. Finally, the results are discussed in Section 5.

2. Inspection of bridges in Switzerland

The inspection, usually made by engineers from governmental road agencies or private companies, is a key phase of infrastructure maintenance at the network level. The bridge-condition evaluation is a statement (at a specific point in time) of its durability, structural safety and serviceability. This information is then used to update a bridge management system, such as KUBA-DB in Switzerland, that aims to minimise intervention costs over time at the network level. An inspection involves the observation and assessment of the condition of a structure through simple and targeted auscultations (generally visual). The goals of a visual inspection are:

- Identify structures and their construction elements showing damage affecting durability.

- Reliable detection of structures with presumably insufficient safety. Structural and operational safety are often distinguished.
- Obtain objective information regarding the condition of the structure in order to recommend the appropriate intervention and its cost, as well as the procedure.

In Switzerland, three types of inspections are made on infrastructure (Swiss Society of Engineers & Architects, 1997). The main inspection covers all aspects of the structure and is made visually or using simple tools. As this inspection is typically performed every five years, one objective of the main inspection is thus to identify structural and equipment components that need an intermediate inspection. Intermediate inspections aim to monitor the condition evolution of specific structural elements and equipment components between main inspections, while specific inspections are only made when the infrastructure is subject to important affectation modifications or after extraordinary loading conditions.

During main inspections, inspectors are going on-site and observe all structural and equipment components that are accessible. Each bridge element is then rated using a condition value from 1 (good), 2 (acceptable), 3 (defective), 4 (bad) to 5 (alarming) condition. Then, two methodologies are used to evaluate the bridge condition based on element-condition assessments:

1. *Global inspection evaluation*: an overall grade is chosen by the engineer in charge of the inspection. Although it is a subjective decision made during inspection, this grade can be seen as an average of all element-condition assessments.
2. *Worst-element method*: the worst score of element-condition assessments provides the overall bridge-condition grade. This method leads to a conservative evaluation as structural and equipment components are not distinguished.

These two methodologies provide complementary information on the bridge condition (average and pessimistic evaluations). These two scores usually are presented on the first page of inspection reports, and maintenance decisions are made based on these evaluations. However, these two types of evaluation may lead to significantly different results, and this situation leads to ambiguous decisions on whether maintenance is required.

3. Risk-based methodology for bridge-condition evaluations

3.1. Overview

The risk-based methodology to evaluate bridge conditions is based on visual inspection. During this inspection, structural components are examined to assess their degradation states. Traditionally, the bridge condition is determined based on its element conditions only. The main goal of this methodology is to include both degradation states of structural components and the consequences of the element failure on global safety to accurately assess bridge conditions. Three risk classes are introduced that express element-failure consequences on global structural safety. This methodology is an extension of the bridge-condition method proposed to Swiss road agencies (Brühwiler, 2010).

Two main constraints have been taken into account in the development of the methodology. First, the method aims to be implemented by road agencies and thus should remain easy-to-use by structural engineers. As these engineers hold the responsibility of decisions, they do not want to have "Blackbox" approaches or that require knowledge beyond their statistical or computational backgrounds. Then, the methodology should be able to directly use inputs in inspection reports, such as grades of element conditions between A to E, in order to avoid the necessity to inspect again all structures. In this methodology, an explicit distinction is made between equipment components and structural elements. This distinction is made as damaged equipment is often planned and is thus handled by the maintenance personnel of the bridge authority, while interventions on structural elements are not planned and usually require contractors and imply relatively high cost.

Figure 1 presents the flowchart of the risk-based methodology to assess the bridge condition. This method is subdivided into four main steps that are developed in detail in Section 3.2. First, the bridge elements of a bridge are separated into three risk classes, depending on the consequences of the element failure on global structural safety. The first class involves equipment components that only affect the operationality of the structure such as the asphalt pavement or lighting, while the third class includes structural elements that are necessary for structural integrity such as main girders, piers, and abutments.

Then, an evaluation of the degradation states of these elements in five grades of qualification is introduced, similar to the assessment currently made in inspection reports in Switzerland. These grades go from A (elements in good conditions) to E (elements in alarming states). Next, a risk-analysis matrix is the key to evaluate the condition of each element based on its risk class and its degradation-state grade. In this risk analysis, an element condition value (from 1 to 5) is given, that considers both the observed degradation and potential consequences in case of element failure. In the last step, the bridge-condition evaluation is taken as the worst element condition value. By incorporating both consequences of failure and degradation-condition assessment, this bridge-condition evaluation aims to assess whether element degradations can affect global structural safety.

As this methodology aims to remain simple for practitioners and to be generally applicable for an entire bridge network, bridges with either specific designs leading to complex static behaviour or with a brittle failure mechanism may require additional investigation. For such structures, the coherence results in terms of bridge-condition scores and recommended intervention measures should be

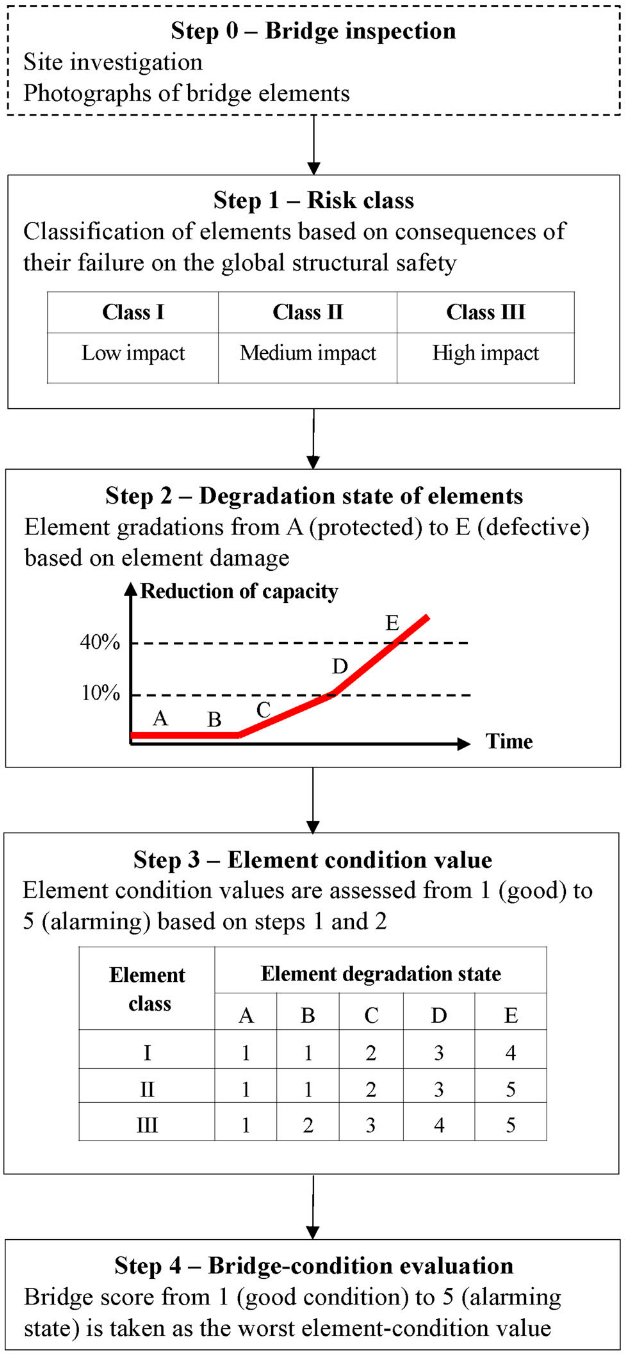

Figure 1. Flowchart of the risk-based methodology for bridge-condition evaluations.

evaluated by inspectors and bridge owners. A strong limitation of visual inspection is that some elements cannot be inspected directly such as prestress tendons in concrete structures. Although these elements may be crucial for the structural-safety assessment, they are not accounted for explicitly in the present methodology for bridge-condition evaluation based on visual inspection.

3.2. Four-step methodology

3.2.1. Step 1 – element risk class

A bridge is composed of several construction elements that deteriorate over time. These elements have different purposes on the bridge. Two types of construction elements can be distinguished according to the type of safety involved:

- The structural safety refers to structural elements. This type includes bridge elements that are related to the supporting structure.
- The operational safety is related to equipment components. This type includes bridge components that are often relevant to the security of users.

The failure of a construction element may have little to important consequences for the global safety of the structure. For instance, in a simple-beam bridge structure, the failure of one of the two prestressed girders will certainly lead to the collapse of the supporting structure, while the failure of one of the kerbs will have little consequences on global structural safety.

Elements are separated into three risk classes according to the magnitude of these element-failure consequences on global structural safety (Table 1). The first risk class involves equipment components and structural elements that have little consequences on global structural safety in case of failure such as the asphalt pavement. The second class includes remaining equipment components, such as kerbs or joints, and structural elements with moderate consequences on global safety such as secondary beams. Finally, the third risk class contains structural elements that have potential large failure consequences such as piers or girders. These risk classes are then included in the evaluation of element condition value in step 3 (Section 3.2.3). The statement on

Table 1. Risk class according to the consequences of an element failure on global structural safety.

Risk class	Consequences of element failure	Consequences for
I	Limited	Serviceability
II	Moderate	Serviceability or structural safety
III	Important	Structural safety

Table 2. Risk class associated with structural elements and equipment components.

Structural elements	
Element	Risk class
Principal elements (girders, arches)	III
Piers	III
Deck	III
Lower slabs (cantilever)	II
Transversal elements (secondary beams, bracings)	II
Abutments,	II
Kerbs	I
Equipment components	
Element	**Risk class**
Expansion joints	II
Bearings	II
Railings	II
Pavement	I
Accessories (lightings, drainage systems)	I

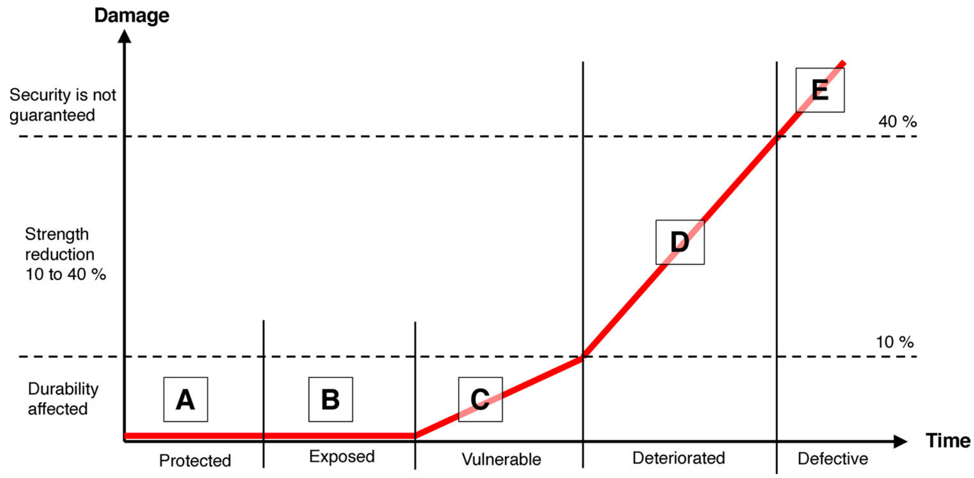

Figure 2. Degradation-state qualification of structural elements.

classification should be made by bridge owners based on available information on the structural system to avoid inconsistency in element qualification between similar bridges on the network. Bridge inspectors should nonetheless evaluate whether this classification is coherent with site observations.

Table 2 presents a non-exhaustive list of structural elements and equipment components associated with their risk class. This choice is made according to the consequences of element failure on global structural safety. Element risk classes shown in Table 2 are general recommendations and thus could be slightly modified from specific bridge cases.

3.2.2. Step 2– degradation state of elements

In the second step, the state of degradation of each bridge element is assessed. This assessment is based on main visual inspections. A novel approach is provided in this section to grade element conditions based on quantitative thresholds. This state qualification uses a 5-level gradation, similarly to the gradation in Swiss inspection reports. This assessment thus allows using information from inspection reports to re-evaluate bridge conditions at the network level. Therefore, the implementation of this risk-based methodology is possible without requiring new inputs of visual inspections. This qualification is divided into a five-level gradation (Figure 2). The element degradation is assessed based on the observed deterioration process. When an element is damaged, the reduction of its capacity should be evaluated by bridge inspectors.

To help inspectors in this evaluation, clear thresholds between degradation states are presented in Figure 2. The first state A consists of protected elements that are currently not subject to degradation. State B includes elements that are exposed to future degradation, while state C contains elements where degradation is initiated but the reduction of strength (or serviceability for equipment element) is lower than 10%. This 10-% limit between states C and D enables the discrimination of elements showing a little and a significant degradation. The 10-% threshold is related to safety factors in the Swiss Standard for existing structures (Swiss Society of Engineers & Architects, 2011, p. 269). The fourth

Table 3. Element condition value according to the element risk class and element degradation state.

Risk class	Element degradation state				
	A	B	C	D	E
I	1	1	2	3	4
II	1	1	2	3	5
III	1	2	3	4	5

state (D) includes elements that are significantly damaged, but this damage does reduce the strength (or serviceability) up to 40%. State E contains elements presenting damage reducing the element capacity beyond 40%. This 40-% threshold between state D and E distinguishes elements where structural safety is no longer covered by partial safety factors (on both the action and resistance side) and thus urgent safety interventions have to be implemented.

For example, when corrosion damage is observed in rebars of the bridge beam, the reduction of the rebar cross-section must be estimated precisely as possible by bridge inspectors. Then, the loss load-bearing capacity of the bridge beam should evaluate. This capacity reduction is then used to select the appropriate element degradation score. When important element damage is observed and the capacity-reduction evaluation is not trivial, inspectors should refer to the two reduction thresholds (10% and 40%) to qualify the element degradation state.

3.2.3. Step 3 – element condition value

In the third step, the current state of degradation of each element is assessed by combining the risk class (Step 1, Section 3.2.1) and the qualification of condition (Step 2, Section 3.2.2). This combination implicitly follows a risk analysis, where the risk is assessed using (Rausand, 2013):

$$Risk = Probability\ of\ failure * consequences \tag{1}$$

Following this risk analysis, a condition value between 1 and 5 is determined for each bridge element using Table 3. Element-condition values are scored from 1 (good condition) to 5 (alarming state). In this table, the element condition value increases when its degradation state is higher as its probability of failure increase. Similarly, the element

Table 4. Assessment of the bridge condition based on the risk-based methodology as well as recommended measures for each score.

Score	Bridge global condition	Damage affecting Durability	Serviceability	Safety	Recommended measures
1	Good	no	no	no	No action
2	Acceptable	yes	no	no	Preventive maintenance
3	Defective	yes	yes	no	Curative maintenance, rehabilitation
4	Bad	yes	yes	yes	Rehabilitation, additional safety measures
5	Alarming	yes	yes	yes	Rehabilitation, replacement, urgent safety measures

condition value is higher when the risk class is higher as the consequences of failures increase with the risk class. This assessment leads to a systematic evaluation of the risk on global structural safety due to the element degradation states. These element condition values are used in the next section to evaluate the overall bridge condition.

3.2.4. Step 4 – bridge-condition evaluation

In the final step, a score on the bridge condition is given based on element condition values. This score is taken as the highest element condition value. As condition values vary between 1 (good condition) and 5 (alarming state), the bridge condition also presents five scores that are shown in Table 4. This score goes from good condition (score of 1) to an alarming state (score of 5). Depending on this value, observed damage on bridge elements will have a different impact on the structural condition, such as durability, serviceability, or structural safety and user security issues. This four-step methodology allows the evaluation of bridge conditions following a risk analysis. Degradation states of bridge elements that have the largest impact on global structural safety have more influence on the bridge-condition assessment. This score provides a representative assessment of the bridge condition based on a qualitative estimation of the element-failure plausibility due to element degradations.

Interventions that are proportionate to the risk of structural collapse can be designed based on visual-inspection results. Recommended measures are related to the bridge-condition evaluation score in Table 4. These relations between bridge-condition score and intervention measures aim to provide guidelines for bridge management. When the bridge is in good condition (evaluation score equals 1) no specific actions are recommended. For any scores above 1, recommended measures are proportionate to the effects of observed damage on durability, serviceability, and structural safety. Bridges in acceptable and defective conditions (scores equal to 2 and 3 respectively) should be maintained to avoid the continuation of deterioration processes. When bridges are in bad conditions (scores equal to 4), structural rehabilitation measures should be taken as the structural safety is compromised. Urgent safety measures are also needed for bridges in alarming states (scores equals to 5) as reduction of element structural capacity may not be covered by safety factors.

By reducing the ambiguity of visual-inspection result interpretation, these relations support decision-makers in their choice of the appropriate interventions based on observed structural damage on infrastructure, leading to better infrastructure management. It is nonetheless important to mention that relations between bridge-condition score and intervention measures are general recommendations. Therefore, they must be adapted for some specific case studies. For example, bridges with a brittle failure mechanism may require additional safety measures when critical-element degradation is observed.

4. Case study

4.1. Presentation of the road

In this section, a case study of 60 bridges belonging to a pass road in the Swiss Alps is used as a case study. The daily traffic in 2019 was around 13,400 vehicles. 60 bridges are found on this 40 km-long road and their condition is assessed based on visual inspection. Most bridges are located at the beginning of the road at a low altitude (Figure 3a) as the road follows a river but roughly one-third of the structures are located above 1000 meters, meaning that they are subject to de-icing salt at a high frequency in winter. These structures have mostly been built in reinforced concrete between 1960 and 1990 (Figure 3b). These bridges have typical structural types such as simple or continuous beams (Figure 3c) with a length often below 50 meters (Figure 3d). These bridges are thus representative infrastructure of the Swiss network. They have thus been built decades ago and stand for important international traffic in a rough climate. For these reasons, structural degradations inherent to reinforced concrete structures, are likely to be observed. Bridges have been inspected throughout their lifespan and maintenance works have been conducted by the road agency.

Degradation states of structural components are first taken from inspection reports made between 2014 and 2020. Based on this data, fifteen bridges with a condition evaluation of 3 to 5 (defective to alarming states) are obtained. These sixty bridges have been inspected again by the authors in 2020. The aim is to evaluate whether element-condition assessments in inspection reports are accurate and up to date. In this paper, condition evaluations of four bridges are presented in Section 4.2. These four bridges have been selected as they are assessed in poor or alarming states (scores of 4 and 5) and they may present significant loss of load-bearing capacity due to element damage. Therefore, these four structures could require urgent interventions, such as traffic limitations or reinforcement. Results of the entire bridge set are summarized in Section 4.3.

4.2. Investigation of the four most damaged bridges

In this Section, the four most-damaged bridges are investigated. Based on inspection reports, these bridges have a

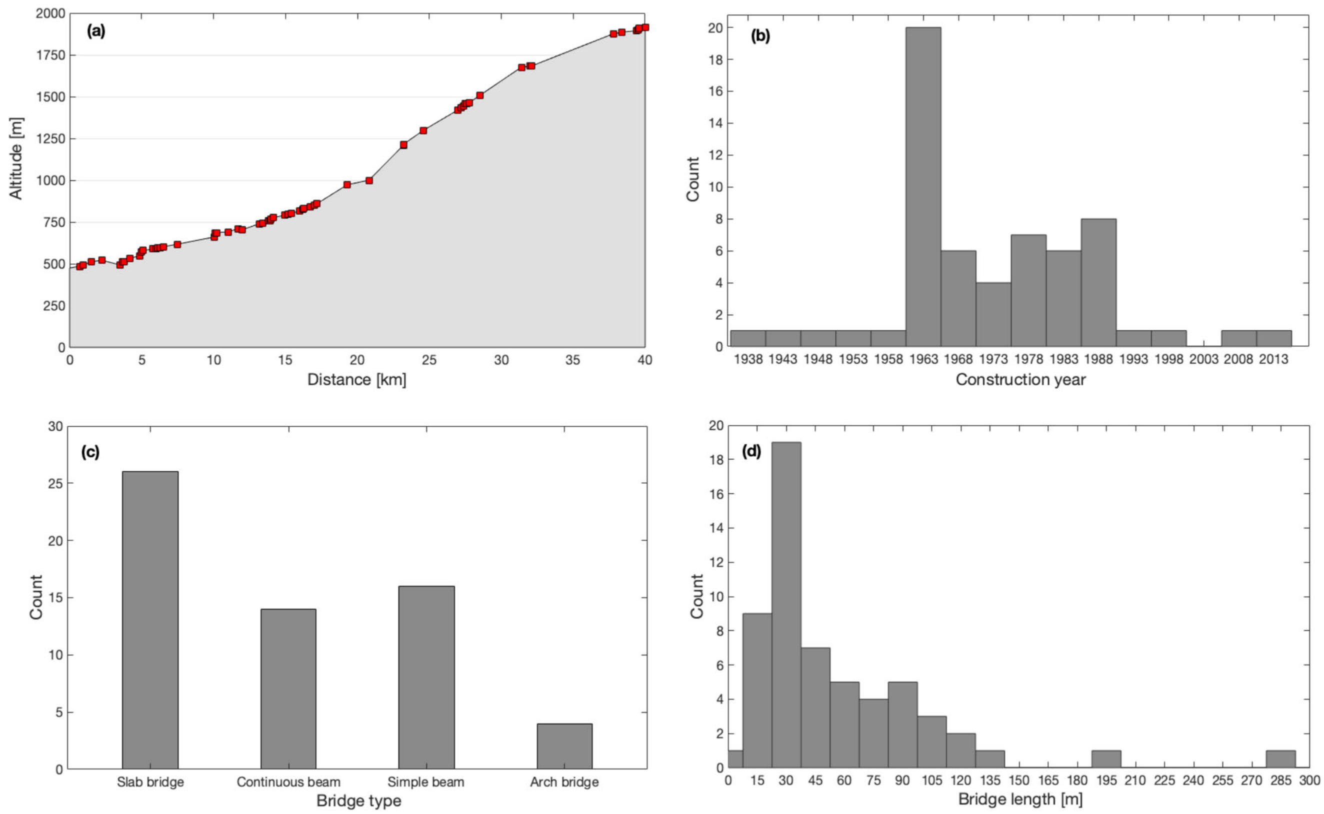

Figure 3. Bridge characteristics. (a) location; (b) year of construction; (c) type of structure; (d) bridge length.

condition evaluation equals to 4 and 5 respectively (Table 5), meaning that important degradations of structural elements have been observed. These bridges have been built between 1963 and 1976 using mostly reinforced concrete. They present typical spans between 10 and 18 meters. These structures are thus representative of damaged concrete bridges in Switzerland. The recent visual inspection of each bridge is presented below. The new inspection aims to evaluate the bridge condition following the risk-based methodology.

4.2.1. Bridge I

The initial bridge-condition evaluation in the inspection report has assessed Bridge I in an alarming state (score of 5) due to important degradations observed on the abutment (Figure 4). An important vertical crack is observed from the foot to the head of the abutment. Looking at the static system, it can be seen that only a small part of the vertical load is taken up by this abutment. The rating of the abutment, initially at E (alarming state) is therefore updated to C (defective state) as the element failure due to cracks observed could not lead to the collapse of the entire abutment as other parts of this element do not exhibit deterioration. Additionally, an analysis of the cross-section of the abutment shows that, even in case of failure, two of the three supports would still be standing. This result shows that the consequences of a failure of the abutment due to scouring – that represents the worst-case scenario – would have little impact on the structural safety because the vertical load could be taken up by the other two supports. The risk class II is thus justified for this structural element.

It is highly recommended to install crack gauges to monitor its evolution in order to avoid an element failure. This qualitative monitoring system has been implemented since 1975 by the road agency. This monitoring has revealed that the cracks have not significantly propagated since 1975, showing that the damage situation is stable. Based on this information, the element degradation C (Figure 2) is thus a more accurate assessment of the element condition. Table 6 presents the element-condition evaluations for Bridge I. Risk classes have been attributed following recommendations in Table 2. Element degradation states were evaluated during the recent visual inspection.

Thanks to this new inspection, the bridge-condition evaluation is updated from 5 to 3 (defective state) compared with the initial evaluation based on the inspection report. As the abutment is showing a defective instead of an alarming state, this new inspection leads to a more accurate evaluation of the bridge condition as the observed damage does not affect the global safety of the structure. This result shows that inspection reports are sometimes pessimistic concerning element-condition assessments that may lead to inaccurate bridge evaluation.

4.2.2. Bridge II

In this section, the assessment of the condition of Bridge II is re-evaluated using the recent visual inspection. Based on the inspection report, the initial bridge-condition evaluation shows Bridge II in bad condition (score of 4) due to

Table 5. Characteristics of the four selected bridges.

Bridge	Initial bridge condition	Year of construction	Bridge type	**Construction material**	Bridge length	Number of spans
Bridge I	5	1976	Cont. beam	Concrete	58	3
Bridge II	4	1966	Arch	Masonry /Concrete	26	3
Bridge III	5	1966	Slab bridge	Concrete	90	10
Bridge IV	5	1963	Slab bridge	Concrete	49	5

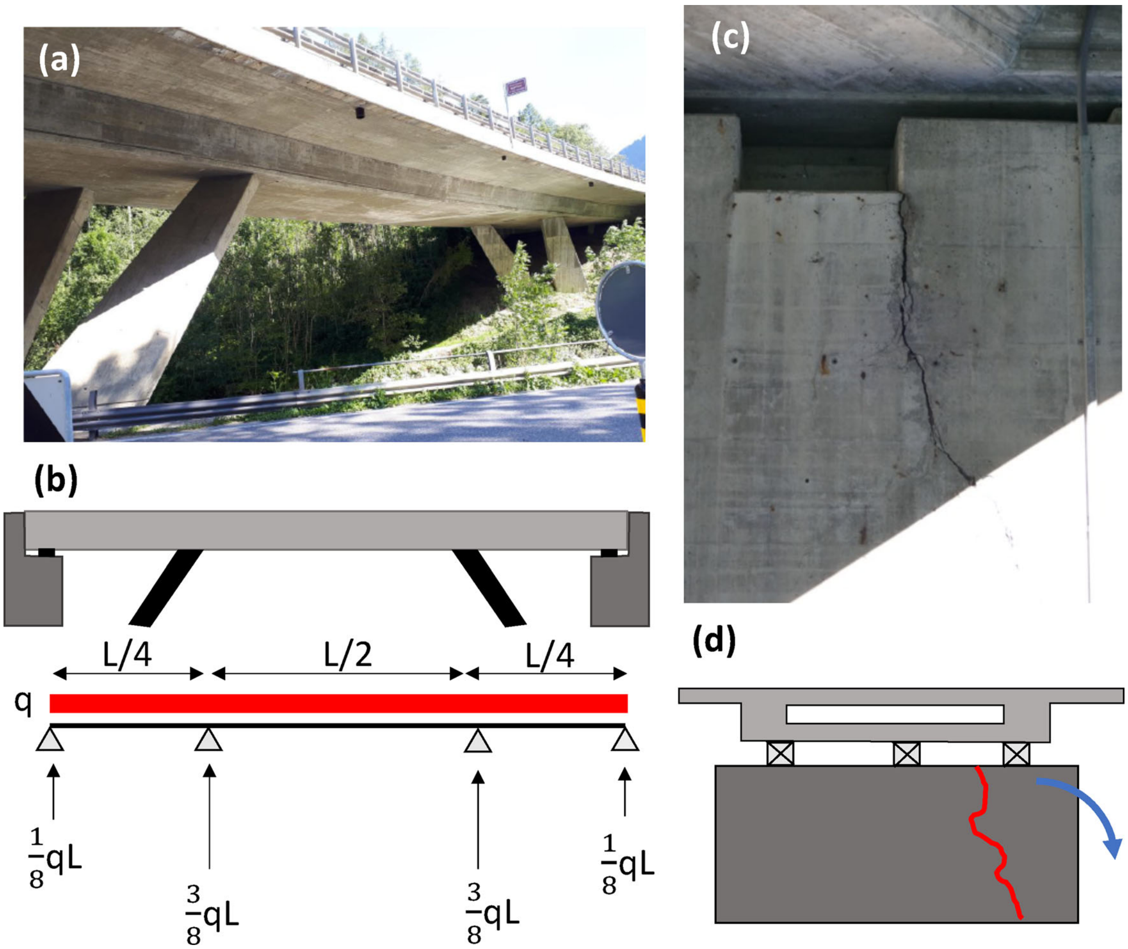

Figure 4. Presentation of Bridge I and detected damage. (a) Photograph of the bridge; (b) Static system; (c) Photograph of the crack at the abutment; (d) Scheme of the potential long-term damage due to the crack.

Table 6. Element condition evaluation – Bridge I.

Element	Risk class	Element degradation state	Element condition evaluation
Abutment 1	II	C	2
Lower Slab	III	B	2
Kerb 1	I	C	2
Kerb 2	I	C	2
Crutches	III	B	2
Wingwall 1	II	D	3
Wingwall 2	II	C	2
Pavement	I	C	2
Joints	II	B	1
Railings 1	II	B	1
Railings 2	II	B	1

important degradations observed on the lower slab. Results of the new inspection are presented in Figure 5. The kerb and the lower slab are significantly damaged (degradation states between D and E). The damage qualification is thus assessed following Figure 2. The damage to the kerb (Figure 5b) is concentrated beyond the railings and does not present any short-term risk to structural safety. However, significant corrosion of the reinforcement is found on the lower slab (Figure 5c and d). A substantial loss of section (estimated at 20% during the recent inspection) is observed for the rebars next to the masonry arch. This degradation may induce a loss of bearing capacity of the concrete slab of the bridge. As this damage certainly reduces the load-bearing capacity of the slab between 10 and 40% (Figure 2), the condition value of the slab of 4 for this structure is therefore validated by the new visual inspection.

Due to the lower slab condition value, the bridge-condition evaluation is thus kept at 4 (Table 7). Bridge II presents significant degradation on the lower slab that could affect its security and interventions are needed. Following recommendations presents in Table 4, asset managers should rehabilitate the lower slab. This bridge is currently rehabilitated by the road agency in order to restore the structural resistance of the lower

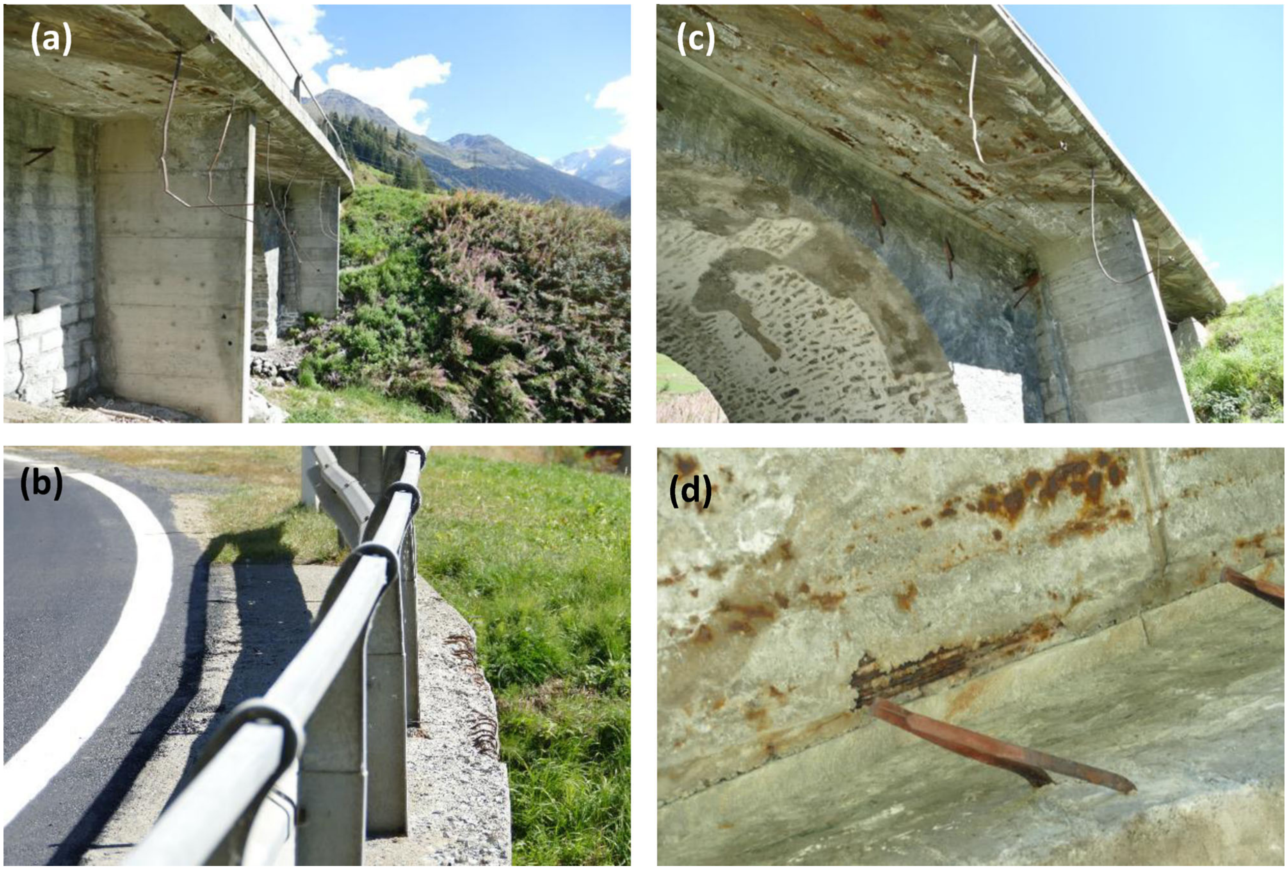

Figure 5. Presentation of Bridge II and detected damage. (a) Photograph of the bridge; (b) Photograph of the bridge of the concrete slab and the masonry arch; (c) Damage on the kerb; (d) zoom on the damage on the slab next to the masonry arch.

Table 7. Element condition evaluation – Bridge II.

Element	Risk class	Element degradation state	Element condition evaluation
Abutment	II	D	3
Arch	III	A	1
Lowe slab	III	D	4
Curb	I	D	3
Pier I	III	C	3
Pier II	III	B	2
Pavement	I	B	1
Railings	II	C	2

slab. Crutches, between the reinforced concrete piers and the lower slab, will be added to compensate for this potential loss of bearing capacity. Thanks to this intervention, the load-bearing capacity of the structure will be increased, and degradation of the lower slab compensated. An intervention on the upper slab and the kerbs are nevertheless still recommended to stop rebar corrosion.

4.2.3. Bridge III

In this section, a new visual inspection is made on Bridge III to evaluate the bridge condition following the risk-based methodology. Based on the inspection report, the bridge-condition evaluation of Bridge III is in an alarming state (score of 5) as one pier and the lower slab (risk class III) have element condition values of 5. Important degradations have been observed on the slab, the last pier I, and the kerb (Figure 6). The kerb shows significant damage that justifies its degradation state of E. Nevertheless, this damage does not affect the structural safety of the structure as degradation is located beyond the railings, meaning that the kerb has a risk class of I. The damage observed on the slab is concentrated in the area below the railings and thus not above the roadway. As this damage does not affect the structural safety of the bridge, the degradation state of the lower slab is updated to D (reduction between 10 and 40% of the structural capacity). This update leads to a new element-condition value of 4 for the lower slab.

Pier I shown in Figure 6c (last pier in Figures 6a and 6c) shows important damage, and its condition is in an alarming state. However, this pier only supports the kerb. Its failure would therefore not affect global structural safety. The risk class associated with this structural component is thus I, resulting in an element condition value equal to 3. The risk class of Pier I is updated due to the bridge characteristic and element condition states are taken from the recent visual inspection. As the worst element condition value is equal to 4 (lower slab), the condition evaluation of bridge III is corrected to a score of 4 (Table 8). Significant damage has been observed that requires rapid interventions. Nevertheless, there is no loss of load-bearing capacity of the structure and no urgent safety measures are needed (Table 4). This example demonstrates the effectiveness of the risk-based methodology to evaluate bridge conditions, based on the failure plausibility (element degradations) and consequences of failure (risk class).

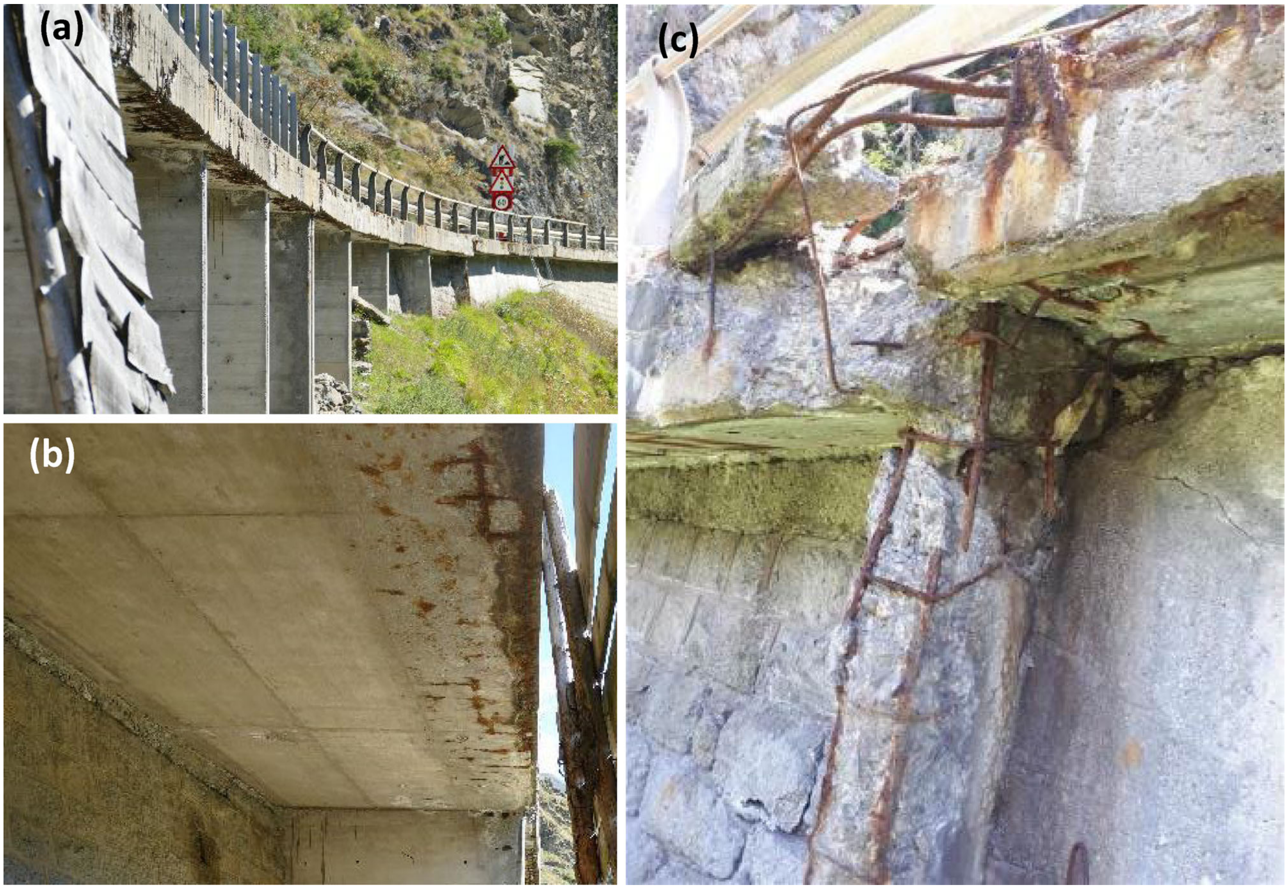

Figure 6. Presentation of Bridge III and observed damage. (a) Presentation of the bridge; (b) Damage on the slab and kerb; (c) Damage on Pier I.

Table 8. Element condition evaluation – Bridge III.

Element	Risk class	Element degradation state	Element condition evaluation
Kerb	I	E	4
Lower slab	III	D	4
Pier A	III	B	2
Pier B	III	C	3
Pier C	III	B	2
Pier D	III	B	2
Pier E	III	C	3
Pier F	III	C	3
Pier G	III	C	3
Pier H	III	C	3
Pier I	I	E	4
Abutment	II	D	3
Wall	III	B	2
Pavement	I	C	2
Joints	II	C	2
Railings	II	C	2

4.2.4. Bridge IV

In this section, the results of a new visual inspection on Bridge IV are presented. The initial bridge-condition evaluation shows a bridge in an alarming state (score of 5) due to important degradations observed on the lower slab. Damaged elements are the kerb and the lower slab (Figure 7), similar to Bridge II (Section 4.2.3). Although the kerb is significantly damaged, this does not affect the structural safety as this damage is concentrated below the railings, justifying the risk class of I for this element. Important corrosion of the reinforcement (visible bars) of the lower slab is observed but this degradation is located only close to the kerb. Figure 7c shows that there is no evidence of corrosion at the roadway. The degradation state of the kerb is thus set to D, as the reduction of structural capacity is below 40%. Therefore, the element condition value of the lower slab is updated from 5 to 4 as its structural capacity is certainly reduced between 10 and 40% (Figure 2).

As the lower slab (condition value is updated to 4), the bridge-condition evaluation is thus corrected to a score of 4 (Table 9). The bridge is thus in bad condition. Damage is currently affecting the durability of the structure and requires rapid intervention, but the load-bearing capacity of the structure is not reduced. Figure 7c shows that urgent interventions have been made by the road agency. Wooden auxiliary supports have been mounted to secure the slab below the roadway. These interventions have certainly been made due to the pessimistic bridge condition evaluations in inspection reports (alarming state). However, an accurate evaluation of the risk-based methodology shows that the bridge is in a bad state rather than in an alarming state, meaning that urgent safety measure is not necessary (Table 4). This example highlights that an inaccurate bridge-condition assessment may lead to unnecessary interventions on bridges.

4.2.5. Summary

In this section, the results of the recent inspection on the four most-damaged bridges are summarised. These results

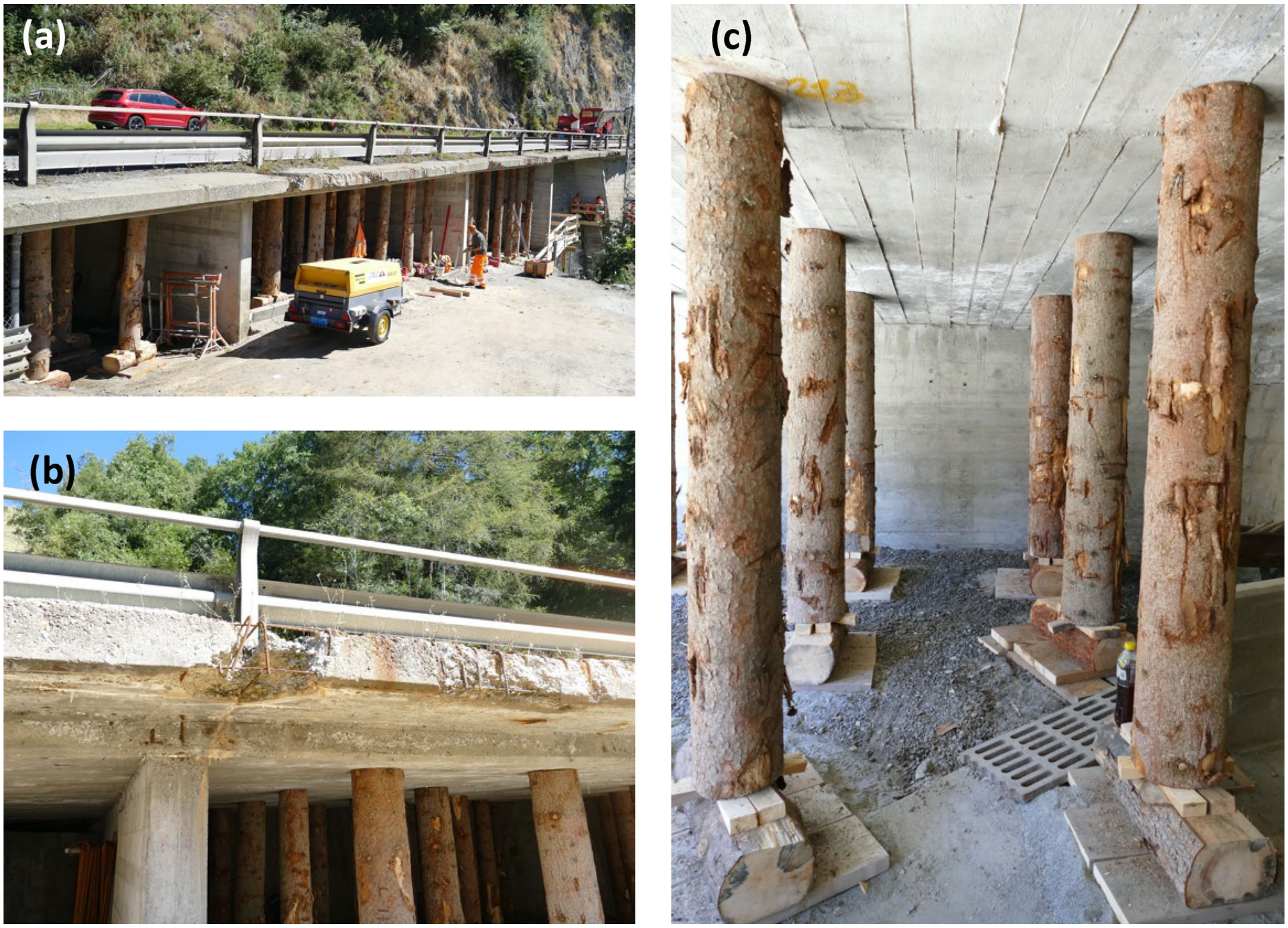

Figure 7. Presentation of Bridge IV and observed damage. (a) Photograph of the bridge; (b) Damage on the kerb; (c) Damage on the slab below the roadway and urgent intervention performed.

Table 9. Element condition evaluation – Bridge IV.

Element	Risk class	Element degradation state	Element condition evaluation
Abutment	II	C	2
Lowe slab	III	D	4
Kerb	I	E	4
Pavement	I	B	1
Pier 1	III	B	2
Pier 2	III	B	2
Pier 3	III	B	2
Pier 4	III	B	2
Railings	II	C	2
Supports	II	D	3
Joints	II	C	2

Table 10. Comparison of the condition evaluation of the four most-damage bridges. Score from 1 (good condition) to 5 (alarming state).

Bridge	Initial evaluation based on inspection reports	New evaluation using a recent inspection
Bridge I	5	3
Bridge II	4	4
Bridge III	5	4
Bridge IV	5	4

are compared with the initial evaluation of their condition based on inspection reports in Table 10. In both cases, bridge-condition evaluations are made using the risk-based methodology, but they differ on either the risk-class estimations of elements or the degradations states of structural elements. The main difference between the new visual inspection and inspection report lies in the approach to qualifying degradation states. In the recent inspection, clear thresholds, presented in Figure 2, are used, while these qualifications were subjectively made in inspection reports. New inspections and bridge-condition evaluations show that no bridge is in an alarming state. There is no need of urgent safety measures. However, these bridges are significantly damaged, especially kerbs and slabs, and important rehabilitation needs to be conducted in the coming years.

4.3. Bridge-condition evaluations

Assessment of degradation states based on inspection reports and the recent inspection are respectively used to quantify element conditions and then bridge condition values (Figure 8). In this figure, the results of the sixty bridges data set are presented. The worst-element method, used traditionally to assess bridge conditions in Switzerland (Section 2), is also presented as a benchmark. Recent inspection has led to significant changes in bridge evaluations as no bridge is in an alarming state (score of 5), while both the worst-element method and the initial bridge evaluations based on inspection reports have suggested that several bridges require urgent safety measures.

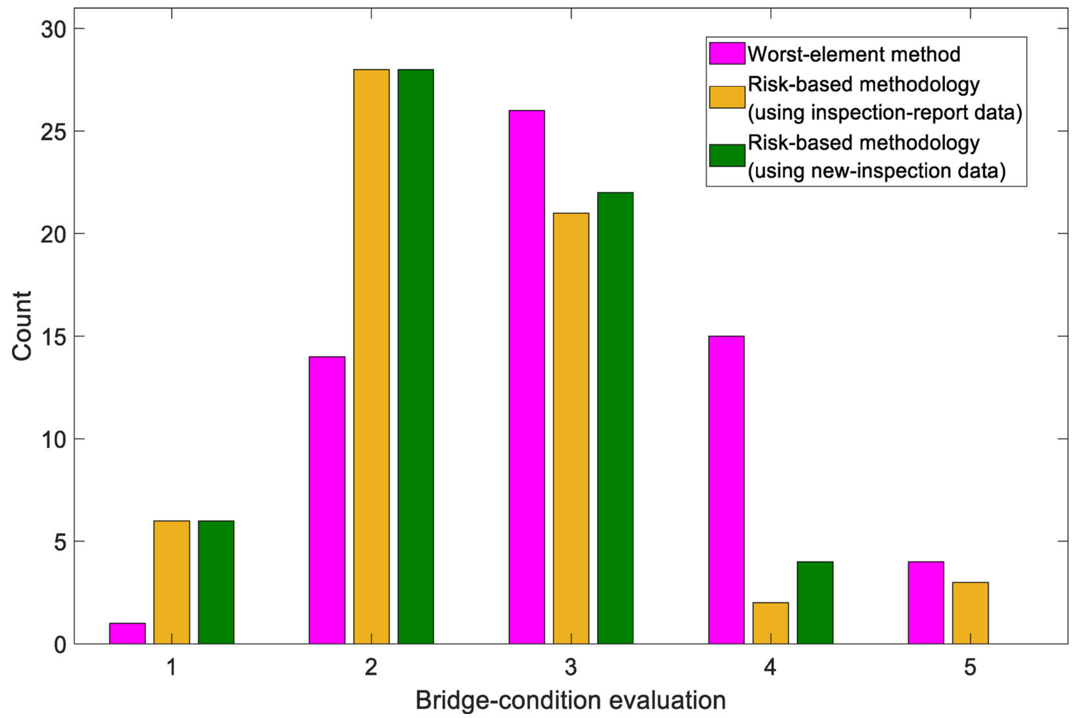

Figure 8. Comparison of bridge-condition evaluation distributions using the risk-based methodology based on inspection reports and the recent inspection.

This result shows that inspection reports often present pessimistic estimations of element degradation states, leading to inaccurate bridge-condition evaluations. In such situations, unnecessary interventions are often realised as shown for Bridge III (Section 4.2.3). Accurate assessments of element degradation states are thus needed to prioritise maintenance and rehabilitation interventions on bridges at the network level. The recent inspection, where elements are assessed using a quantitative method (Figure 2) supports an accurate assessment of bridge condition and is thus recommended.

5. Discussion

The risk-based methodology (Section 3) has been designed to remain simple to be easily implemented by road agencies, but without compromising the reliability of its evaluations of bridge conditions based on the degradation state of elements. This methodology is used based on information already collected in inspection reports to generate new evaluations, allowing quick implementation of the methodology at a network level without requiring additional visual inspections.

The following limitations of the work are recognized. First, the proposed methodology for bridge-condition evaluation aims to remain simple for practitioners and to be generally applicable for an entire bridge network. Bridges with either specific designs leading to complex static behaviour or with a brittle failure mechanism may require additional investigation. For such structures, the coherence results in terms of bridge-condition scores and recommended intervention measures should be evaluated by inspectors and bridge owners.

Second, to accurately evaluate a bridge condition, in principle all structural elements must be inspected but some elements are not accessible for visual inspection. The condition of pre-stress tendons in concrete bridges is typically difficult to evaluate. As this methodology is based on visual inspection, elements that cannot be inspected are not accounted for in the bridge-condition score. However, the condition of these elements may be crucial for the structural-safety assessment. For example, the evaluation of Bridge I (section 4.2.1) will be significantly affected if prestress tendons show corrosion. However, in case of damaged prestress tendons abnormal cracking and deformation may be expected and detected by visual inspection. In such situations, additional measures should be taken either in additional inspection technics such as monitoring and non-destructive tests or safety measures.

These new bridge-condition evaluations conclude that all the bridges on this road do not present significant loss of load-bearing capacity due to degradations. However, significant degradations, such as on kerbs, have been observed and they lead to durability issues. These degradations should be rehabilitated to avoid long-term effects on structural safety and serviceability. A systemic maintenance strategy is recommended to rehabilitate all bridges simultaneously with a similar intervention scheme, optimizing intervention costs.

6. Conclusions

A new methodology is introduced to assess bridge conditions based on visual inspection, following a risk-based analysis. This risk-based methodology has been applied to a road in Switzerland that is composed of 60 bridges. The following conclusions are obtained:

- Visual inspection leads to subjective and inaccurate evaluations when degradation states of bridge elements are qualitatively assessed. The proposed method to quantitatively evaluate bridge-element conditions helps reducing subjectivity in the evaluation of condition states.
- By accounting for the consequences of element failure on global structural safety, the risk-based methodology provides accurate assessments of bridge conditions based on visual inspection.
- This methodology supports decision-makers in the prioritization of maintenance on defective bridges through linking bridge condition value with appropriate intervention measures, improving thus asset management.

In summary, this paper proposes a new methodology to assess bridges based on visual inspection following a risk analysis. Future work consists of providing a maintenance strategy that is generalised to all bridges in defective and bad condition. This strategy will help reduce asset-management costs as rehabilitation interventions will be planned to multiple structures simultaneously.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Adey, B., Hajdin, R., & Brühwiler, E. (2003). Risk-based approach to the determination of optimal interventions for bridges affected by multiple hazards. *Engineering Structures*, *25*(7), 903–912. doi:10.1016/S0141-0296(03)00024-5

Agdas, D., Rice, J. A., Martinez, J. R., & Lasa, I. R. (2016). Comparison of visual inspection and structural-health monitoring as bridge condition assessment methods. *Journal of Performance of Constructed Facilities*, *30*(3), 04015049. doi:10.1061/(ASCE)CF.1943-5509.0000802

Brownjohn, J. M. W., De Stefano, A., Xu, Y.-L., Wenzel, H., & Aktan, A. E. (2011). Vibration-based monitoring of civil infrastructure: Challenges and successes. *Journal of Civil Structural Health Monitoring*, *1*(3–4), 79–95. doi:10.1007/s13349-011-0009-5

Brühwiler, E. (2010). *Mise à jour de la Directive pour l'inspection des ouvrages d'art selon une «Approche Risque», Etat de Vaud, Département des infrastructures, Services des routes, 15 juin 2010. Internal report* (p. 20).

Brühwiler, E., Vogel, T., Lang, T., & Lüchinger, P. (2012). Swiss standards for existing structures. *Structural Engineering International*, *22*(2), 275–280. doi:10.2749/101686612X13291382991209

Campbell, L. E., Connor, R. J., Whitehead, J. M., & Washer, G. A. (2020). Human factors affecting visual inspection of fatigue cracking in steel bridges. *Structure and Infrastructure Engineering*, 1–12. doi:10.1080/15732479.2020.1813783

Catbas, F. N., Susoy, M., & Frangopol, D. M. (2008). Structural health monitoring and reliability estimation: Long span truss bridge application with environmental monitoring data. *Engineering Structures*, *30*(9), 2347–2359. doi:10.1016/j.engstruct.2008.01.013

Cha, Y.-J., Choi, W., Suh, G., Mahmoudkhani, S., & Büyüköztürk, O. (2018). Autonomous structural visual inspection using region-based deep learning for detecting multiple damage types. *Computer-Aided Civil and Infrastructure Engineering*, *33*(9), 731–747. doi:10.1111/mice.12334

Cross, E. J., Koo, K. Y., Brownjohn, J. M. W., & Worden, K. (2013). Long-term monitoring and data analysis of the Tamar Bridge. *Mechanical Systems and Signal Processing*, *35*(1–2), 16–34. doi:10.1016/j.ymssp.2012.08.026

Cunha, A., Caetano, E., & Delgado, R. (2001). Dynamic tests on large cable-stayed bridge. *Journal of Bridge Engineering*, *6*(1), 54–62. doi:10.1061/(ASCE)1084-0702(2001)6:1(54)

Ellingwood, B. R. (2005). Risk-informed condition assessment of civil infrastructure: State of practice and research issues. *Structure and Infrastructure Engineering*, *1*(1), 7–18. doi:10.1080/15732470412331289341

Farrar, C. R., & Worden, K. (2010). An introduction to structural health monitoring. In Deraemaeker A., Worden K. (Eds.), *New trends in vibration based structural health monitoring* (Vol 520, pp. 1–17). Vienna: Springer.doi:10.1007/978-3-7091-0399-9_1

Federal Road Office (FEDRO). (2018). *Rapport 2018 d'état du réseau des routes nationales* (p. 82). https://www.astra.admin.ch/astra/fr/home/themes/routes-nationales/reseau/rapport-d-etat-des-routes-nationales.html.

Frangopol, D. M. (2011). Life-cycle performance, management, and optimisation of structural systems under uncertainty: Accomplishments and challenges 1. *Structure and Infrastructure Engineering*, *7*(6), 389–413. doi:10.1080/15732471003594427

Frangopol, D. M., & Liu, M. (2007). Maintenance and management of civil infrastructure based on condition, safety, optimization, and life-cycle cost. *Structure and Infrastructure Engineering*, *3*(1), 29–41. doi:10.1080/15732470500253164

Frangopol, D. M., Strauss, A., & Kim, S. (2008). Use of monitoring extreme data for the performance prediction of structures: General approach. *Engineering Structures*, *30*(12), 3644–3653. doi:10.1016/j.engstruct.2008.06.010

Ghosn, M., Dueñas-Osorio, L., Frangopol, D., McAllister, T., Bocchini, P., Manuel, L. … Tsiatas, G. (2016). Performance indicators for structural systems and infrastructure networks. *Journal of Structural Engineering*, *142*(9), F4016003.

Ghosn, M., Frangopol, D. M., McAllister, T. P., Shah, M., Diniz, S. M. C., Ellingwood, B. R. … Others, (2016). Reliability-based performance indicators for structural members. *Journal of Structural Engineering*, *142*(9), F4016002. doi:10.1061/(ASCE)ST.1943-541X.0001546

Hajdin, R. (2001). KUBA-MS: The Swiss Bridge Management System. *Structures Congress 2001*, 1–3. doi:10.1061/40558(2001)49

Hajdin, R. (2008). KUBA 4.0: The Swiss Road Structure Management System. *Transportation Research Circular*. In *10th International Conference on Bridge and Structure Management Transportation Research Board New York State Department of Transportation New York State Thruway Authority New York State Bridge Authority Multidisciplinary Center for Earthquake Engineering Research Federal Highway Administration*. https://trid.trb.org/view/873697.

Hearn, G., & Program, N. C. H. R. (2007). *Bridge inspection practices*. Washington, DC: Transportation Research Board.

Loraux, C., & Brühwiler, E. (2016). The use of long term monitoring data for the extension of the service duration of existing wind turbine support structures. *Journal of Physics: Conference Series*, *753*, 072023.

Lounis, Z., & McAllister, T. P. (2016). Risk-based decision making for sustainable and resilient infrastructure systems. *Journal of Structural Engineering*, *142*(9), F4016005. doi:10.1061/(ASCE)ST.1943-541X.0001545

Mirzaei, Z., & Adey, B. T. (2015). Investigation of the use of three existing methodologies to determine optimal life-cycle activity profiles for bridges. *Structure and Infrastructure Engineering*, *11*(11), 1484–1509. doi:10.1080/15732479.2014.976577

Pellegrino, C., Pipinato, A., & Modena, C. (2011). A simplified management procedure for bridge network maintenance. *Structure and Infrastructure Engineering*, *7*(5), 341–351. doi:10.1080/15732470802659084

Rausand, M. (2013). *Risk assessment: Theory, methods, and applications*. Hoboken, NJ: John Wiley & Sons.

Runcie, P., Mustapha, S., & Rakotoarivelo, T. (2014). Advances in structural health monitoring system architecture. In *Proceedings of the the 4th International Symposium on Life-Cycle Civil Engineering, IALCCE* (Vol. 14, pp. 1064–1071).

Sánchez-Silva, M., Frangopol, D. M., Padgett, J., & Soliman, M. (2016). Maintenance and operation of infrastructure systems. *Review. Journal of Structural Engineering*, *142*(9), F4016004. doi:10.1061/(ASCE)ST.1943-541X.0001543

Schellenberg, K., Vogel, T., Chèvre, M., & Alvarez, M. (2013). Assessment of bridges on the Swiss National Roads. *Structural Engineering International*, *23*(4), 402–410. doi:10.2749/101686613X13627351081759

Seo, J., Duque, L., & Wacker, J. (2018). Drone-enabled bridge inspection methodology and application. *Automation in Construction*, *94*, 112–126. doi:10.1016/j.autcon.2018.06.006

Smith, I. F. C. (2016). Studies of sensor data interpretation for asset management of the built environment. *Frontiers in Built Environment*, *2*, 2–8. doi:10.3389/fbuil.2016.00008

Swiss Society of Engineers and Architects. (1997). *Conservation des ouvrages, SIA 469* (p. 20. Swiss Society of Engineers and Architects, Zurich, Switzerland.

Swiss Society of Engineers and Architects. (2011). *Existing structures, SIA 269, 269/1-269/7*. Swiss Society of Engineers and Architects, Zurich, Switzerland.

Thompson, P. D., Small, E. P., Johnson, M., & Marshall, A. R. (1998). The Pontis Bridge Management System. *Structural Engineering International*, *8*(4), 303–308. doi:10.2749/101686698780488758

Wang, C., Li, Q., & Ellingwood, B. R. (2016). Time-dependent reliability of ageing structures: An approximate approach. *Structure and Infrastructure Engineering*, *12*(12), 1566–1572. doi:10.1080/15732479.2016.1151447

Wong, K.-Y. (2007). Design of a structural health monitoring system for long-span bridges. *Structure and Infrastructure Engineering*, *3*(2), 169–185. doi:10.1080/15732470600591117