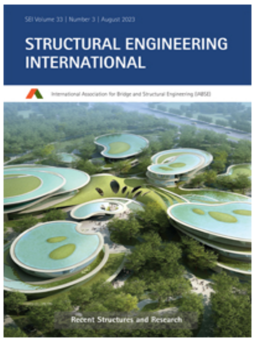

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Assessment of Bridges on the Swiss National Roads

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Abstract

The main strategic goal in the assessment of the existing Swiss national road network is to provide a high level of availability of the roads for traffic and reduce interferences caused by construction or repair works. Therefore, renovation works tend to be executed in large maintenance sections for which the complete infrastructure is repaired in order to ensure a period of 15 years without the need for additional construction works. Before 2008, the existing bridges were maintained mostly individually under the responsibility of local cantonal administrations. Entering into the new maintenance strategy requires a careful assessment of the structural conditions. Visual inspections and laboratory testing programs are required in order to bring the structural condition of different structures to a similar level and to fulfil all standards as long as costs are not disproportional to the benefits. Structural safety is evaluated according to the new Swiss code for existing structures, SIA 269, which was published in 2011. For typical short span bridges and overpasses from the early 1970s, which represent the largest number of existing objects, focus has to be set on the shear verifications of slabs without stirrups as well as on the bending capacity of cantilever slabs. Within the structural assessment, actions, material properties, geometrical properties and structural models shall be updated. Partial safety factors can also be updated by means of semi or full probabilistic approaches, in order to verify structural safety.

Keywords: existing bridges; maintenance; inspections; condition assessment; structural verification.

Introduction

The responsibility for the maintenance of the Swiss national road network was transferred in 2008 from the cantons (member states of the Swiss Confederation) to the federal administration.[1] The national roads cover 1900 km (of which 1800 km are already built) with more than 3000 bridges, mainly built between 1960 and 1985 (*Fig. 1*). Prior to 2008, renovation works were mostly scheduled as individual projects for a single or a small number of bridges. With the handing over of responsibilities and in order to minimize traffic disturbances, the bridges are now preferably repaired in large so-called maintenance sections, involving repair and upgrade of all elements of the highway: the road system itself (pavement and drainage), the mechanical and electrical installations as well as other relevant topics related to, for example, traffic engineering or environmental impact.

The condition of single bridges depends significantly on the date of the last repair. In order to implement the new maintenance strategy and to ensure a period of 15 years without the need for additional construction works, a careful assessment is required. The main challenge for an economical preservation of the infrastructure is the estimation of the further deterioration process of the single elements and to utilize the remaining lifetime. The crucial question is whether postponing a specific repair work increases the repair costs disproportionately.

From a structural perspective, focus is set on ensuring the structural safety of existing bridges. Compared to new structures, reduced requirements for the safety margin can be justified, for example, by accurately updating the load models according to the traffic impact actually present.

This article describes selected technical issues from a consultant's point of view, providing an overview of the main findings from the conceptual planning of bridge maintenance and structural assessment. The main steps to keep an infrastructure in good shape are explained. First, the different programs within condition assessment and strategic maintenance planning are described, followed by an overview of the applied codes and guidelines as well as a short description of typical bridges. The next two sections explain the process for condition assessment and structural verifications. Finally, an overview of the typical measures taken on the basis of condition assessment and of subsequent repair works is given.

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Assessment Programs

Bridges and overpasses within the highway perimeter are assessed by means of various programs ranging from operational maintenance to long-term inspection plans.

The operational maintenance teams check the bridges once a year. If needed, they carry out small maintenance works to ensure proper serviceability of the bridges and to minimize the deterioration processes. These works can involve the grouting of pavement joints, small repair works or ensuring the accessibility and good functioning of locks and doors.

The main inspections are carried out by engineers every 5 years. The first main inspection is preferably carried out previous to the expiry of the warranty period of the construction works. The aim of the main inspection is to update the bridge management system (KUBA-DB, acronym for the German term Kunstbauten-Datenbank) with comprehensive information on the structural elements, the deterioration mechanisms and the current conditions. The condition is specified according to *Table 1*. From the conditions of the single elements, a global condition for the entire structure is derived. Future development of the database shall enable an early estimate

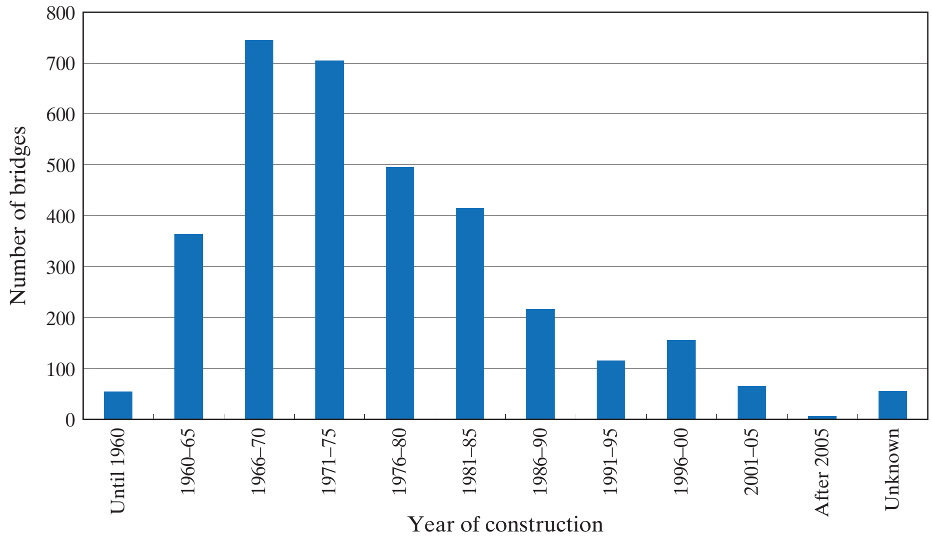

Fig. 1: Number of bridges on the Swiss national road network by year of construction, modified from Vogel et al., 2009[2]

Level	Condition	Damages
1	Good condition	No or insignificant damages
2	Acceptable condition	Insignificant damages
3	Damaged condition	Significant damages
4	Bad condition	Large damages
5	Alarming condition	Urgent countermeasures
9	Condition not evaluated	Condition can not be inspected

Table 1: Condition levels

of the required maintenance investments based on proper prediction of the deterioration process.

Emergency inspections take place additionally after accidental events such as collisions, fire or flood. The records of the emergency inspections also need to be stored with the bridge documents.

A further assessment program for bridges is the evaluation of earthquake vulnerability. A standardized two-step approach allows an efficient identification of bridges with low risk of damage, classifying them with a lower priority for further evaluation. The first step is carried out by means of a questionnaire based on the typology of the structure,[3] and it has basically been completed for the entire national road network. The second step is being implemented into the UPlaNS-projects (see below), or triggered independently in case the respective maintenance planning is not scheduled yet.

Maintenance Planning (UPlaNS)

The main strategic goal that has been implemented by the federal administration in 2008 when taking over the full responsibility for the national road network is to coordinate renovation works for the complete infrastructure within large maintenance sections up to 15 km in length. The principal aim is to minimize traffic interference. Therefore, construction sites shall not be longer than 3–5 km (within project sections of maximum 15 km) and a period of at least 15 years after completion of a renovation without the need for additional construction work shall be ensured. Between two sections under construction, a distance of at least 30 km shall be planned. Aiming at lesser impact for the traffic users when traffic lanes need to be closed, the tendency is towards longer construction periods and increased night work.[1]

The maintenance planning for the national roads (UPlaNS, as acronym for the German term) is scheduled in three planning phases each lasting for approximately 1 year: In the first phase (Generelles Erhaltungskonzept), the basis for strategic decisions is prepared, including condition assessment, the identification of major technical issues and boundary conditions as well as cost and construction time estimates. In the second phase (Massnahmenkonzept), the basis for selecting the appropriate measures is elaborated and recommendations are given. In the third phase (Massnahmenprojekt), the proposed measures are elaborated.

An advantage of UPlaNS is the raising of the different structures within the maintenance section to a similar level of code conformity and increasing the degree of standardization by considering the guidelines of the Federal Roads Office (FEDRO). Through comparisons, it can be ensured that investments are carried out where most value is generated, for example, where the condition is the worst or where increase in safety is the most cost efficient. Significant synergy is gained by the simultaneous treatment of a large number of structures.

The implementation of the UPlaNS strategy requires a change in the cycle of repair works. In some cases, there exist maintenance projects for individual bridges that have been prepared prior to handing over the responsibility to FEDRO in 2008. If the time schedule of UPlaNS is not in agreement with the deterioration process assumed in these projects, they might need to be executed independently in advance of what is planned within UPlaNS, thereby losing some of the synergy and increasing the coordination costs.

Codes, Standards and Other Technical Guidance

In 2011, the codes for existing structures SIA 269/i[4] were published as complement to the Swiss codes for new structures, SIA 260 to 267.[5] With the code series SIA 269, for the first time a complete and consistent basis for the verifications of existing structures has been provided, including criteria for assessing whether the cost of the envisaged measures is disproportional with respect to the remaining lifetime of the structure. The code SIA 269 also defines reduced requirements for structural safety and serviceability in comparison to the standards for new structures.

Along with the current codes, standards and guidelines from other associations, FEDRO provides guidelines and a technical handbook[6] with standardized solutions for most design-relevant topics, aiming at a maximum cost–benefit ratio, while guaranteeing safety over the entire lifecycle of the infrastructure and reducing traffic interruption during later maintenance.

Information is also provided on the selection of materials and planning processes as well as on the detailing level for the specific three phases. The handbook is a practice-oriented working tool that leaves sufficient design flexibility to the engineer.

The concept of dealing with existing structures has developed during the last decades in different parts of the world. Yet, coordinated standards and terminologies are still missing. The same matters are called differently by different communities.[7] In German, the term *Erhaltung* covers all the activities related to existing structures.

Overview of Structures

Most bridges on the national road network were built about 40 years ago. Within one UPlaNS maintenance section of approximately 10 km, the number of bridges can vary significantly, easily reaching 30 bridges and overpasses in urban areas.

For a standard highway on the Central Plateau of Switzerland, most bridges are overpasses. Typical systems are bridges with V-columns or continuous slab bridges with an intermediate support in the central reserve of the highway (*Fig. 2*). Most highway bridges are small structures spanning creeks and underpasses, for which frame structures or slab bridges are appropriate; larger structures crossing gorges and valleys are less frequent. For these, the most frequent bridge type is the continuous hollow box prestressed concrete girder (*Fig. 3*).

For easier manufacturing, the thickness of slabs and frames was designed in many cases such that shear could be resisted without stirrups. In general and in comparison with modern bridges, requirements for concrete cover were significantly lower in the 1960s and 1970s. In addition, the design often underestimated the need for accessibility for inspections. Access to joints and bearings was not always given the same priority as today.

After 40–60 years of service, even bridges without any initial deficiencies need to be upgraded or replaced to serve during further decades.

Condition Assessment

Condition assessment is essential to identifying current and potential deficits. On the basis of the condition, the residual service life can be estimated and measures planned to improve durability, which can either be achieved by repair works or by deceleration of the deterioration process. Therefore, a deep understanding of the deterioration processes is an important requirement for the bridge inspectors. It is important to distinguish between structural deficiencies and durability issues because the time frame for countermeasures may be extended.

Deterioration of bridges is mainly caused by water and chlorides, and therefore, the condition of the waterproofing and the level of chloride penetration are the most relevant issues to be examined.

For structural evaluation (see below), the present material properties are of crucial importance. Therefore, apart from visual inspections, laboratory testing programs also provide a basis for condition assessment and estimation of the further deterioration process. Prior to visual inspections, the structure's documents need to be studied in order to capture all the relevant parts. Archive documentation, visual inspections and laboratory testing are described in the following.

Archive Documentation

The availability of archive documentation is fundamental. Prior to inspections, the particularities of each structure have to be evaluated in order to increase the awareness of the inspector regarding weak points of the

(*a*) (*b*)

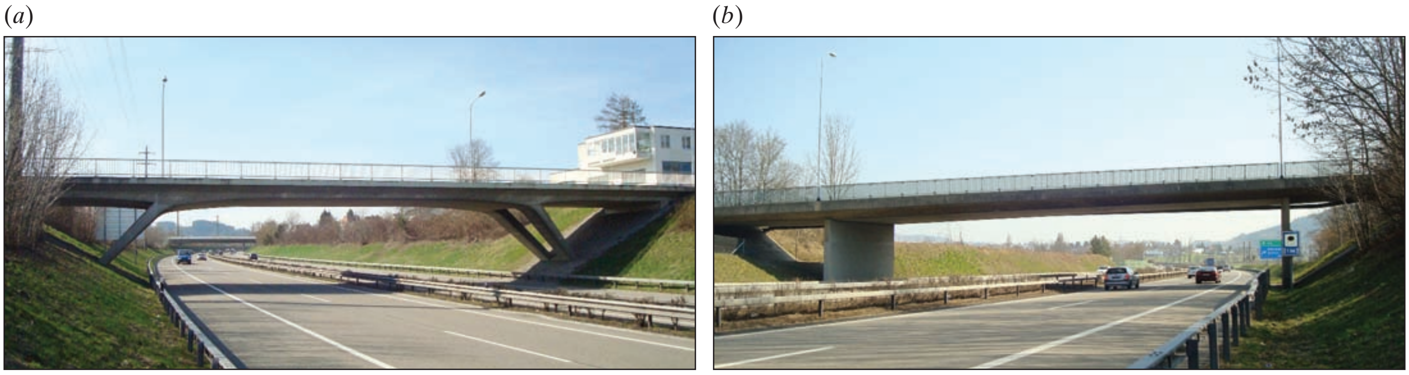

Fig. 2: Typical overpasses: with V-columns (a) and slab type bridge (b)

(*a*) (*b*)

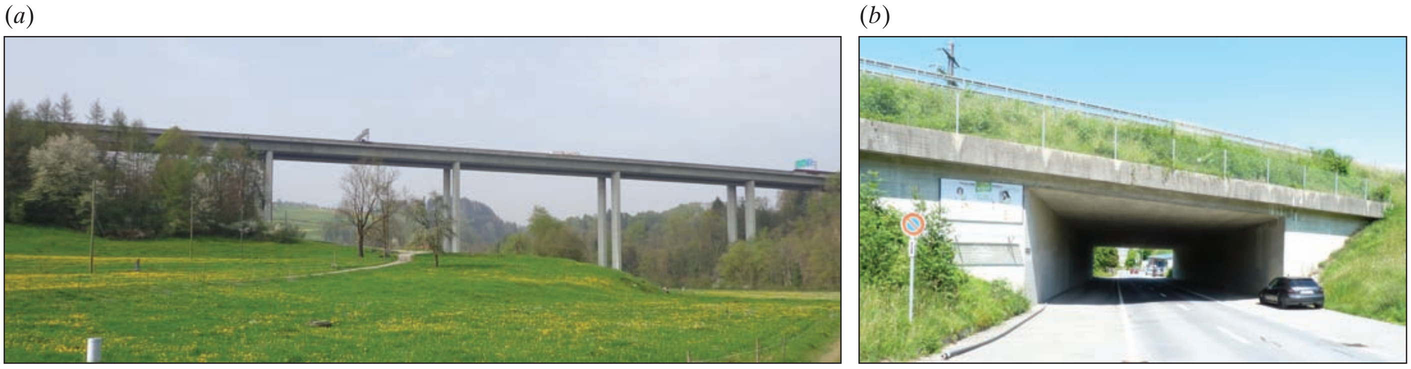

Fig. 3: Longitudinal section of typical highway bridges: continuous spans box girders (a) and frames (b)

structure. For structural verification, archive documentation is indispensable. Construction drawings with the reinforcement and the prestressing layout contain the main information. Access to the original static calculations and past verifications reduces the time for verification significantly. A careful study of the documents and a critical comparison between the documents and the structure on site are a prerequisite to identifying possibly missing documentation related to later changes of the structure; it has to be checked whether the files on the last repair works have been added properly to the archive documents.

For the assessment of existing bridges, not only the current structural codes but also old codes and product information are of significant value. If in doubt, the best information on the applied products can, in general, be taken from the billings of the contractor. To identify the type of prestressing tendons, prestressing records provide helpful information. The owners of bridges have to emphasize on archiving the respective files, for example, workshop drawings, material and equipment profiles of bearings, expansion joints, prestressing tendons, railings, water proofing systems and other applied products. Valuable information for identifying bad functioning can be obtained from measurements of bearing displacements or control measurements of settlements over time.

Maintaining the archive has to be seen as an investment for the future maintenance of the structures. Complete documentation and, in particular, pictures of the object (from construction or from previous inspections) significantly reduce the amount of work and preparation time for the assessment.

Visual Inspection

All bridges on the national road network are inspected every 5 years, either by the owner or by an assigned engineer. Deviations from the 5 years interval need to be justified. Inspections are generally carried out visually. In particular, critical elements such as bearings and expansion joints or half-joints have to be inspected hands on. The accessibility of all relevant elements is a key factor for proper inspections[8] and must therefore be considered already during design. For better documentation, pictures have to be taken including references on the location, e.g. providing the name or numbering of the respective element (*Fig. 4*).

These inspection findings form a starting point for triggering maintenance measures, which can range from simple operational maintenance up to immediate renovation works independent of UPlaNS.

Fig. 4: Example for reference on inspection pictures

Laboratory Testing

Visual inspections are not sufficient to assess the condition of the structures. The required amount of laboratory tests is defined after the visual inspections and consideration of findings such as leaks or wet surfaces. Laboratory tests shall be carried out in two phases, adjusting the total amount and exact location of samples on the basis of the results of the first phase. This two-step approach requires more time, but expensive testing and poor results can be avoided. Whenever possible, priority shall be given to non-destructive test methods in order to limit the amount of damage done to the concrete surface and structure.

Depending on the amount of information required, specialist contractors shall carry out a selection of the following works on site: checking the condition of the waterproofing with inspection openings (*Fig. 5, (a)*); taking concrete samples (drill cores and borehole cuttings); measuring the depth of concrete cover; measuring the carbonization depth in inspection openings; carrying out potential field measurement (see exemplary results *Fig. 5, (b)*).

From drill cores and borehole cuttings, the content of chlorides is determined for layers of 10 mm, and concrete strength and porosity are measured. A larger number of samples is required if an updated concrete strength is needed for structural verifications. In particular cases, alkali aggregate reaction tests are also carried out if the

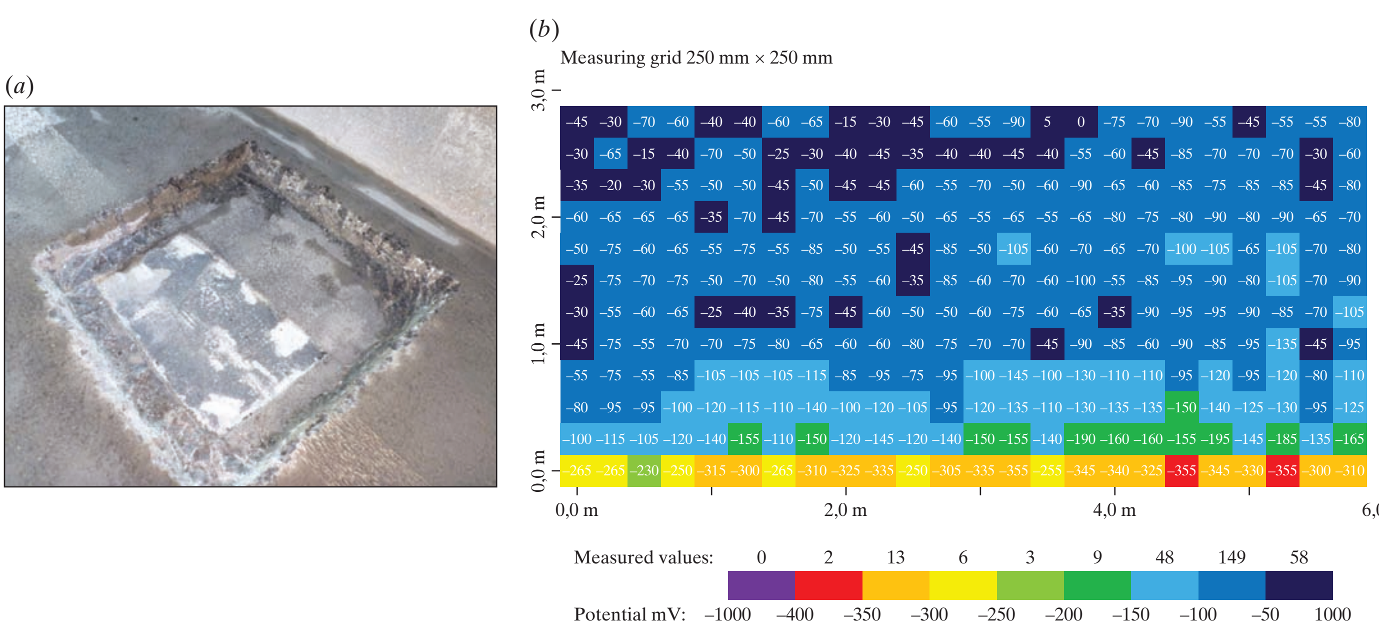

Fig. 5: Inspection opening in pavement (a) and results from potential measurement (b)

structure shows indications of being endangered.

In prestressed concrete bridges, corrosion of the prestressing tendons significantly compromises structural safety, and therefore, any indication for deficiencies in the corrosion protection of the tendons is of great interest.

Non-accessible Members

The assessment of a structure becomes difficult if the conditions of non-accessible members are not known. Details of concern are, for example, buried tensile elements or non-accessible voids in slabs (*Fig. 6*).

Such members have to be inspected either by expensive opening or by endoscopy. An alternative to assessing tensile elements is to assume their failure as an accidental loading situation and to ensure that no collapse can occur.

Findings

In bridges of approximately 40 years of age, the following damages are found most frequently: Leaking water proofing at the edges and around sumps; damages within box girders due to leaking drain pipes (*Fig. 7*); damages at supports and walls exposed to de-icing salt; local concrete damages due to insufficient concrete cover or cracks; damages around leaking expansion joints or pavement drainages; deficiencies in the corrosion protection of the tendons; and defective vehicle restraint systems and utility installations. Several substantial damages are caused by bad detailing, particularly those related to the drainage.

Structural Assessment

Evaluation of an existing structure requires an approach completely different from the dimensioning in the design phase, even if the chosen verification formats of structural safety and serviceability might look similar.

In principle, all actions and properties of an existing structure are certain, although they are not exactly known. Some of them might even be unknown and difficult to be identified.

Existing structures might incorporate materials, provisions and details that are substandard compared to actual regulations. In a design, they would not

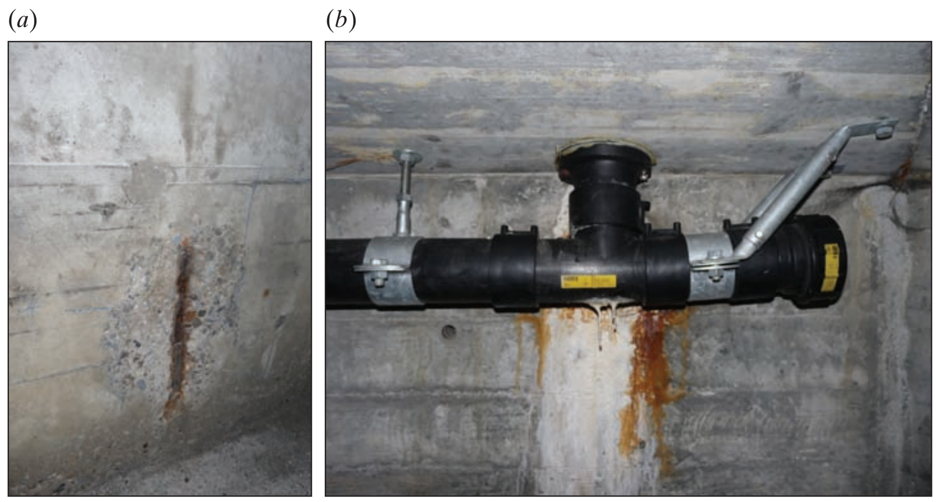

Fig. 7: Corroded reinforcement (a) and leaking penetration of a drain pipe (b)

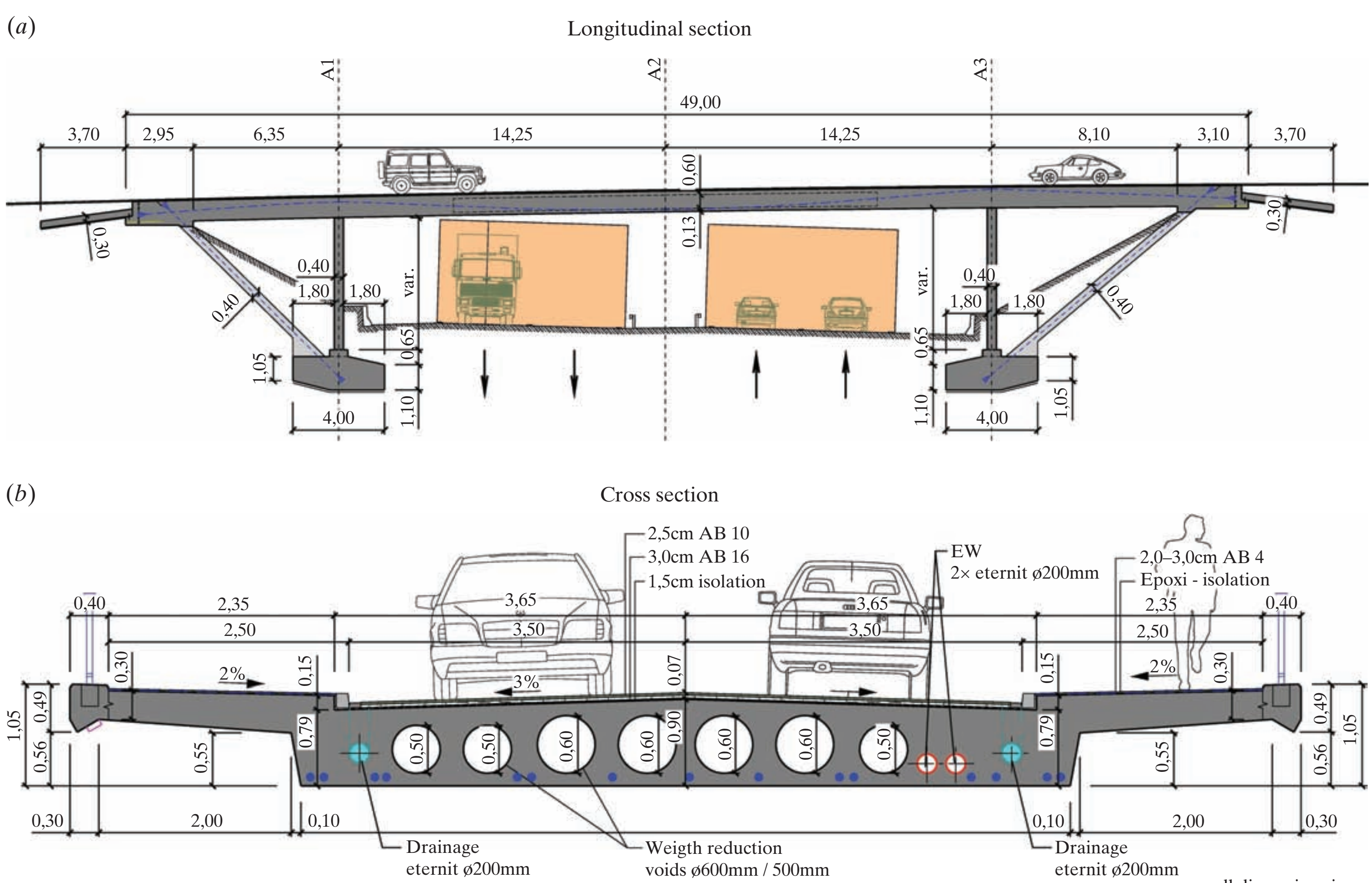

Fig. 6: Example of buried tensile elements in the slopes of the highway (a) and not accessible voids in slab bridges (b)

be accepted; in an evaluation, however, a resistance has to be assigned to such items as well.

Any change of the given properties of an existing structure to increase resistance means touching the structure (repair, strengthening, modification, etc.), with all related consequences such as restrictions in use, costs, etc. That is why more refined methods than the ones used in design are generally more appropriate to verify structural safety.

General Assessment Procedure

An essential part of structural assessment is the identification of critical components and verification sections, such as girders with inadequate or missing shear reinforcement, indirect force transfer, cantilever extensions or highly stressed components.[9] In addition to standard structural analysis according to the relevant standards, the detailing of the essential parts and potential deficiencies from the construction process have to be checked. A typical example is the additional welded bars to strengthen cantilever slabs on which noise protection walls have been built. For the welds, fatigue has to be evaluated. The most significant updates of structural verification are usually due to changes in the regulations and of the material properties with time, both described in the following sections.

In the FEDRO guidelines, the standard procedure for structural verification is defined as follows:

Loads and resistances need to be verified according to the Swiss codes for new structures, SIA 260 to 267, under consideration of the material properties as defined in the archive documentation. If the verification is not possible, material properties shall be updated (see below). In case the geometrical dimensions of the structural element are verified by appropriate measurements, the partial safety factor for permanent loads can be reduced (see below).

For the shear verification of concrete members without shear reinforcement, the reduction factor k_v is given directly depending on the longitudinal strain at a specific height, instead of being defined by the ratio of design moments to bending resistance, as is done for new structures. With the longitudinal strain, the influence of prestressing can easily be considered.

If the verification fails, traffic loads can be reduced according to the provisions in the code SIA 269/1 for actions on existing structures. The code covers prospective traffic evaluation until 2025; therefore, the expected lifetime of the bridge should be limited to this period unless a later evaluation of the traffic load models will be undertaken.

The reduction of both the partial safety factor for permanent loads from 1,35 to 1,20 and the traffic loads has a significant influence on the verification results. As an example, for a prestressed continuous slab bridge with spans of 11, 17 and 11 m and a slab thickness of 0,7 m, the degree of compliance for shear verification in the governing section without shear reinforcement over the piers increased from 0,63 to 0,94. In most cases, these assumptions, together with updated material properties, are sufficient to meet the verification of standard bridges or overpasses. Because of the large variety of factors influencing the result of a verification and since every bridge is an individual case, it is not acceptable to assume that structural safety is fulfilled in presence of a substandard degree of compliance, without more detailed evaluations.

If structural safety has not been proved so far, a more detailed structural analysis shall be carried out by considering load redistributions due to plastic deformations. Where the depth of the flexural compression zone exceeds 35% of the effective depth (or where material properties indicate the risk of brittle failure), a verification of the deformation capacity has to be provided.[5]

If verifications cannot be fulfilled with all the measures mentioned above, a dialogue with FEDRO's specialists is required in order to have the application of resistance models approved, which are not covered by the current structural codes, such as, kinematic models, partial consideration of concrete tension strength or application of probabilistic approaches[10].

The options of restriction in use, strengthening or replacement of a bridge are only considered when all previous steps did not succeed in verifying the structural safety.

In the following, all issues worth an update shall be mentioned and illustrated with examples.

Updating of Actions

For existing structures, permanent actions can be identified more precisely than in the design of a new structure. Regarding self-weight, the key issue is whether the construction drawings have been strictly respected, which can be checked by random examination and surveying of the geometrical dimensions.

Imposed loads tend to be higher than those designed and tend to increase during the service life, for example, due to additional layers of pavement.

Traffic actions for new structures should take into account the anticipated increase of axle loads during the design service life. For existing structures with a reduced remaining service life, traffic loads may be reduced, for example, based on the evidence obtained through traffic measurement.

Accidental actions—for instance, from natural hazards—have often been neglected in the original design. From a record of what the respective structure or similar structures have suffered till now, appropriate assumptions for the future can be derived.

Updating of Construction Materials and Geotechnical Properties

The properties of construction materials can vary with time. The code SIA 269/2 for existing concrete structures contains design values for the material properties to be applied in the verification.[11] For concrete, mild reinforcement and prestressing steel, values are provided for typical materials in accordance with former codes from 1989, 1968, 1956 and 1935, respectively.[4]

For concrete structures, the increase of concrete strength may allow activating a considerable reserve. This increase can be estimated by applying the respective correlations (for instance, according to SIA 269/2, equations (3.1) and (3.2)[4]) and/or be checked by random sampling. The increase of concrete strength with time can have a significant influence on the verification of shear sections without shear reinforcement. In addition, for the compression struts in load introduction zones, or when verifying sufficient rotational capacity in order to redistribute forces in strongly prestressed sections, increased concrete strength can provide additional safety. The code SIA 269/2 for existing concrete structures specifies the number of testing samples required in order to define the verification values.[4] Special attention has to be paid to the integrity and condition of the concrete in order to identify possible frost–defrost damages or other processes that reduce the strength of the concrete.

The material properties of the reinforcement shall be updated as well. The yield strengths are usually significantly lower than the values found in the original structural calculations. One must keep in mind that global safety factors were used differently in former code generations and that the design value also considers the statistical spread of the yield stress, which was substantially larger due to manufacturing quality. When the type of reinforcement cannot be deduced from the archive documents, it is recommended to take samples during the condition assessment.[6]

Decrease in strength due to deterioration processes may occur to all construction materials. In such cases, instead of an updated material property, a reduced cross section may be taken into account, which represents the updating of a geometrical property.

Geotechnical properties may need updating in cases where the properties of in situ and backfill material or the groundwater level do not meet the assumptions used in design.

Updating of Structural Models and Geometrical Properties

In the design phase, structural models may have been simplified on the safe side, considering the limited computational facilities at that time. Reserves may be activated by applying the theory of plasticity. The lower bound theorem of plasticity, requiring equilibrium and compliance with yield conditions, is therefore difficult to apply when the structure has a certain complexity. The upper bound theorem, however, requiring a kinematically admissible mechanism, is quite easy to use, since the dominant failure mode is often obvious and the virtual work of inner and outer forces can readily be calculated.[12]

Updating of Ultimate Resistances and Deformation Capacity

For bending, cross-sectional verification is close to reality and—apart from more refined constitutive relations for the applied materials—updating the ultimate resistance is not worth considering. Deformation capacity may be decisive for the extent of plastic redistribution of bending moments and it usually depends on the detailing encountered.

For shear resistance, where the models used in design are substantially simplified, more refined models have a large potential in the assessment.

For example, webs of concrete girders have been designed till the 1980s elastically by limiting the principal tensile stress in concrete and applying a truss model with diagonals inclined at 45° to determine the cross section of the stirrups. Updating the resistance model may proceed in different steps and may imply in this case:

- applying flatter diagonals as also provided by modern design codes;
- using stress fields instead of strut and tie models, which also cover the required depth of the struts, proper anchorage of the ties and limited stresses in the nodes;
- trying to further decrease the inclination of the diagonals beyond design code provisions. In this case, concrete strength in the diagonals has to be chosen depending on principal strain as well as bond between diagonals, and stringer reinforcement has to be controlled.[12]

Resistance of substandard details is a wide field. In some cases such as inadequate anchorage length, common design rules (anchorage length for full anchorage equal to a multiple of the diameter) can be replaced by more fundamental laws such as a bond slip relation on the stress level.

Verification Formats

Deterministic Approach

In most cases, a deterministic verification format is appropriate, similar to that used in design. This means comparing action effects E_d (bending moments, shear forces, stresses) with resistances R_d (bending capacity, shear capacity, strengths) at the design level. As both values are updated, this should also be notified, for instance, by an index *act* for actual. As a consequence *design level* should be replaced by *examination level*. Since both values are given, exceedance of $R_{d,\mathrm{act}}$ over $E_{d,\mathrm{act}}$ is not always achieved but the ratio can be calculated according to Eq. (1).

$$n = \frac{R_{d,\mathrm{act}}}{E_{d,\mathrm{act}}} \qquad (1)$$

This ratio is called degree of compliance n. A larger value means better compliance and unity means coincidence of action effect and resistance.

At least for one parametric verification situations, this format allows an easy communication among owners and engineers. Fulfilling structural safety means reaching $n \geq 1{,}0$ for all verifications. More information on codification issues can be found in Ref. [13].

Figure 8 shows how the comparison of action effects and resistances can be represented in the time domain. Any intersection of lines for action effects and resistances means reaching $n = 1{,}0$. This happens first when code values of action effects and resistances for new structures are compared. By updating one or both of them, the need for action can be postponed.

Semi-probabilistic Approach

Updating may not only mean getting more appropriate values for the properties concerned but also modifying the partial factors given by the codes.

According to EN 1990,[14] the following partial factors are used on the action side:

- $\gamma_{f,i}$, which takes into account the possibility of unfavourable deviations

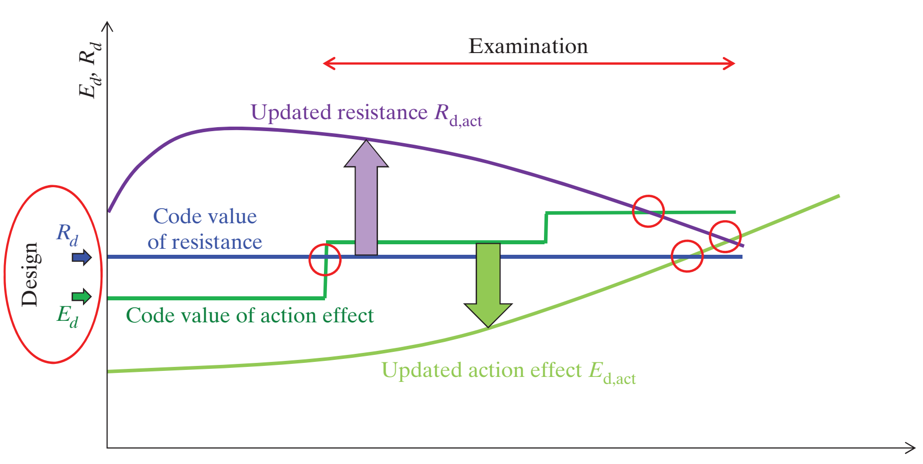

Fig. 8. Comparison of action effects and resistances with the deterministic approach in the time domain

of the action values from the representative values $F_{\mathrm{rep},i}$

- γ_{Sd}, which takes into account uncertainties in modelling the effects of actions.

For first-order calculations, that is, proportionality of actions and action effects, both partial factors can be multiplied according to Eq. (2). Compared to Eq. (6.2b) of EN 1990,[14] the index i is omitted because only one action shall be considered.

$$\gamma_F = \gamma_{Sd} \cdot \gamma_f \tag{2}$$

The partial factor γ_F can be applied either on the actions or on the action effects. Assuming that an action effect is normally distributed, γ_F can be formulated and updated as follows:

$$\begin{aligned} E_{d,\mathrm{act}} &= E\{\gamma_{F,\mathrm{act}} F_{\mathrm{rep,act}}\} \\ &= \gamma_{F,\mathrm{act}} E\{F_{\mathrm{rep,act}}\} = \gamma_{F,\mathrm{act}} E_{m,\mathrm{act}} \\ &= (1+\alpha_E \beta_0 \nu_{E,\mathrm{act}})\, E_{\mathrm{m,act}} \end{aligned} \tag{3}$$

with $\gamma_{F,\mathrm{act}}$ denominating the updated partial load factor, $F_{\mathrm{rep,act}}$ the updated representative value of the considered action, $E_{m,\mathrm{act}}$ the mean value of the updated action effect, α_E the sensitivity factor, β_0 the target value of the reliability index and $\nu_{E,\mathrm{act}}$ the updated coefficient of variation of the considered action effect ($\nu_{E,\mathrm{act}} = \sigma_{E,\mathrm{act}}/\mu_{E,\mathrm{act}}$), respectively. With corresponding data, $E_{m,\mathrm{act}}$ and $\nu_{E,\mathrm{act}}$ can be determined for the specific project, and for β_0 generally accepted values are available (EN 1990,[14] Annex B or JCSS probabilistic model code[15]). The sensitivity factors (α_E in this case) result from a full probabilistic approach. Values from experience on the safe side are mentioned in EN 1990,[14] Annex C.

As an example, the load factor $\gamma_{Gj,\mathrm{sup}}$ for unfavourably acting permanent loads shall be interpreted, which in many countries is set to 1,35, being the proposed value of EN 1990.[14] According to Eq. (6.2b) of EN 1990,[14] this load factor corresponds to γ_{Fi} with $G = S$ and $j = i$ and may be split into γ_{Sd} and γ_f as shown in Eq. (2).

Assuming that model uncertainties in actions and action effects are considered with $\gamma_{Sd} = 1{,}1$, a partial factor of $\gamma_f = 1{,}227$ can be assigned to the uncertainty in representative values of the permanent load. Further, assuming that only self-weight is considered and the density of the structural material is a deterministic value, the variation results only from scatter of the dimensions. By applying Eq. (3), estimating $\alpha_E = 0{,}7$ and choosing $\beta_0 = 4{,}7$ from EN 1990,[14] Annex B, $\nu_{E,\mathrm{act}} = 0{,}07$ can be calculated, which is in line with the note to clause 4.1.2 of EN 1990,[14] which reads, "This coefficient of variation can be in the range of 0,05–0,10 depending on the type of structure."

Some codes for existing structures allow generally updating the partial load factor for self-weight for different reasons. As an example, $\gamma_{Gj,\mathrm{sup,act}} = 1{,}20$ can be used according to SIA 269[4] provided that the actual dimensions of the structure are checked appropriately. Applying the same values stated above, the result is $\nu_{E,\mathrm{act}} = 0{,}03$. This means that for distributed load, the depth as the only dimension that matters has to be determined with a standard deviation not larger than 3% of the mean value.

Ultimate resistances and stiffnesses are also considered as normally distributed. The corresponding equation for resistances reads

$$R_{d,\mathrm{act}} = \frac{R_{m,\mathrm{act}}}{\gamma_{Rd,\mathrm{act}}} = (1+\alpha_R \beta_0 \nu_{R,\mathrm{act}}) R_{m,\mathrm{act}} \tag{4}$$

with $\gamma_{Rd,\mathrm{act}}$ denoting the updated partial resistance factor, $R_{m,\mathrm{act}}$ the mean value of the updated resistance, α_R the sensitivity factor, β_0 the target value of the reliability index, and $\nu_{R,\mathrm{act}}$ the updated coefficient of the considered resistance, respectively.

Similar equations exist for log-normal distributions as they are used for material properties and for Gumbel distributions to model variable and accidental actions.

Full Probabilistic Approach

The semi-probabilistic approach reaches its limits when several partial factors shall be updated, because the sensitivity factors become decisive and should not only be estimated but also properly calculated, for instance, with the first-order reliability method (FORM).

The full probabilistic approach is based on the reliability theory, which requires respective knowledge and is only partially codified. A general reference is the probabilistic model code.[15] As some authorities may be particular about the level of safety to be applied, an option for the reliability index might be to not use the proposed target values but to count back from the respective code regulations for new structures.

With a full probabilistic approach, dependencies of different random variables can also be considered. An increase of a concrete slab depth, for instance, does not only lead to an increased self-weight but also to an increased lever arm of the reinforcement and therefore to an increased bending resistance.

Prediction of the Development of the Condition

Relevant deterioration mechanisms are identified already on site as part of the condition survey. Together with laboratory tests and calculations, further development of the condition and as a consequence of structural safety can be anticipated.

Remedial Measures and Their Restraints in Time

Most of the measures applied to existing bridges are related to durability requirements, and they aim at reducing further process of deterioration. Measures include the replacement of water proofing, the replacement of concrete cover in the splash zones with chloride infiltrations and the removal of drainage systems from box girders. The measures are related to the time schedule for the next intervention and the assessment of the remaining service life of the single bridge parts. This requires a careful assessment in order to achieve the most economical and safe solution over the entire life cycle of the road infrastructure.

Although the aim is to carry out all renovation works at once, sometimes immediate measures are required to ensure safety. Often, even small maintenance work can have a high impact on the prevention of the deterioration process, and therefore, it should not be postponed to the scheduled repair works.

In climate zones with cold winters, chlorides are the most severe cause of deterioration for reinforced and prestressed concrete structures. The most promising concept to prevent chlorides from reaching the reinforcing steel is to prevent it from reaching the load-bearing structure at all. When structural parts remain exposed to chlorides, bulk concrete may be covered by a layer of a denser material, or the steel reinforcement may be replaced by a material that is less susceptible to corrosion.

Conclusion

The assessment and estimation of the further deterioration process is the main challenge for an economical preservation of bridges. A general procedure for the assessment allows for a definition of a global cost-effective maintenance strategy for the Federal Road Office. From the assessment of bridges on the Swiss national roadway, the following conclusions can be drawn:

1. A proper archive of construction drawings, design basis, inspection reports, condition assessments and structural calculations reduces significantly the planning costs and is an important investment for the maintenance of the structures.
2. During structural evaluations, focus should not only be set on the structural calculations but also on the assessment of detailing.
3. Exploitation of the remaining service life prior to repair and entering into a new repair cycle due to changes in maintenance strategy require a careful condition evaluation and an estimate of the development of the deterioration process.
4. The extent of damage from chloride infiltration can be significantly reduced by reacting early (prior to chlorides reaching the level of reinforcement).
5. Laboratory tests shall be carried out in two phases, resulting in a more precise definition of the second testing campaign, according to the information required for defining the appropriate extent of repair measures.
6. A strong structural understanding and analysis capabilities can often prolong the service life of an existing structure, being well aware of structural deficiencies.
7. Updating is the key procedure to adequately take into account the differences between verifying structural safety for a planned or that for an existing structure.
8. To assess structural safety, a deterministic approach is appropriate in most cases. A semi-deterministic approach may help judge whether more data are suitable to update partial safety factors. A full probabilistic approach, however, requires deeper knowledge and will therefore be restrained to special cases.
9. The experience of assessing existing bridges is valuable for the design of new durable bridges, aiming at reducing future traffic disturbances to a minimum.

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