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EXISTING BRIDGES – BURDEN OR OPPORTUNITY?

It is widely accepted that safety and serviceability are primary concerns in bridge design. However, for the most of bridges' service life, these concerns are addressed indirectly by a qualitative measure, defined herein as condition state, which is based upon observable damages recorded during inspections. Condition state is at best, only loosely correlated to safety and serviceability. It would be more reasonable to address safety and serviceability in inspection process directly, using the information on bridge performance obtained during the design and construction. This seems inevitable given the ageing, deterioration, growing traffic and climate change. A vague measure for the deviation of inspected bridge from the "as new" condition i. e. condition state is simply not adequate tool to cope with these challenges. The future Bridge Management Systems (fBMS) should therefore include assessment of safety and serviceability based on inspection results and Structural Health Monitoring (SHM). This can be further enhanced by combining or merging BMS with Bridge Information Models that are currently being developed. The fBMS will thus become an invaluable decision-support tool not only for maintenance planning but also for specification of heavy vehicle corridors, risk assessment due to natural hazards, etc.

Keywords: bridges, service life, reliability, safety, serviceability, performance Indicators, maintenance, BIM

1. INTRODUCTION

There is a broad consensus that the benefits of transportation infrastructure for the society cannot be overestimated. The investments in transportation infrastructure raise the growth potential of a national economy, which can be fully exploited by fostering division of labor. It is difficult to quantify the economic benefit of road infrastructure but its lower bound is estimated to be between 4% [1] and 10% ([2] and [3]) of Gross Domestic Product (GDP). Apart from purely economic benefit, the road infrastructure enables road users to be involved in various activities that yield private, public, and social benefits [4]. Maintaining these benefits on the long run in economically efficient, environmentally responsible, and socially reconcilable manner is the fundamental task of road authorities. They are bound to provide fast, safe, comfortable, and affordable travel.

The road infrastructure comprises various components such pavement structure, retaining walls, galleries, tunnels, bridges, etc. From the users' perspective, it is irrelevant whether a road is carried by a bridge or being in a tunnel or merely resting on soil, so long safe, fast, comfortable and affordable travel from origin to destination is provided. Given that bridges provide passages over otherwise hardly surmountable obstacles, their inability to accommodate the actual traffic can have significant impact on safe, fast and comfortable travel. The road authorities or more concrete the part of them responsible for bridges must specify the traffic that the existing bridges can accommodate, which is in face of ageing road infrastructure and growing traffic increasingly challenging task.

Bridges or parts of them can fail harming life and limb and inducing adverse consequences for economy and environment. A failed bridge causes detours and therefore impact travel times. In some cases, a failed bridge can render a region completely inaccessible with disastrous economic effects. It is therefore not surprising that the **structural safety** is the primary concern of bridge owners since it affects both safe and fast travel. Besides structural safety the bridge owners care about **serviceability**, which relates to **traffic safety** and user comfort that can be affected by bridge deflections and vibrations. If safety or serviceability requirements are not met, the road authorities need to post or even closed the bridge and thus affect road users and the whole economy adversely. This means that road authorities are bound avoid any traffic restriction on the bridges and, at the same time preclude bridge failure. Considering the extent and the age of the road infrastructure in developed countries, this is increasingly challenging task. The tools currently available to road authorities and their engineers to find the balance between safety/serviceability and traffic requirements seem not to be adequate and, in this paper, recommendations are made that may facilitate the management of existing bridges in future.

2. CHALLENGES

Safety and serviceability were always the primary concerns in bridge design. However, in course of time the requirements have changed significantly, and the existing bridges are characterized by the several generations of design codes. They have changed both with regard to actions and resistance models. It is therefore not surprising that the old, but undamaged bridge may not fulfill safety and/or serviceability requirements for the current traffic loading.

Furthermore, safety and serviceability can be jeopardized by deterioration processes or sudden events. The resistance of deteriorated bridges can in time reach a level, at which there is an immediate danger of structural failure. In addition to it, the new insights (e.g. statistical analysis) in frequencies and magnitude of sudden events can render some bridges as unsafe and require posting or even their closure.

The increasing traffic volume and traffic loads are probably the most significant challenge regarding the existing bridges. The traffic mix is shifting toward the larger share of heavy weight vehicles, effectively increasing the occurrence probability of load situations that exceed current design loads. Furthermore, there is an increasing number of special transports, i.e. the ones that exceed legal limits and require special permits. In Switzerland, passages of these transports cannot be regarded as rare occurrences as they occur on weekly or even daily basis. Similar situation is also in the USA as reported in [5]. This trend will increase in the future as the transportation industry is interested in using larger trucks with higher axle loads in order to improve their economies of scale. The stiff competition will also lead to platooning i.e. to the trains of wirelessly coupled trucks. The wireless coupling allows to significantly reduce the safety distance between the trucks. This seems to result in a particularly aggressive load situation as these trucks also break simultaneously. The break forces that are mostly neglected in road bridges must be considered in the future and existing bridges need to be assessed for this action.

Finally, climate change may lead to more frequent and intensive gravitational hazards, such as flooding, avalanches, landslides, rockfalls, etc.

In summary, the prudent road authority needs to plan and execute timely intervention in order to cope with following challenges:

- Potentially unsafe bridges that are designed using bygone codes of practice.
- Bridges with reduced resistance due to deterioration or mechanical damage.

- Bridges exposed to natural hazards that are not or not adequately considered in design.
- Increasing traffic volume and loads that can render some bridges unsafe.
- Increased exposure of bridges to natural hazards due to climate change.

In face of these challenges one is inclined to regard existing bridges as burden that requires ever increasing funding. However, the existing bridges are also an opportunity for structural engineers equipped with diagnostic knowledge to specify both economically efficient and environmentally friendly interventions. Moreover, in the same way structural engineers propelled the infrastructure boom in the 20th century, they will be instrumental in the transformation of transportation infrastructure in meeting ever-changing societal needs.

3. CURRENT ASSESSMENT AND DECISION-MAKING

The practice in dealing with existing bridges differs quite significantly from country to country, but the common denominator is that it relies on visual inspections. The visual inspections are – if performed by a qualified structural engineer – cost efficient and very valuable source of information. During the inspection, observations are recorded and evaluated. The result of inspections is qualitative indicator, which is named differently from country to country as condition rating, condition state, condition class, etc. Herein, the term condition state is used. Whereas in the design phase the safety and serviceability concerns are addressed directly in quantitative manner, in the service phase, based on inspection results the condition state is determined. The condition state is a vague measure for the deviation of inspected bridge from the “as new” condition. The direct assessment of safety and serviceability during an inspection is regarded as not cost efficient since it is commonly assumed that it always requires an in-depth material investigations and structural analysis.

Based on condition state, owners trigger often costly in-depth investigations or even maintenance actions. In practice, once an in-depth investigation based on condition state is triggered, the maintenance intervention is very likely to follow, even if a bridge can still be used without restrictions. The reasons are different from country to country, but one is surely the visual appearance and related perception of safety that entice authorities to remove all visible damages with appropriate maintenance interventions. In some (rare) cases, a maintenance action is triggered if a bridge fails structural safety and serviceability checks, with the load and resistance models for the design of new bridges. This is clearly inadequate and uneconomical, given the remaining service life and possibilities to reduce uncertainties on existing bridges. Thus, some countries have introduced specialized safety and serviceability checking formats for existing bridges in their code of practice (e.g. [6]).

The above-mentioned approach seems not to be very logical. In the design phase, the wealth of information about safety and serviceability for different load situations is created. This information is unstructured and mostly in paper form. After the commissioning of newly constructed bridge, the documents containing this information is handed over to the road authorities or operators that act henceforth as trustees of the bridges assigned to them. The documents are mostly in archives and in general not easily accessible. During the service life, inspections are performed with no consideration of safety and serviceability information produced during the design and construction phases. It is only within the in-depth investigation that the safety and serviceability are assessed again. There is a substantial gap during the service life of a bridge, in which decision are made based on qualitative indicators, that are sometimes unrelated to the key concerns of road authorities: safety and serviceability.

In most countries, decision/making is supported by databases, in which the results of inspections are stored, sometimes in great detail. The information from design phase i.e. critical load combinations, safety factors, assumed traffic loads is usually not stored in these databases. In some road agencies, there are load rating software that facilitate evaluation of special transports, but it is rarely used in conjunction with inspection results.

Even more surprising is that the relevant information on safety and serviceability is often not stored in the database after maintenance interventions. It can be assumed that the provisions of the current code of practice are fulfilled due to maintenance interventions, but it is not recorded if these are exceeded and by what margin.

It should be noted that within the in-depth investigations a substantial work effort is necessary to find information from the design phase or previous maintenance activities. In some cases, the information on existing bridges is lost due to negligence or some accident (e.g. fire, flooding).

In some ways, the current bridge management undergoes amnesia because

- relevant information from the design phase and/or in-depth investigation is not stored and/or
- information is stored only in paper form and is lost due to negligence or accidents.

It is not that road authorities and operators are not aware of this deficiency, but to remedy it, they need to be provided tools and resources to efficiently store and access the elaborated information on their bridge inventory. In the time of growing awareness of data importance and big data, it is high time to establish an organizational setting for business processes to ensure the benefit of collected data on the long term.

4. ASSESSMENT

The challenges listed in chapter 2 can be only efficiently coped with, if the bridge owners have all necessary information at their fingertips. This means that the current databases need to be significantly improved to accommodate all relevant information either from design phase, inspections, or maintenance interventions. This transition can be quite costly and therefore needs to be performed gradually in several phases as outlined in the following chapters.

4.1 SAFETY AND SERVICEABILITY OF UNDAMAGED BRIDGES

The information on safety and serviceability margin of an undamaged (pristine) bridge is essential in the service phase. This information should be structured and include all relevant load cases, which would also allow owners to have a clear picture of possible failure modes and related vulnerable zones that need to be observed in more detail.

The current databases are not structured to accommodate the graphical representation of structural systems and load situations. The material properties and load effects need also to be included in the database as searchable data and coupled with graphical representations. The same apply to load models and provisions of current and previous codes of practice.

A large effort is required to obtain and store information for all existing bridges and this cannot be done within a short time period. Ideally, it could be done together with inspections or in-depth investigations and in this way, one can gradually fill the database.

Fortunately, there is a simplified method to assess safety and serviceability margins due to traffic loads. If the load model used originally for the design of a bridge is known, one can assume that the bridge is designed according to it. This means that the bridge resistance is in minimum as high as to sustain the internal forces due to the load model multiplied with the safety factor. In some sense, the originally used design load model is a proxy for the resistance (or service limit) of the bridge. However, to obtain internal forces, one still need a structural system.

Based on the experience from the load rating software (e.g. [7] and [8]) most non-landmark bridges can be simplified with a series of simply supported beams. Somewhat more sophisticated alternative is to model a bridge with a continuous girder as used in traffic simulations (e.g. [9], [10] and [11]). The simplified model considers only the load transfer in longitudinal direction. The load transfer in traverse direction i.e. across the deck is indirectly considered by defining appropriate effective widths. If the bygone codes of practice didn’t require dimensioning in traverse direction, the presented simplification can be problematic. Furthermore, modelling of skew decks or girders with skewed support with simply supported beams is challenging and requires good understanding of the load carrying paths in these structures. Further details on this approach can be found in [12].

Owners can decide, based on their needs to store

- the actual structural system as used in analysis or
- a continuous girder model as used often used in simulation to obtain maximum load effect or
- a series of simply supported beams as in some load rating software.

Independent of this choice, the results of a thorough structural analysis on an adequate structural system can be used to update the resistance (or service limits) of the model stored in the database. The safety or serviceability margins against the current design loads can be expressed therein either as

- the degree of compliance, that can be evaluated for each load situation as a ratio between the available resistance/service limit and resistance/service requirements based on the total factored load effect, or as
- the traffic load capacity factor with which the traffic load can be multiplied and still fulfill the safety and serviceability requirements.

The latter seems to be more useful for road authorities to assess special transports or future traffic load.

4.2 RELIABILITY OF UNDAMAGED BRIDGES

The modern codes define the safety and serviceability in terms of reliability i.e. the probability that a bridge will be fit for purpose during its service life. The partial safety factors in modern codes are calibrated to satisfy these reliability requirements. In [13] the target annual reliability index β for safety is 4.7 (corresponds to occurrence probability of $1.3\cdot10^{-6}$) and for serviceability 2.9 (corresponds to occurrence probability of $1.9\cdot10^{-3}$). The bridge is considered as safe and serviceable if specified reliability indexes are not below these target values. If for an existing bridge the degree of compliance is above 1, one can assume that the reliability index for safety exceeds the target value. However, the degree of compliance below 1 doesn't necessarily mean that the bridge doesn't meet reliability requirements. In [14] traffic load capacity factor is evaluated based on reliability assessment for 15 similar concrete bridges in UK that are constructed in 1960's and 1970's to the same design requirements. Nevertheless, the traffic load capacity factors – derived from reliability assessment - vary between 1.9 and 5.2. Given that at that time the design was based on global safety factor, the results are not surprising. For the bridges that are designed or examined using modern codes of practice the scatter is significantly smaller as demonstrated in [15]. However, even for these bridges the evaluation of reliability may be economically beneficial if existing bridges can still be used without restrictions.

Assessing the reliability of existing bridges can be tedious task as one needs to model all actions and material properties as stochastic variables. However, based on experience and available data, a simplified reliability assessment can be performed using the similar approach to the one mentioned in chapter 4.1 (see also [16]). The original design load situation can be used to assess the characteristic value of resistance R_c^o against the chosen failure mode. If the percentile of the characteristic value R_c^o and the type of its distribution is known, one can obtain the resistance distribution for a chosen failure mode. The recommendations for percentiles of characteristic values, standard deviations and distribution types based on construction materials can be found in literature (e.g. [17]). To compute load effects current design loading needs to be used. In general, several actions contribute to load effect and their characteristic values represent different percentiles of their distributions. In addition, the actions are modeled with different distribution types. For instance, the load effect due to the traffic load is normally modeled by extreme distributions. This is supported by measurements and simulation that are performed within research projects all over the world (e.g. [9], [10], [15], [18]). After all, traffic load models are derived from probabilistic analysis based on traffic simulations and weigh-in-motion measurements (e.g. [19]). The distributions for the self-weight and dead load as well as for other actions can be derived based on percentile assumption of their characteristic values following the recommendations from literature (e.g. [17]). The derivation of distribution for load affect *e* and resistance *r*, for the chosen failure mode is illustrated in Fig. 1.

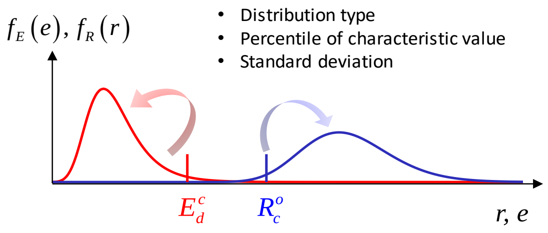

Figure 1. Estimating distribution of load effect and resistance

The load effect can be determined on the simplified structural system and the reliability index can be computed. The reliability obtained in this manner can be regarded as a rough estimate as the material and action uncertainties are modeled based on literature and experience data. These results can be improved if reliability analyses would be performed on the relevant sample of the bridges of same type. The systematic detailed reliability analyses can be also used to update assumptions regarding distribution of stochastic variables.

The traffic load capacity factor can be also obtained based on reliability assessment as in

[14]. It is a deterministic coefficient with which the stochastic effect of traffic load can be multiplied and still fulfill the reliability criterion.

4.3 INSPECTION AND IMPACT OF DAMAGES ON SAFETY AND SERVICEABILITY

In order to assess the impact of damages on safety and serviceability, the inspection procedures need not to change significantly. However, there is some additional information that is indispensable if the effect of deterioration and damages is to be appropriately considered in assessment of bridges:

- Based on the design documentation, relevant failure modes need to be defined. These failure modes correspond to the critical load situations used in design and
- for each failure mode, vulnerable zones (see [20] and [21]) are to be defined, in which damages have the largest impact on safety and serviceability.

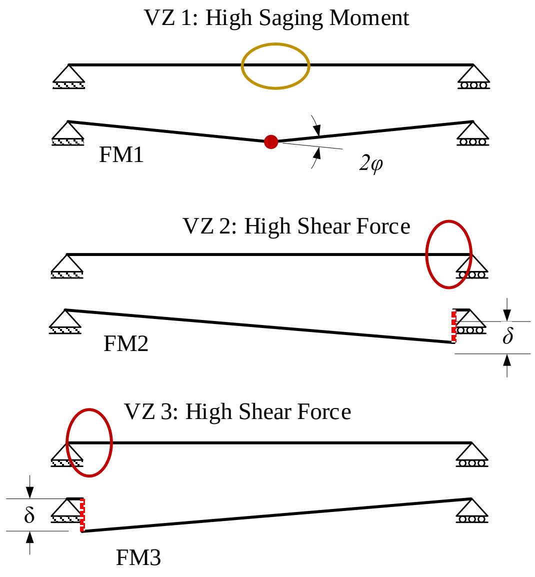

Figure 2. Vulnerable zones and failure modes

Experienced inspectors know intuitively where these zones are, but they can confirm themselves with the readily available information in [22]. The damages outside vulnerable zones can also trigger failures, but for them to occur the extent of damage needs to be significantly larger than in the vulnerable zones. If this seems likely, one needs to define an additional failure mode that can be triggered by the observed damages.

For a simply supported beam the vulnerable zones and corresponding failure modes are illustrated in Fig. 2. In this example failure modes (FM1, FM2 and FM3) are chosen to be collapse mechanisms. However, other failure modes can be selected based on owner’s preferences. For instance, the extent of spalling or crack width can be chosen to be failure criteria.

For each failure mode, the corresponding degree of compliance, if semi-probabilistic format is used, or reliability, if probabilistic assessment is required, is to be evaluated for an undamaged bridge. This can be done beforehand either using the simplified approach described in chapter 4.1 and 4.2 or by in-depth examination as described in chapter 4.5.

4.4 REALIABILITY OF DAMAGED BRIDGE

The estimation of the impact of inspection (mostly visual) findings on reliability is up to now not seriously considered as a viable option. Visual inspections are considered to be subjective and uncertain allowing only qualitative outcome such as condition rating. Although it is undeniable that observations made during visual inspection are often fuzzy, they can be useful if their inherent uncertainty is modelled properly. In [23], a subset of observations collected in a survey are identified to have an impact on reliability. The corresponding uncertainties both regarding the inspection process and an impact on reliability are however not addressed, which remains to be the topic of a future research.

In addition, there is also useful data that is simply not collected. For instance, if merely “Corroded reinforcement” on a certain bridge element is reported, this means that the reinforcement corrosion can be anywhere on its elements i.e. its location needs to be uniformly distributed. Likewise, a spalling area and a section loss can be also modelled with slightly informative or non-informative distributions. If, however additional information is available such as that the reinforcement corrosion is located in vulnerable zone, the uncertainty with regard to its influence on reliability can be significantly reduced. The quantitative information on spalling area and section loss can further reduce uncertainty.

To consider the effect of inspection findings the Bayesian network can be used as shown in Fig. 3. In this example it is assumed that the visual inspection revealed a spalling area with the reinforcement corrosion with a section loss of e. g. 10%. This is a typical entry as shown in the survey performed by the WG1 of the COST Action 1406 (see [23]). The location of the defect is not known and there is inherent uncertainty with regard to this section loss, which can be modelled in the node “Corroded reinforcement” in Fig. 3.

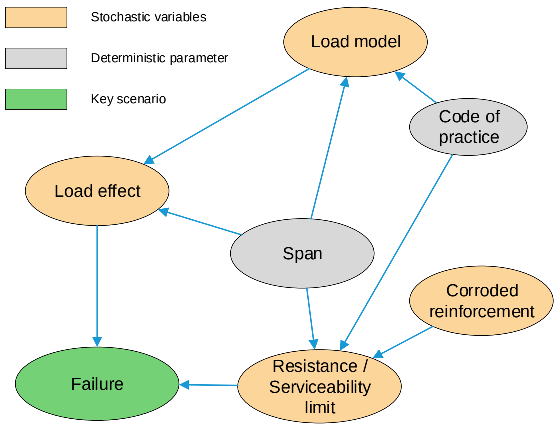

Figure 3. Reliability evaluation of damaged bridge

4.5 IN-DEPTH INVESTIGATIONS

If the results of an inspection raise doubts regarding acceptable safety and serviceability, the in-depth investigation should be triggered. The in-depth investigation should include all measures that may reduce uncertainties such as testing of material properties, checking of dimensions, stiffness measurements, etc. Furthermore, archive documents must be duly examined since they may reveal assumption made regarding load situations and material properties. For hidden structural elements such as foundations and reinforcements, old plans are the only source of information. Finally, the exposure of bridge to natural hazard needs to be investigated based on the newest findings (e.g. update of magnitudes, re-assessment of site condition).

The structural analysis needs to be performed with nonlinear methods that address failure modes appropriately and yield realistic failure probabilities. This doesn’t necessarily mean that sophisticated analysis is necessary, in most cases the skillful application of the limit theorems of the theory of plasticity is sufficient.

The bridge should be examined for all relevant load situations and the results need to be stored in the database in a structured form. Gradually, by means of in-depth investigations, high quality information on all bridges will be stored in the databases allowing bridge owner to manage their inventory efficiently. The growing experience will also allow for more accurate assessment of reliability based on inspections as Bayesian nets can be updated introducing new high-quality data.

5. MAINTENANCE PLANNING

Bridge Management is not confined to bridge assessment based on inspections and in-depth investigations but also includes maintenance planning. The short-term maintenance planning is based on in-depth investigations and structural analysis and include detailed specification of interventions that are to be taken shortly thereafter. The mid- to long-term maintenance planning is a process, in which different intervention scenarios are developed. The interventions are not specified in detail and their costs are rough estimates backed by experience. The goal is to estimate financial and other needs well in advance and avoid unpleasant surprises. Furthermore, early planning allows to choose the optimum time for interventions and reduce long-term costs.

The general approach is presented in Fig. 4, where it is assumed that an inspection is performed “today”. The results from the inspection revealed some damages that in conjunction with the actual loads lead to worsening of the safety and serviceability levels that, however, still meet the requirements for existing structures. This procedure is explained in previous chapters. For mid- to long-term maintenance, planning forecasts for serviceability and safety are performed predicting that serviceability criterion will be not fulfilled at the time instance marked “Tul”. This means that the intervention needs to be executed no later than at that point in time, if serviceability requirements are not to be violated. However, it may well be that a scenario that includes an intervention at the time instance “Top”, has lower long-term costs than the one with the intervention at the time instance “Tul”. The Fig. 4 doesn’t show any interventions after “Tul”, but normally the ensuing interventions are considered in long-term costs.

The forecasts of safety and serviceability over time defines the time instance at which, at the latest, an intervention is necessary. However, these forecasts cannot be used to define the type and the costs of the interventions. To this end afore-mentioned qualitative indicators (e.g. condition rating, condition state, condition class, etc.) are used. The application of qualitative indicators to generate interventions is well-established in current approaches to maintenance planning as explained in the following chapter. The problem lies with the usage of these qualitative indicators as proxies for safety and serviceability. The worst condition state represents herein the safety and

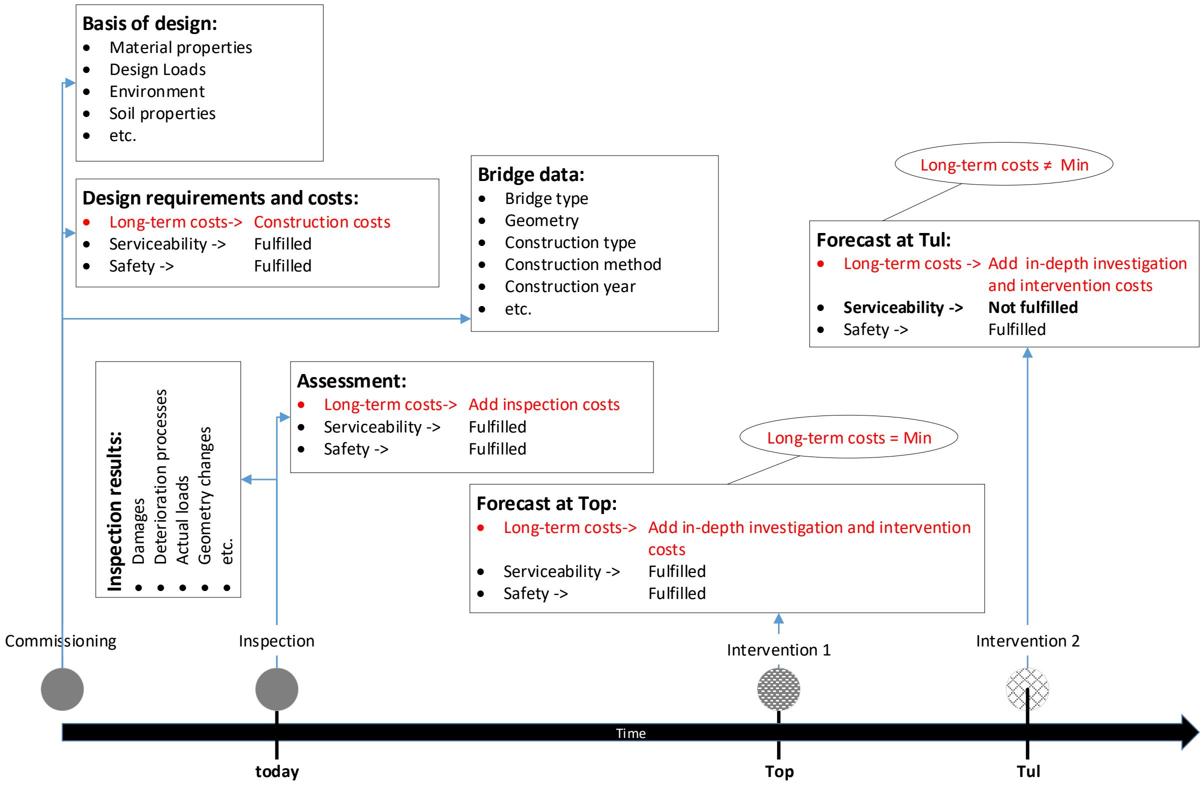

Figure 4. General approach to mid- to long-term maintenance planning

serviceability threshold. To remedy this problem of mid- to long-term maintenance planning adaptations are suggested that are explained in the following chapters.

5.1 CURRENT APPROACH TO MAINTENANCE PLANNING

Currently, maintenance planning is based on qualitative indicators. The procedure can vary quite significantly from country to country, but the main distinction lies in the choice of **assessment unit**. The assessment unit is the physical entity of the lowest granularity that is assessed during inspections. The assessment units can be whole bridges, bridge components (super-, substructure and equipment), bridge elements, group of damages or even single damages. All these different assessment units can be found in current BMS, based on the owner or operator's needs.

The scale of condition state is chosen in such a manner that only if an assessment unit is assigned into the worst condition state – being a proxy for safety and serviceability thresholds - immediate interventions are required. The maintenance planning considers therefore only interventions that are to be initiated before the worst condition state is reached. The optimum maintenance intervention(s) is/are the ones that minimize the long-term agency costs and in some cases user costs during these interventions, as in [24].

The interventions are performed on **planning units** that in some BMS coincide with assessment units and in the others, they differ from them. If assessment units are damages, then it is often more reasonable to plan interventions on affected bridge element or the whole bridges than on a single damage. Based on the condition state of assessment units, the intervention on planning units are determined based mostly on heuristic rules. To this end, technically feasible maintenance intervention on planning units are catalogued together with their unit costs and effectiveness. For instance, for the same condition states of assessment units, both rehabilitations on elements as well as replacement of the whole bridge are technically feasible. The choice of the optimum intervention is subject to minimization of the long-term costs as in [25].

This approach has significant drawbacks since it focuses solely on restoring damage-free bridges, without considering directly the safety and serviceability or consequences of possible failures. It is therefore that mid- to long-term maintenance planning can significantly deviate from the short-term planning and executed interventions, which are often triggered by safety and serviceability criteria.

5.2 DETERIORATION MODELS

The key ingredient of mid- to long term maintenance planning is a deterioration model. The deterioration model allows condition state forecasts of assessment units and determine possible maintenance interventions in the future. The deterioration models can be derived from physico-chemical deterioration processes, and there is significant research in this area (e.g. [26], [27]). Notwithstanding the undeniable progress in this research, most deterioration models in current BMS are based on statistical analysis of past condition data (e.g. [28], [29]). Many BMS use Markov chains to model deterioration as it supports the discrete scale for condition states and transition probabilities can be easily derived from condition data. Finally, with Markov decision process, which is based on Markov chains and catalogued interventions, the optimum set of intervention can be estimated with modest computational effort. However, Markov chains are mostly employed for elements or components, whereas their applicability for individual damages waits to be proven.

5.3 IMPROVEMENT TO THE CURRENT APPROACH

The current approach to mid- to long-term maintenance planning based on condition states of assessment units is used quite successfully to define maintenance scenarios and estimate long-term costs. However, it doesn't consider safety and serviceability directly and therefore the estimation of the optimum time instance to perform intervention can be quite wrong. A bridge with high safety and serviceability margin may be used significantly longer than suggested by an assessment unit in the worst condition state. The opposite is also true: A bridge barely meeting serviceability requirements may need to undergo an intervention even before a single assessment unit reaches the worst condition state.

On one side, it is necessary to estimate both condition states of assessment units and based on them define intervention scenarios on planning units and related costs. On the other side, the reliable forecast of safety and serviceability are needed to estimate the remaining service life without interventions. It is shown in the previous sections that meaningful safety and serviceability assessment is possible only if individual damages or damage groups underlying the same damage process are assessed. This means that the assessment unit must be either an individual damage or a damage group. Consequently, the deterioration models need to be developed for these assessment units and based on the evolution of these assessment units, the safety and serviceability can be evaluated. The current deterioration processes used for elements and components can be quite useful as baseline for calibration of deterioration models for damages and damage groups.

The improved approach is presented in Fig. 5 with damage group as assessment unit as in Swiss Bridge Management System KUBA. An individual damage can also be a damage group, so there is no loss of generality if a damage group is used as an assessment unit. The basic bridge data include apart from element data also the most probable failure modes. These failure modes can be determined from bridge design documents as explained in 4.3. A bridge can have several elements and several failure modes. A failure mode can include several vulnerable zones as shown in 4.3. For instance, a collapse mechanism of an hyperstatic structure has always several places where rupture or yielding occurs and these are vulnerable zones. These vulnerable zones can also participate in several failure modes. Hence, there is many-to-many relationship between the “Failure mode” and “Vulnerable zone”.

Using the deterioration model for an assessment unit, the severity and extent of the damage group can be predicted at some time point T. The impact of the damage group on resistance and/or service limits in vulnerable zones can be estimated using heuristic rules or Bayesian nets as in [30]. Following the same procedure as in 4.1, the degree of compliance for safety and serviceability at the time T can be assessed. These steps are represented in the gray column in Fig. 5 to highlight the addition to current maintenance planning procedure.

The path from damage group forecast at time T to maintenance interventions is already implemented in KUBA and many other BMS. Herein, the catalog of technically feasible maintenance interventions for each damage type and severity of a given element type is of pivotal importance. The cataloged interventions are characterized by their unit costs and effectiveness. The cost predictions are generated by the heuristic rules and optimization depend on these data. The catalog is the result of a statistical analysis of executed preservation projects and is subject to changes reflecting developments in construction industry. The unit costs refer to a specific measurement unit. The unit for maintenance

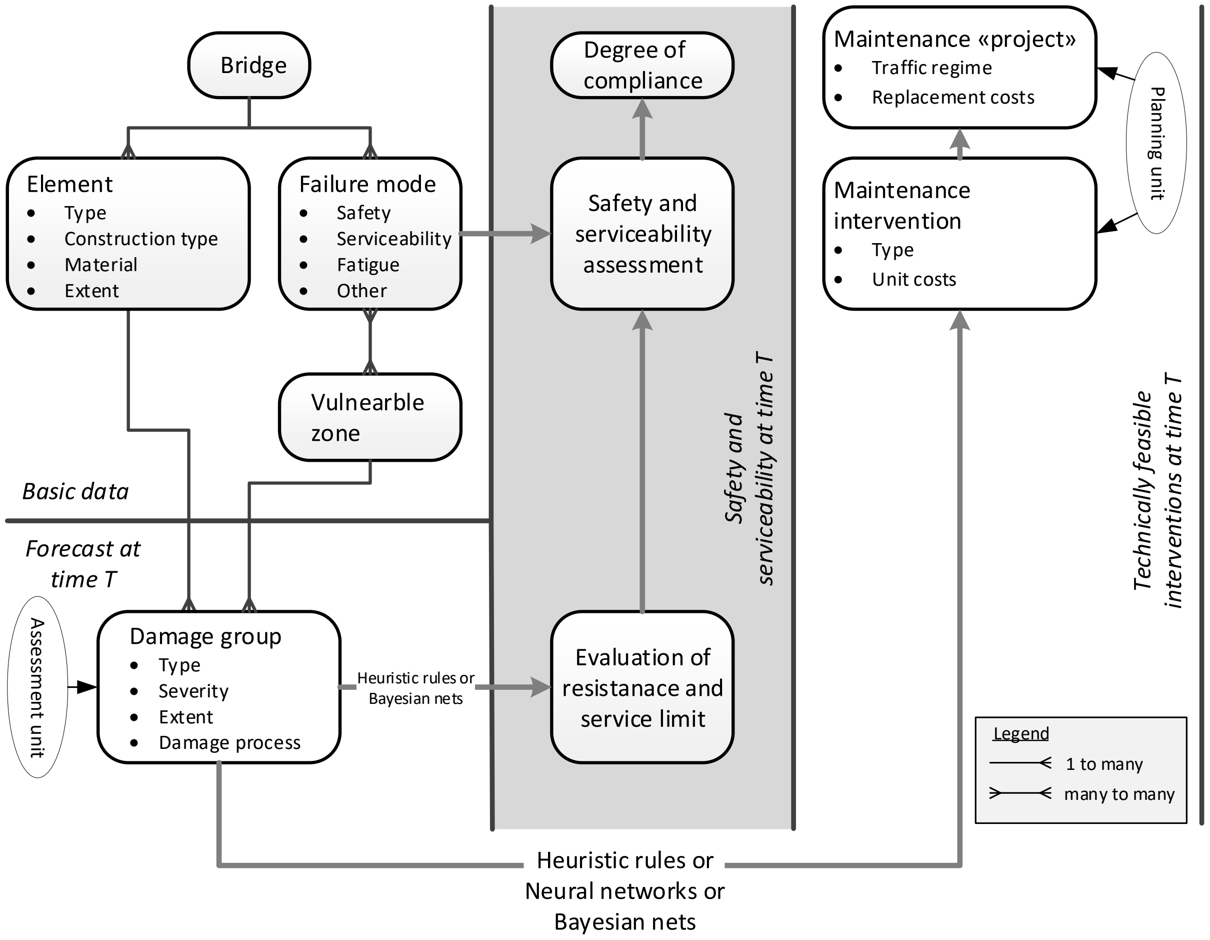

Figure 5. Assessment of degree of compliance related to safety and serviceability and determination of maintenance intervention at time T

work on steel elements, for example, is the square meter [m^2], i.e. the surface area. This unit must be the same unit used to measure the extent of damage groups.

The technically feasible maintenance interventions are then aggregated using heuristic rules and threshold values in maintenance “projects” on bridge level. The quotation marks indicate that these are not engineering “project”, but rather a very general outline of the maintenance work that is feasible at the time T. In addition to “projects” aggregated from elements, a replacement “project” is added as an option, as it can be assumed that it is the costliest maintenance option. For the high-volume bridges, a traffic regime and eventual closures during the execution of the maintenance works needs to be defined. This information is needed to evaluate societal costs. The interested reader can find further details on estimation of user costs in [31].

A maintenance intervention results in improvement in degree of compliance regarding safety and serviceability. Currently, the estimation of this improvement is not possible, since there are only data on improvement in condition states. Also, similar refers to the effectiveness of the intervention. Still, the effectiveness of intervention related to condition states can be useful: If the condition state is restored to the best condition state after the intervention, one can assume that also the degree of compliance of the undamaged bridge is restored.

In summary, the proposed improvements allow decision maker to

- estimate remaining intervention-free service life of a bridge in rational manner, using safety and serviceability assessment,
- consider the improvement in safety and serviceability and compare with the costs to obtain this improvement, and
- plan reliable financial needs and needs for other resources on mid to long-term, considering the forecasts of traffic loads.

The data collection effort to implement these improvements is quite modest. However, the data needs to be collected conscientiously and the procedure to evaluate degree of compliance related to safety and serviceability needs to be updated to match performed in-depth investigations.

One step further would be to replace the degree of compliance with reliability assessment at some time T as explained in 4.2. The estimation of reliability over time as in [32] is just a stepping stone to estimation of risk over time.

5.4 APPLICATION OF BIM

It is foreseeable that Building Information Models (BIM) of both newly built and existing bridges will be available (see e.g. [33] and [34]). These models will be included into the Bridge Management System (BMS) and will significantly enhance the quantity of useful information in future BMS (fBMS). A BIM can embed realistic structural system of a bridge as well as the relevant load situations (see [35]). The evaluation of the reliability or safety/serviceability would be therefore possible quasi, on-the-fly within the fBMS, provided that the observations and results from SHM can be adequately integrated in BIM.

In principle, the inspection results can be directly captured in the BIM using photogrammetry or some other procedure. Cracks, spalling, deformation, and other defects will be a part of a BIM, which in most cases alter the BIM geometry. An information model and a candidate binding to Industry Foundation Classes (IFC) has been developed in [36]. In [38] the damages are modelled using exiting IFC entities. Both studies demonstrated that that IFC provides sufficient functionality to serve as a basis for integrating relevant defect information and imagery.

The results of past inspections, e.g. damages are stored in a temporal BIM, which is an enhancement of the existing temporal databases. This would enhance possibility to statistically estimate deterioration models. Furthermore, the temporal BIM is a valuable data source that will allow researchers to better understand physical deterioration processes. The data stored in fBMS include also other changes that a bridge experience during its life span. This includes strengthening, widening, seismic retrofit and other structural changes. In short fBMS is similar to the 6D BIM or Asset Information Model (see [37]), which continues to be updated during the whole service life of a bridge.

For purposes of maintenance planning, the BIM with damages can be used as the basis for the deterioration simulation, which can provide significantly more accurate forecast that the current methods. The reasons for this are twofold:

- The resistance and loads i.e. probability of failure of an intact structure is duly taken into account.
- The exact location of a defect is known so that its effect on the safety and serviceability can be assessed in a more accurate manner.

The same applies to maintenance scenarios, which can be determined more accurately, both regarding their types as well as regarding their costs estimates.

6. CONCLUSIONS

The need for more economic utilization of transportation infrastructure is also a challenge for bridge owners. They need to have readily available, high quality information on their bridge inventory in order to cope with gradual deterioration, growing traffic demands and increased frequency and magnitude of natural hazards. To obtain and store this information is a task that cannot be accomplished in a short time. In this paper, the methods are proposed that use data that is already available and allow their gradual refinement. They allow better exploitation of inspection results to assess safety and serviceability and improved decision making regarding in-depth investigations and maintenance interventions. The assessment of safety and serviceability during the whole service life allows also more responsive processing of special permits and established corridors for heavy weight vehicles.

The presented methods are only steppingstones toward a new generation of BMS that will integrate BIM and allow more accurate and prompter information on bridge behavior. Current databases need to be enhanced with BIM. The data generated during the design and construction process must be handed to the authorities or operators that act henceforth as their trustees. It is essential that this data can be transparently and intuitively used in the exploitation phase. To this end, the owners need to set requirements that are independent of software packages used in design and construction phase.

Finally, the road authorities and/or operators must provide both financial and personal resources to maintain a fBMS and its data. Owners need in-house competence both in structural and decision engineering as well as in information technology similar to the banking sector, where competence in information technology, financial and decision engineering is required. It is not a coincidence that in both sectors the term “Asset Management” is widely used.

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