Assessment of existing steel bridges: codes and standard

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Abstract. The assessment of existing structures adopting a specific code or standard is a technical procedure that is provided only in some nation. The possibility of harmonizing these type of procedure is needed in Europe, together with a completely new plan of infrastructural renewal. In this study new insight on this theme are provided, together with some code proposal for the new Eurocode era. Many existing bridges all over the world were not designed for the high service loads and the increased number of load cycles that they are exposed to today. Some bridges will have to be either strengthened or replaced in the next decades. Advancing their age, bridges could be subjected to a large variety of not designed actions or could also be not accurately maintained, leading to a particular state in which they need particular care and attention, in order to remain in service. Moreover, existing structures were not exempted from serious failures and engineers had regularly to suffer setbacks. These setbacks contributed in many cases, however, to research and advancements in better understanding structural behaviour and developing new theories (Kuhn et al. 2010). In these cases, the assessment procedures are needed.

1. Introduction

Many existing bridges all over the world were not designed for the high service loads and the increased number of load cycles that they are exposed to to-day. Some bridges will have to be either strengthened or replaced in the next decades. Advancing their age, bridges could be subjected to a large variety of not designed actions or could also be not accurately maintained, leading to a particular state in which they need particular care and attention, in order to remain in service. Moreover, existing structures were not exempted from serious failures and engineers had regularly to suffer setbacks. These setbacks contributed in many cases, however, to research and advancements in better understanding structural behavior and developing new theories (Kuhn et al. 2010). In these cases, the assessment procedures are needed. The assessment of an existing structure aims at producing evidence that it will function safely over a specified residual service life. It is mainly based on the results of assessing hazards and load effects to be anticipated in the future, and of assessing material properties and geometry taking into account the pre-sent state of the structure (JCSS 2001). Guidelines for existing structures exist in a large number of countries. Thereby many countries have presented documents for particular categories of structures. In Canada, Germany, the Netherlands, Switzerland, UK and USA such guidelines have been prepared at a detailed level. In any assessment, the problem of fixing risk acceptance criteria is difficult since it must be compatible to codes for new structures (limit state analysis, safety factor format, etc.), and with national determined parameters (generally partial safety factor values) (Kuhn et al. 2010). As far as specific code and standards are not available,
technical guide or pre-standard documents should be used. Moreover, procedures coming from
evidenced based or field related experience, are quite extensively used also by bridge and
infrastructures owner. Basing on past studies and research, a simplified approach has been developed
by the author and applied in recent investigations of existing bridges. This approach is reported in the
following paragraphs.

![Figure 1: A multi span historical truss bridge.](image)

2. The assessment procedure of existing bridges

Ist level: The preliminary evaluation is the first level of investigation aiming at removing existing
doubts about the safety of existing structures, adopting fairly simple methods and identifying critical
parts or members in the structure. In order to identify critical members, it is necessary to carry out an
intensive study of the available original design documents, along with a visual inspection of the
structure and a photographic survey. The inspection procedure is often coded by infrastructural
agencies manuals and procedures; however, at least the following points must be checked:

- The bridge construction is conforming to the original drawings and/or differences between
  as-built and drawings.
- Bridge modification during service (rehabilitation, strengthening, changes in the static
  system, etc.).
- Presence of any visual evidence of degradation (damaged expansion joints, supports,
corrosion, cracks, vibration or loose rivets, collision, lack of structural members etc.).

Moreover, if available, inspection and maintenance reports can be used, and reference should be made
to the evaluation report. The preliminary evaluation should include codes and recommendations
analysis procedure where available, and conservative assumptions where information is lacking or
doubtful. In this way, critical construction details can be identified.

IInd level: The aim of the detailed investigation is to update the information obtained in other analysis
by carrying out a refined assessment, especially for those members for which adequate safety was not
confirmed by preliminary evaluation. At this stage a specialized consultant should assist. In this phase
a FEM numeric model of the entire structure is developed. Based on the current code provisions, the
structure should be recalculated, and verification tables should report whether the structural members
are safe or not. Concerning specific issues, such as the fatigue and seismic behaviour of the bridge,
detailed code provisions should be referred to. From this step-level investigation, non-destructive
testing (NDT) could be used in order to characterize the basic material properties of the structure. The
final report of the investigation should establish whether the structure is verified against specific issues
and has sufficient static strength against actual loadings.
IIIrd level: In case of key structures that have major consequences in terms of risks or costs related to a decision, a team of experts is needed in order to carefully check the conclusions and proposals reached in the last phase. Discussions and further assessments using specific tools can also be carried out to help reach decisions. At this level, on-site testing could be adopted in order to provide the dynamic identification of the structure, as reported in the following example.

IVth level: This advanced level of investigation should be reserved for recurrent bridges along infrastructural nets, in which a rational procedure of analysis and intervention could help in determining if retrofitting interventions could be adopted, or if rational dismantling large scale operations are required. The procedure is based on a detailed survey of the existing bridge, a FEM analysis, a code verification procedure, NDT diffused sampling, and, based on these data on real scale testing of one case study structure, aims to determine the global static and cyclic behaviour of the bridge. In specific cases, on-site dynamic identification could be performed. Concerning the fatigue assessment, in this case a LEFM investigation is required. Concerning seismic analysis, non-linear analysis is required. Specific material testing analysis should be performed dealing with the case analysed. The advanced testing result should report on the various analysis performed and should clearly state verification results indicating the specific retrofit needed for recurrent interventions. An advanced testing operation is reported in the following section, dealing with a recurrent existing bridge type in service along the railway lines.

3. Assessment case studies

As reported in the aforementioned step level classification, various stages of analysis could be adopted by bridge owners or managing agencies. Some examples have been developed by the author and could be found in detail in Pipinato (2016) the assessment of a new bridge is presented in order to evaluate different typologies of construction alternatives to gain different lifetime; while in Pipinato (2014) the assessment and rehabilitation of steel railway bridges using fiber-reinforced polymer (FRP) composites in the particular situation of the rehabilitation of metallic civil infrastructure using fiber reinforced polymer (FRP) composites is evaluated. The residual life of historic riveted steel bridges could be also assessed with an analytical approach or introducing an orthotropic steel deck design to extend the lifetime of plate and box girder bridge and viaducts, as explained in Pipinato et al. 2014 and in Pipinato (2014a). And however steel bridge exhibited in the past a wide amount of problems not evidenced in other bridges (Pipinato 2014b), for this particular type of structure a variety of technologies to repair and retrofit are available: this is the case reported for the fracture propagation and life cycle design of girders (Pipinato 2014c), or for advanced solutions of the corrosion protection (Pipinato 2014d). For network of bridges, however, an integrated solution has been presented in order to understand what is the possibility of prioritizing the bridge retrofit (Pipinato 2013a). A particular asset of bridges in which the lifecycle assessment should be performed from the design stage is the case of long span bridges, where the traffic is represented also from exceptional moving loads and the consequent fatigue expected lifetime could fail in less than ten years from the construction stage if a correct detailing is not perceived (Pipinato 2013b-2013c-2010d); similar issues comes also from the original construction alternative choses, as demonstrated in Pipinato et al. 2012a. The particular case of fatigue sensitive materials of course is more recurrent in steel bridges where retrofit and assessment alternatives are in part applied (Pipinato 2012b), in part not well investigated, as is the case of coupled damages (seismic and fatigue, Pipinato 2012a,b, Pipinato et al. 2012c,d,e,f, Pipinato et al. 2011c,d). Wherever there is the possibility to investigate with full scale tests existing bridges, e.g. where managing agencies are interested to know the structural behaviour of recurrent structures along their network, this could be an interesting occasion to understand how materials decay could influence the static and fatigue behaviour of bridges: this is the case both of railway (Pipinato et al. 2011a,b, Pipinato 2011, Pipinato 2010b, Pipinato et al. 2010a,b,c,e Pipinato 2010, Pipinato et al. 2009, 2008a,b, Pipinato et al. 2007) and roadways (Pipinato 2010a). A particular and further subset is represented by monumental and large bridge structures (Pipinato and Modena 2010): in this case, a long and time-
consuming but useful procedure should be performed, by evaluating all the assessment steps described before, in order to understand in detail the aforementioned problems that could influence the final retrofit design decision.

4. Estimation of knowledge level and confidence factor

The application of the aforementioned assessment procedures, lead to consequences in the structural analysis of the structure. Generally, as much information and tests have been performed onto the bridge, as much knowledge has been accumulated onto the structure, leading to more accurate data on the structural properties of materials, and on the structural behaviour of the bridge itself. On the basis of this, a knowledge level listing could be drafted out, and consequently the so-called confidence factors could be applied, in a very similar procedure to the Italian existing standard for the assessment of existing buildings (Ministerial Decree, 2008).

KL1-Knowledge level 1:
- Geometry: the geometry of the structure is known or from a survey or from original drawings. In the latter case a visual survey is required to confirm the documentation. Collected data should be sufficient for developing a linear analysis.
- Structural details: details are not available from drawings and are designed according the practice of the construction age. A limited in situ verification is requested. Local resistance verification are required.
- Materials property: material properties are not available, neither from the original documents, nor from original tests. Usual values of the practice are adopted, validated from limited in-situ tests.
- Structural analysis type: The safety assessment in the case of limited knowledge is usually performed by static and dynamic linear analysis methods.

KL2-Knowledge level 2:
- Geometry: the geometry of the structure is known or from a survey or from original construction drawings. In the latter case a visual survey is required to confirm the documentation. Collected data should be sufficient for developing a linear or a non-linear analysis.
- Structural details: details are available from original drawings or from not original construction documents. In this last situation, a limited verification of common details is performed. Local resistance verification are performed.
- Materials property: material properties are available, from the original documents, or from original tests. Extensive in situ tests are performed to validate the original data whereas they are available from design and not from tests.
- Structural analysis type: The safety assessment in the case of limited knowledge is usually performed by static and dynamic linear or non-linear analysis methods.

KL3-Knowledge level 3:
- Geometry: the geometry of the structure is known or from a survey or from original drawings. In the latter case a visual survey is required to confirm the documentation. Collected data should be sufficient for developing a linear or a non-linear analysis.
- Structural details: details are available from original drawings or from original construction documents. Available data enable the implementation of a complete linear FEM model, performing local resistance verification, or the implementation of a non-linear model.
- Materials property: material properties are available, from the original documents, or from original tests, or from an extensive in situ testing program. In the first case, limited in situ tests are developed to confirm the historical values; if the values obtained are minor than the original, an extensive in situ program is settled and performed. Available data enable the implementation of a complete linear FEM model, performing local resistance verification, or the implementation of a non-linear model.
- Structural analysis type: The safety assessment in the case of limited knowledge is usually performed by static and dynamic linear or non-linear analysis methods.
The confidence factor range should be calibrated according to the engineering knowledge level of the structure. Suggested values are in the following range:

- Confidence factor $\alpha$: 1.30-1.35
- Confidence factor $\beta$: 1.20-1.25
- Confidence factor $\gamma$: 1.00-1.10

Although this procedure is suggested, it remains on the engineering choice of the structural engineer to establish the use of the confidence factor of the corresponding knowledge level, or in alternative, to use a lower confidence factor, when doubts arise from calculation. The confidence factor (CF) is considered a partial safety factor to be applied to the design strength in order to take into account for the lack of knowledge when analysing existing structures:

$$ F_d = f_m / (CF\gamma_m) $$

5. Bridge rating worldwide

The AASHTO LRFR Guide Manual is the first bridge load rating method in the United States to be based on modern principles of structural reliability and limit states design. The essential ingredients of a reliability-based design and evaluation include probabilistic models of the structural resistance and loads and a method for analysing the reliabilities (or, conversely, the limit state probabilities) that are relevant to each bridge limit state. Such methods and tools have been applied to developing the AASHTO LRFD Specifications and the LRFR Guide Manual and are expected to be relevant also to improve rating methods for other countries. Details are available in the archival literature (Nowak, 1999; Moses, 2001).

Section 7 of the Austrian Bridge Design Standard provides rating guidelines with a commentary. The concept of rating is based on the limit state design philosophy and both serviceability and ultimate limit states are considered. The ultimate action is defined as an action that has a 5% probability of being exceeded during the design life, which represents an average return interval of 2000 year; while the survivability action is defined as one having 5% probability being exceeded per year, corresponding to a return interval of 20 years.

Document BD 21/01, Assessment of Highway Bridges and Structures, adopts a limit state format with appropriate partial safety factors for condition evaluation of most highway bridges except for cast iron bridges and masonry arch bridges. It is stipulated that bridges built after 1965 should normally be evaluated for serviceability as well as for the ultimate limit states; bridges constructed before 1965 do not need to be assessed for service limit states. Requirements for fatigue endurance however are not included in the standard and the reason stated is that the past stress history of each structure, which could profoundly influence fatigue limit checking, cannot generally be determined to the accuracy level required for assessment.

The GBSM (2012) is a reference document dedicated in particular for railway bridges. However, it shows a clear and easy procedure for the bridge analysis.

6. Conclusion

The assessment of existing structures adopting a specific code or standard is a technical procedure that is provided only in some nation. The possibility of harmonizing these type of procedure is needed in Europe, together with a completely new plan of infrastructural renewal. From the analysis of the documents presented, a review of existing assessment approaches and states rating practices have revealed a number of research issues that must be addressed for existing bridges evaluations (GDT 2009):

- The bridge may contain archaic structural materials. Design documentation may be missing.
- Material strengths in situ may be vastly different from the standardized or nominal values assumed in design. On the one hand, concrete strength can increase by as much as 150% beyond the 28-day standard basis due to continued hydration; on the other hand, the strength can deteriorate due to
aggressive environmental attack from physical or chemical mechanisms. Failure to consider best estimates of strength and the time-dependent nature of the structural strength and stiffness invariably will lead to an erroneous estimate of in situ strength.

- Analytical approaches to bridge evaluation usually (but not always) yield a conservative measure of actual load-carrying capacities [Bakht and Jaeger, 1990]. This conservatism is the result of assumptions made in the analysis regarding load sharing, composite action, support conditions and nonlinear behaviour, in addition to differences in material strengths noted above.
- Discrepancies among the different approved rating methods were noted. These discrepancies were confirmed by preliminary rating calculations performed on bridges. The reasons for these differences must be completely understood and addressed in developing new guidelines or codes.
- Satisfactory bridge performance over a period of years of service provides additional information not available at the design stage. This information should be taken into account in designing in-service inspection programs and in making decisions regarding upgrading and rehabilitation.
- Current condition assessment relies heavily on visual inspection. More quantitative models of structural deterioration have been developed but have yet to be incorporated in condition assessment procedures.
- A test load must be a significant fraction of the expected maximum live load for the proof test to be informative and to lower subsequent risk. If the test load is increased to an informative level, the probability of damaging the bridge during the load test increases as well. This trade-off between information gained and likelihood of damage must be part of the decision to load-test a bridge rather than relying on other rating methods.
- Uncertainties in loads and resistances at the design stage are reflected in the safety factors (or load and resistance factors). At the evaluation stage, uncertainties can be either greater (e.g., due to deterioration) or less (measured properties; successful load test). These uncertainties must be identified and analysed.

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