Sustainable Bridges – Past and Future
Reflections on a European Project 2003 - 2007

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Abstract

Twenty years ago, in 2003, a European project was started to increase the sustainability of existing railway bridges. This paper summarises what was achieved and looks ahead. Nine Working Packages were organized: (1) Background material; (2) Guidance by stakeholders; (3) Condition Assessment and Inspection Guidelines; (4) Loads, Capacity and Resistance Guidelines; (5) Monitoring Guidelines; (6) Repair and Strengthening Guidelines; (7) Demonstration with Field testing of Bridges; (8) Demonstration on Monitoring on Bridges; and (9) Training and Dissemination

Some of the main results (from 4 Guidelines and 47 Background documents) are highlighted and some experiences, conclusions and thoughts about the future are given. Hidden strengths and weaknesses are discussed, analyses and codes for assessment can be improved, new monitoring and strengthening methods are available and life length can be prolonged.

Keywords: Bridges, Management, Assessment, Modelling, Monitoring, Testing, Codes, Load-carrying capacity, Strengthening, Life-length

Figure 1. Three types of existing railway bridges being studied: Masonry Arches, Steel Beams supported by Reinforced Concrete Arches and a Steel Truss carried by a Steel Arch.

1 Introduction

"Sustainable Bridges – Assessment for Future Traffic Demands and Longer Life Length" was a project carried out in 2003-2007. The overall aim was an increased use of the European railway network, by allowing higher axle loads on freight vehicles and increasing the maximum possible speed of passenger trains. The project established the following three specific goals for bridges:

- Increase the transport capacity
- Extend the residual service life
- Enhance management, strengthening and repair systems

A consortium was formed of 32 partners drawn from railway undertakings, consultants, contractors, research institutes and universities to undertake an Integrated Research Project to be funded by the European Commission and the partners, [1].

2 Background and Guidance

The work wasn't limited to a specific bridge type or material, but aimed to be of universal applicability, see Figure 1. The work was organized in nine Working Packages, WPs. One of them, WP2, provided guidance from the stakeholders, while five produced background reports to four guidelines:

- Inspection & Condition Analysis (ICA) [2]
- Load & Resistance Assessment (LRA) [3]
- Monitoring (MON) [4]
- Repair & Strengthening (STR) [5]

Two WPs worked with field testing of bridge capacity and monitoring and the last one with dissemination, see Table 1 and [6]. In the following, some of the still valid results are presented together with reflections on how to make our bridges more sustainable.

3 Inspection & Condition Assessment (ICA)

The Guideline [2], is divided into 11 Chapters and 3 Annexes concerning among other things:

- Review of the railway bridges inspection practice in Europe (Chapter 2);
- Classification of degradation processes (Chapter 3);
- Review of the railway bridges assessment and condition rating practice in Europe (Chapter 4)
- Non-Destructive Tests (NDT) toolbox (Chapter 5 and Annex 3);
- Detailed guidelines on the inspection and condition assessment of concrete, metal and masonry arch bridge superstructures, and the bridge transition zones (Chapters 6 to 9 respectively);
- Description of terminology (Annex 1) and Defect catalogue (Annex 2)

- *Table 1. Overview of Publications (Web Address: https://ltu.diva-portal.org/smash/. Search for "Sustainable Bridges Background Document X.X" or Title)*

Sustainable Bridges Background Reports

WP 1 - Start up and Classification
1.2 European Railway Bridge Demography, 15 pp.
1.3 European Railway Bridge Problems, 18 pp.
1.4 European Railway Research, 44 pp.

WP 3 - Inspection and Condition Assessments
3.2 Inventory on condition assessment methods, 63 pp.
3.3 Condition Assessment Procedures, 79 pp.
3.4 Steel bridges. Stress measurements, 94 pp.
3.5 Combination of radar data of different polarisation, 48 pp.
3.6 Scanning system for concrete surfaces, 23 pp.
3.7 Impact-echo system for crack depth measurement, 29 pp.
3.8 Radar tomography system, 51 pp.
3.9 Corrosion detection, 35 pp.
3.10 Lab test results on the effect of steel bar corrosion, 137 pp.
3.11 Nonlinear FEM model, reinforced concrete, 90 pp.
3.12 LIBS (Laser-Induced Breakdown Spectroscopy), 34 pp.
3.14 Cross hole tomography, 58 pp.
3.16 NDT Toolbox, 53 pp.
3.17 Demonstration of measurements, 27 pp.

WP 4 - Loads, Capacity and Resistance
4.3 Loads and dynamic effects, 150 pp.
4.4 Safety and probabilistic modelling, 328 pp.
4.5 N-L analysis and remaining fatigue life of RC bridges, 192 pp
4.6 Improved assessment. static & fatigue res. old steel railway bridges, 218 pp.
4.7 Masonry arch bridges, 277 pp.

WP 5 - Monitoring
5.1 Monitoring instrumentation techniques, 135 pp.
5.3 Prototype – crack sensor sheet - optical fibres, 78 pp.
5.4 Prototype – fibre optic grating sensor, 42 pp.
5.5 Prototype - MEMS, 47 pp.
5.6 Prototype – shaker for vibration tests, 70 pp.
5.7 Prototype – wireless communication network, 58 pp.
5.8 Prototype – smart data processing, 58 pp.
5.9 Prototype – TOF Fiber optic sensor, 18 pp.

WP 6 - Repair and Strengthening
6.2 Repair and Strengthening of Railway Bridges – Literature and Research Report – Extended Summary, 807 pp.
6.3 Field tests, 181 pp.
6.4 Method statement guideline, 74 pp.

WP 7 - Field Testing of Bridges
7.2 Riveted steel bridge, France, 73 pp.
7.3 Concrete bridge, Sweden, 406 pp.
7.4 Masonry bridge, Poland, 113 pp.

WP 8 - Demonstration of Bridge Monitoring
8.2 Demonstration of bridge monitoring, 129 pp.

WP 9 - Dissemination
9.2 Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives, Overall Project Guide, 28 pp.
9.3 Sustainable Bridges – Assessment for Future Demands and Longer Lives, Conference Proceedings, Wroclaw 2007, 492 pp.

Guidelines
Inspection & Condition Assessm, of Railway Bridges (ICA), 259 pp.
Load & Resistance Assessments of Railway Bridges (LRA), 428 pp
Monitoring of Railway Bridges (MON), 93+125 pp.
Repair and Strengthening of Railway Bridges (STR), 137 pp.
https://ltu.diva-portal.org/smash/

The guideline on inspection and condition assessment has, at the time of its writing, gone beyond the state of the art of inspections guidelines available elsewhere. Connecting degradation mechanism and a defect catalogue to related investigation methods (with a focus on non destructive technologies) has been done here the first time in a consistent way. Focus has been on geometry evaluation (such as precise position of tendon ducts) and damage localization (e. g. cracks and delaminations caused by rebar corrosion). As there was already guidance available for steel structures, a major part of research was related to reinforced/prestressed concrete as well as masonry. The NDT toolbox contained several innovative techniques, e. g. Ultrasonic echo and radar testing using automated scanning systems, see Figure 2. These systems have been optimized and improved after the project and are now used in research and validation projects in several countries, including overseas.

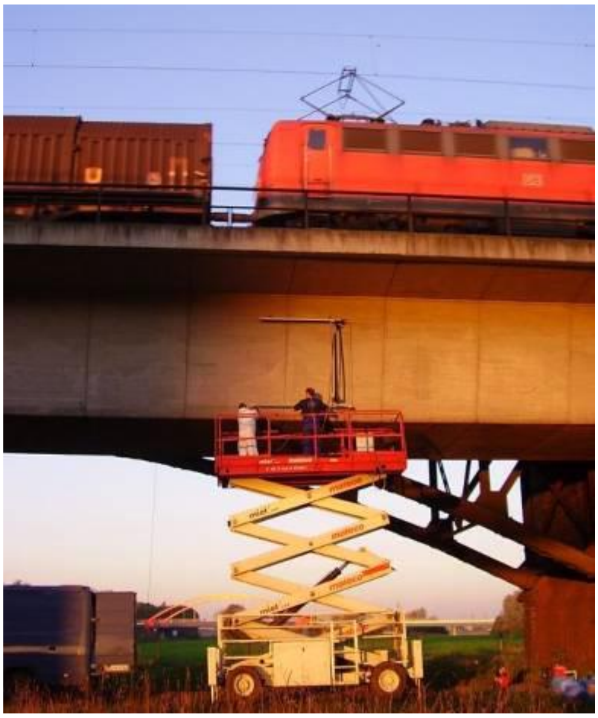

Figure 2. Automated ultrasonic scanning of a RC railway bridge in Germany (Picture: BAM)

An innovative Impact Echo system has been developed in the frame of Sustainable Bridges as well. However, there have been several technological breakthroughs after the end of the project, e. g. multichannel ultrasonic equipment with an improved depth range and resolution. The defect catalogue and classification scheme has later been refined by Rosemarie Helmerich [7] and is still of great value.

Meanwhile, the methods described in the ICA guideline are increasingly used around the world. For example, it will influence the update for the German guidance documents on object-oriented damage analysis for road bridges (OSA). In addition, there is now a German standard on formal qualifications scheme for concrete related NDT. First courses are expected for 2025 latest. However, there is still a lack of standards for many aspects.

4 Loads & Resistance Assessment (LRA)

The Guideline [3], has been prepared aiming to follow somehow the structure of the EC codes and it is divided into 10 Chapters and 12 Annexes concerning:

- Assessment procedure (Chapter 2);
- Requirements, safety formats and limit states (Chapter 3, Annexes 3.1-3.7);
- Basic information for bridge assessment (Chapter 4);
- Load and dynamic effects (Chapter 5, Annex 5.1);
- Concrete bridges (Chapter 6);
- Metal bridges (Chapter 7, Annex 7.1);
- Masonry arch bridges (Chapter 8, Annexes 8.1 and 8.2);
- Foundations and transition zones (Chapter 9);
- Improvement of assessment using information from testing and monitoring (Chapter 10, Annex 10.1).

In most of the topics related to railway bridges assessment the Guideline uses the current state-of-the-art knowledge and the presently best practice. Nevertheless, in many subjects it proposes the use of new and innovative methods and models that have been developed, obtained or systematized due to research performed.

The guideline, which was first of its kind, provided the basis for a significant step forward in the efficiency in management of railway bridges in Europe with focus on both load and resistance at both line level, bridge level and bridge element level. This is irrespective of the user being a railway bridge owner, a consulting engineer, a research institute or a contractor. The work significantly contributed to achieve the three project specific bridge goals: (1) Increase capacity, (2) Extend residual service life, and (3) Enhance management, strengthening and repair systems.

Since completion of the project in 2007, further development has taken place in connection with other European railway research and development projects as MAINLINE, Capacity for Rail (C4R) and Shift 2 Rail, [8].

Railway projects being planned and implemented in 2023 all have high focus on reduction of both economic and environmental impacts. Our Sustainable Bridges work being started 20 years ago is thus still very relevant.

5 Monitoring (MON)

The partners of the monitoring work package addressed several topics concerning the improvement and testing of existing monitoring technology to structural monitoring of railway bridges. A significant effort was spent to develop and test wireless sensor networks for structural monitoring, which, at that time, was an emerging technology. Wireless monitoring promised to increase the flexibility and reduce the deployment costs of short to medium term monitoring applications. The challenge was to design a hard- and software that was easily adaptable to various tasks, able to operate reliably for several months and produce accurate data. Monitoring of dynamic processes was particularly challenging because of the limited resources of the hardware and the strong limitations imposed by the power supply (batteries). Within the project, significant concepts (distributed data processing, event-based monitoring) were tested that provides knowledge and experiences to finally achieve the goals. Real life test deployments on railway bridges demonstrated that a data intensive application such as strain cycle monitoring is feasible, [9-10]. Today, in environmental and precision agricultural monitoring wireless sensor networks is a well-established technology. So far, commercial structural monitoring seems to be less innovative although for monitoring slowly varying physical processes that generate moderate data sizes in most cases wireless sensor networks can easily replace wired measurement systems providing also significant cost benefits [11]. Several companies worldwide offer devices and services for monitoring with wireless sensor networks. One of the most prominent, Decentlab GmbH (www.decentlab.com), was founded by two members of the Sustainable Bridge project.

A second Important task was to draft a Guideline for Structural Monitoring, [5]. The guideline addresses bridge owners and structural engineers and avoids terminologies and technicalities concerning monitoring technologies. It provides a procedure for how to specify, design, implement and operate monitoring systems in a systematic and coherent way. The guideline introduces the concept of a model monitoring system as the fundamental planning tool for specifying the physical monitoring system. This tool allows bridge owners and structural engineers to specify their requirements on a monitoring system by using concepts that are familiar to them. The concept of model monitoring system permits to separate the roles and responsibilities of the different actors and to clearly define the interface between a structural engineer and monitoring experts. The task of the monitoring expert is to implement and operate a monitoring system that conforms to model monitoring system specified by the structural engineer.

Besides the general part described above the guideline contains four sub-guidelines dealing with specific topics of bridge monitoring:

- Monitoring of steel railway bridges;
- Experimental estimation of structural damping of railway bridges;
- Corrosion monitoring systems for reinforced concrete bridges;
- Reliability of monitoring systems for bridges.

6 Repair and Strengthening (STR)

The Guideline [6], aims to assist the railway owners in deciding necessary strengthening measures for concrete, steel or masonry railway bridges. In addition, also possible strengthening measures for the bridge subsoil are presented.

Strengthening of bridges is usually performed to fulfil the safety requirements regarding the ultimate limit state (ULS). Therefore, the principal focus in this Guideline is on the methods suitable for this purpose. However, many of the strengthening methods that are described in this document will also be applicable when measures are needed to fulfil the serviceability limit state (SLS), for example increased stiffness of the structural elements or decrease crack sizes in concrete members.

The scope of the guideline has been limited to modern methods and strengthening systems known to the authors or developed within the project, in this case focus was on advanced composites for repair and strengthening, but also external prestressing was discussed. Methods that can be considered traditional or methods that can be considered well known to the railway owners have not been presented. The guideline tries to highlight strengthening methods that are environmentally friendly, not disturbing the ongoing traffic and at the same time are economically competitive.

The guideline is divided into a Graphical Index (GI) document, Method Description documents and Case Study documents. The Graphical Index document is a tool guiding the users (i.e., bridge administrator, bridge assessment engineers, etc.) through the strengthening methods presented in the Guideline in order to find the most suitable method for the specific case and then, to indicate where in the Guideline the relevant information (i.e., method description and case studies) regarding this method can be found. The method descriptions give detailed description of the strengthening method referred to, equipment used, benefits and drawbacks and a cost estimate of the method. In the case studies different field applications of the method descriptions are presented.

Since the project was finished the need for repair and strengthening of concrete structures has increased and the need for applicable strengthen methods. The use of advanced composites for rehabilitation of concrete structures is now accepted within the European union and the technique is also presented in codes and standards, i.e., EN-1504. Common design rules are currently on is way in the new updated Euro Code. However, even though the increased number of strengthening projects on concrete structures during the last 20 years, the need for strengthening railway bridges has been small. New models for calculation and a better understanding of their structural capacity have led to what can be denoted administrative upgrading, which also is presented in this project.

The Project “Sustainable Bridges” led to a considerably larger understanding of the strengthening technique and its possibilities. Today there are many hundreds of structures only in the Scandinavian countries that have been strengthened with CFRP (Carbon Fibre Reinforced Polymers) since 2007, for example road bridges, parking houses, beams and columns, slabs in office buildings etc.

7 Field Testing, Demonstration and Dissemination

In order to demonstrate new and refined methods for assessment and field testing, developed in the project, field tests of three existing bridges were carried out, see Figure 3, 7.2-7.3 in Table 1 and [12]. On five other railway bridges new monitoring methods and technologies were tested, see 8.2 in Table 1. The bridges had span lengths in the range 10 to 52 m emphasizing the target to demonstrate monitoring technologies suitable for small and medium size bridges that present the great majority of the European railway bridge stock.

Apart from existing technologies, the prototypes developed in the project were tested.

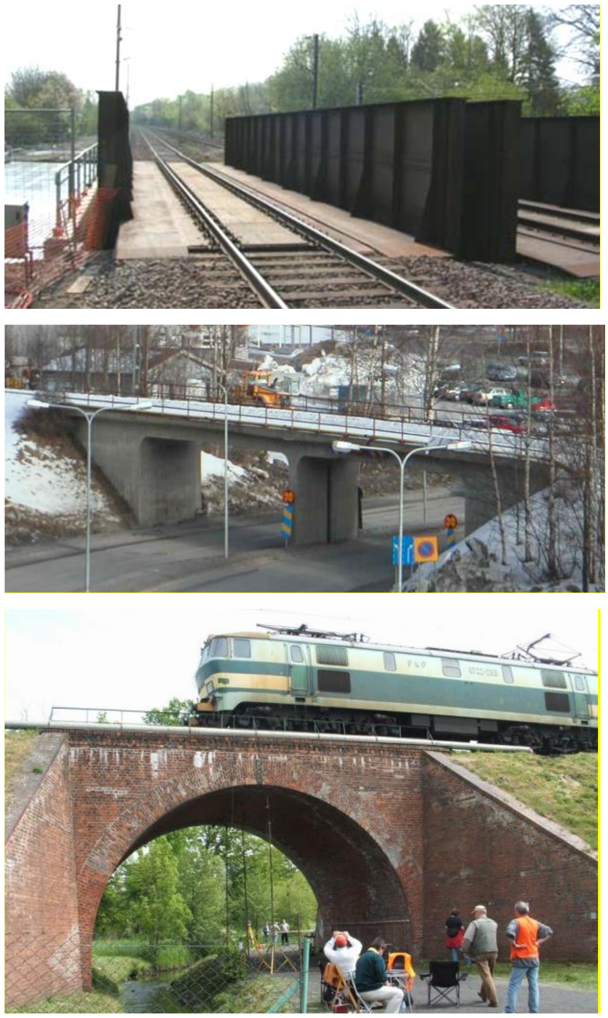

Figure 3. Field tests: Riveted Steel Beam, Reinforced Concrete Frame and Masonry Arch

These include short-term monitoring with prototype automation-based monitoring system; long-term monitoring with traditional computer-based instrumentation; monitoring with prototype wireless sensor network; structural dynamics monitoring with prototype shaker system; and short-term monitoring with conventional laboratory instruments.

The proposed procedures have been successfully verified for inspection and condition assessment, load carrying capacity, monitoring, and possible strengthening of the tested railway bridges. Solutions described in the Guidelines elaborated in the framework of the Project are up to now directly applied in many countries or were used as a background for preparation of national rules.

Observed consequences of dissemination of the Project results confirm proper selection of distribution methods, in the form of four international specialist trainings (2006, 2007), international conference "Sustainable Bridges" (Figure 4) as well as over 500 publications based on the Project results (books, journal articles, conference papers) published during the Project time and in the years after.

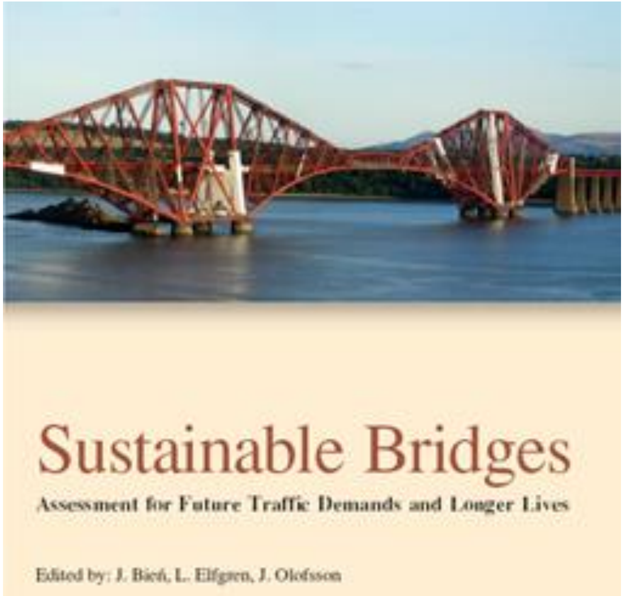

Figure 4. Cover to the Proceedings of the final International Conference in 2007, [6].

Results of the Project were also presented on a CD and on the Project web-page. This has now been replaced by a searchable Digital Repository; https://ltu.diva-portal.org/smash/.

Additional, impact arrived after the Project in the form of integration of the research teams, improvement of cooperation with national railway administrations as well as further international research collaboration of involved teams [8].

8 Conclusions and Outlook

Using the methods and procedures in the presented guidelines [2-5], it was found that there are often hidden capacities in existing bridges. The main reasons for this are conservative code models and safety factors. They have been established to balance variations and what may go wrong in the production stage. However, in existing structures you are able to use actual loads and material properties which leads to more realistic assessments. These views have been implemented in many countries.

On the other hand, there may be unobserved weaknesses caused by e.g., corrosion, fatigue and unknown boundary conditions as scour. Shear and punching of concrete structures can also still cause problems and a good understanding of the flow of forces is often essential. Advanced but uncalibrated computer programs may give unsafe conclusions. Some experiences from advances regarding e.g., drones and Artificial Intelligence are summarized in the recent EC project IM-SAFE (https://im-safe-project.eu/).

Major benefit to project was having many end users as partners, which meant that each main work package had immediate access to practical advice, thus ensuring that the researchers remained focussed on the final aims of the project.

Society may learn and save money from the experiences from more "full-scale" failure tests [13] to further improve the understanding of existing bridges and to harvest their "Value of Information" before they are destroyed. The tests should, as far as possible, be based on realistic load cases, in order to optimize the outcome, [14]. Different bridge types can be tested to check their real capacity and give a background for establishing and calibrating numerical models of them [15].

The monitoring and strengthening methods presented in the guidelines [4, 5] still form a valid base for methods to give our bridges longer lives and to be more sustainable.

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Figure 5. Final review meeting in Wroclaw, Poland, Oct 9, 2007. Top from left: Jens S Jensen, Björn Täljsten, Risto Kiviluoma, Lennart Elfgren, Ernst Niederleithinger, Glauco Feltrin, Jan Olofsson, Brian Bell, Björn Paulsson, Jan Bien. Front from left: Rosemarie Helmerich, Patrick van Honacker, András Siegler, Dermot O´Dwyer and Britta Schewe

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The documents in Table 1 can be obtained from https://ltu.diva-portal.org/smash/. Search for “Sustainable Bridges Background Document X.X “ or Title.

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