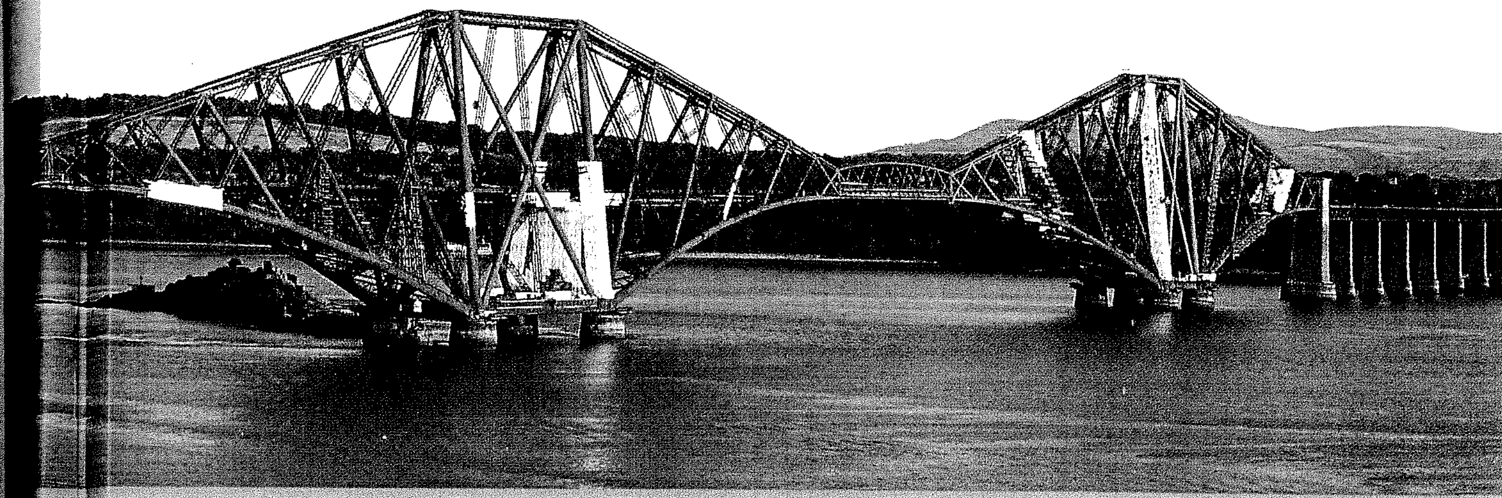

Sustainable Bridges

Assessment for Future Traffic Demands and Longer Lives

Edited by: J. Bień, L. Elfgren, J. Olofsson

A guideline for railway bridge inspection and condition assessment including the NDT toolbox

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The member states of the European Union organise the regular inspection and condition assessment of their railway infrastructure asset on national level. Advanced non-destructive testing is not included as part of most regular railway bridge inspection rules. The paper presents a guideline for inspection and condition assessment of railway bridges promoting especially non-destructive testing (NDT) methods. Besides the state of the art, the guideline summarises the latest steps of research, performed within the project Sustainable Bridges (SB) and documented as background documents. Based on the owners needs, the guideline gives hints for application of NDT to all bridge types including subsoil and foundations. The guideline proposes, how to implement the refined non-destructive inspection tools for concrete bridges, metal and masonry arch bridges. For the use by bridge owners decision makers or inspectors during inspections the bridge defect catalogue and the NDT toolbox with one page information about the available non-destructive testing techniques should be useful.

1. INTRODUCTION

1.1. Bridge condition assessment

Realistic estimation of the condition of the ageing existing railway bridge stock requires detailed knowledge of the current situation based on inspection results. The railway bridge owners, represented by their infrastructure departments, usually apply their own national procedures for regular inspections and/or condition assessment. Both, inspections and condition assessment systems, are typically part of national bridge management or asset management systems. In most of the countries, the basic annual inspections are mainly based on visual inspections from underneath a bridge. Often, internal conditions or beginning degradation processes inside the quite well appearing structure cannot be detected early enough. Refined inspections on touching distance are usually made once in five to ten years. Advanced NDT techniques, in contrast to simple methods as Schmidthammer, are not included as part of most regular railway bridge inspection procedures. Application of advanced testing techniques requires specialised and experienced personnel. But even for simple methods, the physical background must be comprehensively known to the users.

In the presented Guideline the term *bridge condition assessment* is used in a very general meaning as an expression describing a set of activities undertaken to characterise current state of bridge structure. The most frequently considered aspects of *bridge condition* can be listed as follows:

- *Bridge condition assessment* (*rating*) – evaluation of the local and/or global state (technical condition) of a bridge in the form of numerical or linguistic rating based on a predefined scale.
- *Load capacity assessment* – activities undertaken to determine the ability of a bridge to carry load based on the structure technical parameters and degradation level.
- *Safety assessment* – process of evaluation of remaining bridge safety measured in terms of partial safety index, reliability index or probability of failure.
- *Durability assessment* – process of evaluation of remaining lifetime of a bridge.
- *Serviceability assessment* – evaluation based on the criteria governing normal use of a bridge as a part of the transportation system.

All procedures of bridge condition assessment are usually based on the results of inspections and take into account defects as well as degradation processes identified in the considered bridge. General classification of typical defects and also classification of degradation mechanisms are proposed in the Guideline.

1.2. The Railway owners needs

Many of the member states and railway infrastructure owners miss assessment rules to estimate the current resistance of an existing railway bridge, since only Eurocodes for new structures are introduced as assessment rules. The Sustainable bridges project enhances assessment methods to better estimate the safety of existing railway bridges in order to withstand future traffic demands as higher axle loads in freight traffic or faster passenger trains.

The objectives of the work package 3 within the project focussed in particular on the enhancement of non-destructive testing (NDT) methods, NDT-equipment and modelling of defects and deterioration for reinforced and prestressed concrete railway bridges. In the first phase of the project, an analysis of the European bridge stock by the railway bridge owners revealed, that better assessment methods are not only required for reinforced and prestressed concrete bridges, but that many masonry arches suffer from deterioration and need to be in the focus of research as well as steel bridges made of old materials. In detail the following needs resulting from maintenance problems were formulated as problems for the topic inspection and condition assessment:

- Better inspection tools to identify in reinforced concrete bridges:
  - reinforcement corrosion,
  - early detection and description of cracks and spalling (incl. concrete cover),
  - defects in tendon ducts (incl. corrosion),
  - carbonation,
  - waterproofing defects.
- Better inspection tools for detection in steel bridges:
  - corrosion and delamination,
  - fatigue cracking,
  - loose connections,
  - coating defects,
  - brittle fracture.

- Better inspection tools for identification in masonry arch bridges:
  - material degradation,
  - cracking,
  - ring separation,
  - waterproofing defects,
  - fracture of stones or bricks.

The Guideline presents deterioration modelling, defect description and non-destructive testing methods addressed to the problems listed above.

2. RESEARCH IN THE WORK PACKAGE INSPECTION AND CONDITION ASSESSMENT

As consequence after the bridge stock analysis, additionally to the technical research topics formulated in the proposal of the project planning, a guideline for inspection and condition assessment was developed for all bridge materials, which includes both, the state of the art and the new research results as refined data acquisition, new measurement set-ups and data processing.

During the work with 12 European partners, was realised, that a common terminology is not available for railway bridge infrastructure tasks. English is a largely unknown language to bridge inspecting people, especially in the new member states in Eastern Europe. Even in English speaking countries it is not easy to find unique terms for the same meaning of defects. Therefore, Annex 1 contains a first initiative to propose terms and definitions with focus on NDT and inspection open to be completed and updated. *Annex 1: Terminology and Definitions*, focuses on non-destructive testing, inspection and condition assessment. *The Railway Bridge Defect Catalogue (Annex 2)* presents classification of typical defects for all basic bridge types. *The NDT Toolbox* provides information about non-destructive testing procedures to railway bridge inspectors in compact and comprehensive one-page information in *Annex 3*.

The guideline with the annexes, see scheme in Figure 1, can be transferred to the railway community in a more generic way and may be used as a internationally recommended knowledge supplementary to their national inspection and assessment rules. The guideline consists of two major parts: a more general first part with the analysis of the current situation in railway bridge inspection and condition assessment and the second part is related to material specific issues. The material specific part is focused on material specific NDT-test requirements and presents NDT-methods appropriate for various bridge materials.

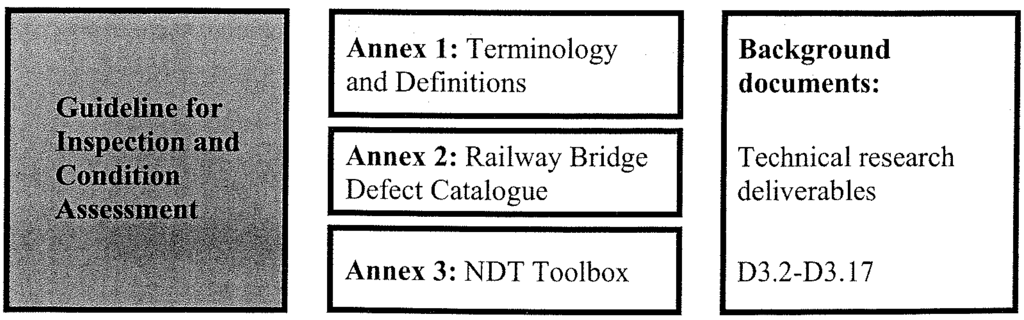


Figure 1. Structure of the *Guideline for Inspection and Condition Assessment*

The deliverables with the detailed results of technical research are forming the background documents. The attached databases are assumed to help European railway organisations in development of condition assessment procedures by implementation of the advanced tools presented in the Guideline and in the background documents:

- Standard testing of bridges and modelling of defects:
  - inventory on condition assessment and inspection (Casas, 2004),
  - condition evaluation: Proposal of a unified condition assessment procedure (Bień et al., 2005),
  - condition assessment and inspection of steel railway bridges.
- Verification of construction plans and localisation of inhomogeneities:
  - evaluation program to combine radar data of different polarisation (Stoppel et al., 2006),
  - prototype of 2D-scanning system for automated measurements Impact Echo techniques for crack depth measurement (Krüger et al., 2007),
  - prototype of radar tomography system (Cruz et al., 2007).

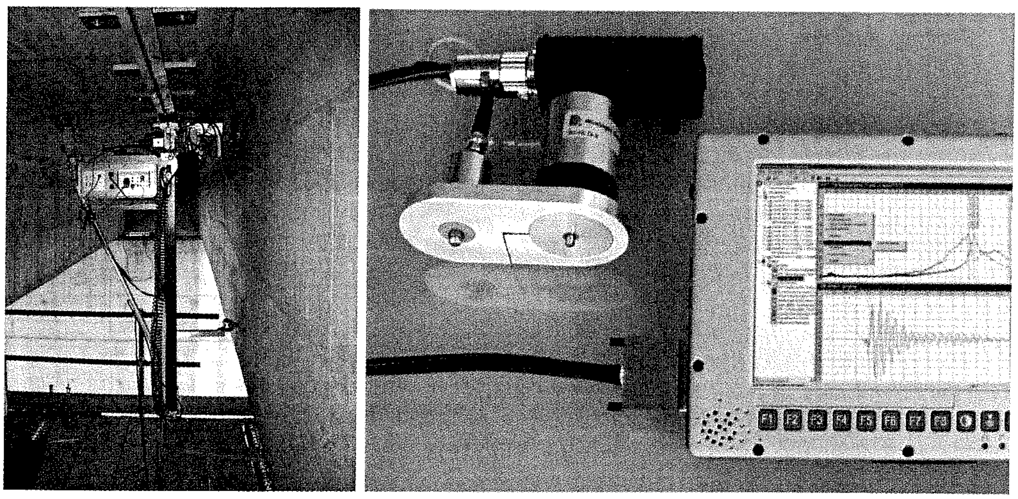


Figure 2. Examples for developed equipment: 2-D scanning system for automated NDT-measurement (left photo – BAM 2004) impact-echo-depth measurement (right photo – UStutt 2007)

- Steel corrosion in RC-bridges and electro-chemical measurement methods:
  - Electrochemical Techniques to detect to corrosion stage of reinforcement in concrete structures (Bäßler, 2005), see Figure 3,

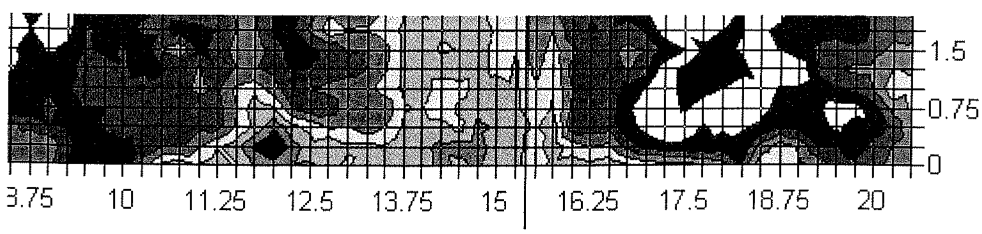


Figure 3. Result of the potential field measurement (Helmerich, 2007)

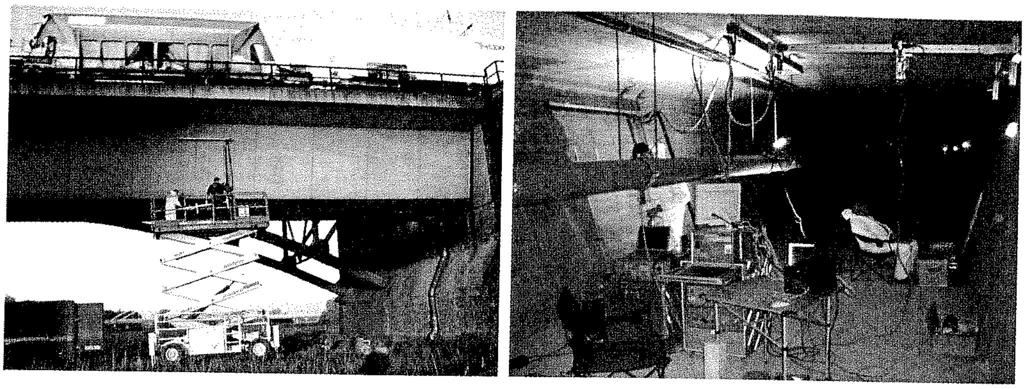


Figure 4. Application of automated measurement with advanced NDT-sensors to a German railway bridge Impulse radar, Ultrasonic-echo and impact-echo sensors measured the same area with precise geometric correlation. Data fusion was carried out with the obtained data

  - review of laboratory test results on the effects of steel bar corrosion (Horrigmoe et al., 2007),
  - finite element modelling of reinforced concrete structures attacked by corrosion (Horrigmoe et al., 2007),
  - optimum setup for a LIBS system for application on site (Wilsch et al., 2006).
- Assessment of pile foundations and subsoil:
  - NDT methods for existing foundations (Niederleithinger et al., 2005),
  - investigation and testing embankments in the transission zone (Holm, 2006).
- Application and Demonstration, see Figure 4 (Streicher, 2006).

3. INSPECTION AND CONDITION ASSESSMENT TOOLS

3.1. Procedures

The guideline discusses European concepts for inspection and condition assessment of railway bridges based on the analysis of the state of the art and describes also defects and degradation processes. The deterioration rate and aging effects of bridge structures depend strongly on the quality of design, execution quality, the bridge maintenance level and in-service conditions. Advanced non-destructive testing is mostly applied in inspections special, usually called in because of doubts or increased user requirements. NDT-based evaluation helps to discover internal voids and inhomogeneity, independent, whether they were caused during construction or in-service, e.g. due to continuous deterioration. Advanced NDT have reached to the level, that materials characteristics or internal inhomogeneity can be investigated quite quickly and more reliable than a decade before. Automated data acquisition using non-destructive echo methods offer high geometrical correlation, thus the images resulting from different NDT-methods can be overlaid to discover hidden construction defects, characterize in-depth damage from impacts as lorry or ship impact or the extend of environmental impact such as earthquake, flooding or thunderstorms to the inner structure.

Figure 5 shows the various levels of inspections proposed in the Guideline. Most bridges of the asset will probably never be investigated more than in regular inspections, usually performed by visual methods or by means of simple NDT techniques. Even for visual inspection it is necessary to educate the inspector, so that he understands the most important deterioration processes and knows critical details in different bridge types.

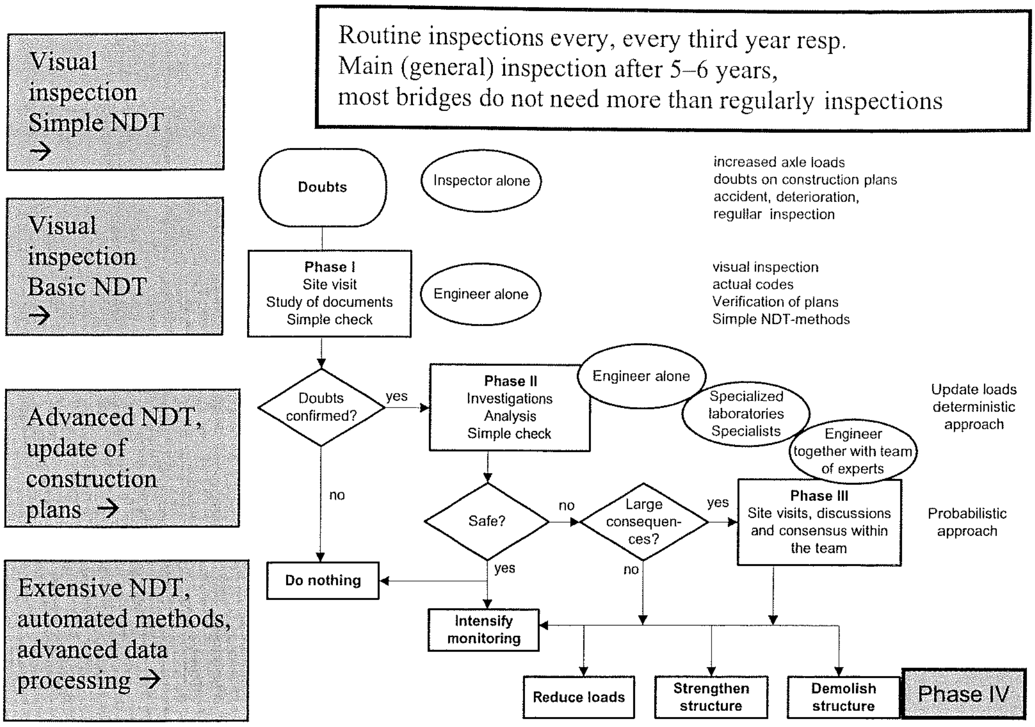


Figure 5. Levels for use of NDT in inspection or in phase-wise reassessment

Simple inspections are e.g. the application of the tapping test in concrete bridges, ultrasonic thickness measurement in steel bridges or the use of the Schmidt-hammer. Even for simple methods, the inspector should know the physical background. Thus he should know, e.g., that the Schmidthammer delivers realistic values only for young concrete. The propagating carbonation near the surface falsifies the result and pretends higher compression strength.

If refined information about the inner structure is needed, combination of advanced NDT--data obtained in special inspections or during reassessment increases the accuracy of the result.

3.2. NDT Toolbox

With the increasing age of the bridge stock, the need for better condition evaluation tools increases. Referring to the analysis of the railways in 2004, only 33% of the European bridges is younger than 50 years, with decreasing tendency. The decision making infrastructure responsible persons and the inspectors need more information about appropriate testing non-destructive and minor-destructive testing methods for railway bridges.

A NDT-toolbox presents applicable NDT-methods for bridge inspection including the most important information about their application, as physical principle, education needed for use, influence on the traffic, time consumption, a.s.o. Non-destructive testing methods have been continuously improved. Data sets can be now acquired automatically, reconstructed and fused. In the end, the inner conditions can be visualised in images. Usually, each material type requires other sensors. Homogeneous steel is much easier to investigate then concrete. Concrete is actually a composite material consisting of aggregates, differing in size and other parameters on one side and cement matrix on the other side. Porosity, humidity, beginning deterioration influence the results. Thus, all methods are presented with respect to the material. The methods can be distinguished after their physical background as:

- acoustical methods (e.g. impact echo, Ultrasonic echo or transmission),
- electro-magnetic (e.g. reinforcement detectors, impulse radar),
- electrochemical (e.g. potential field, Galvapulse),
- radiography a.o.

The Figure 7 shows the description of a one page information about impact echo and ultrasonic echo using an array with dry point contact transducers. These sensors can be applied to a concrete surface using automated scanning equipment at the same time (Stoppel, 2006). Echo methods have the additional advantage, that only one side of a bridge must be accessible. A software is currently prepared supporting the NDT-toolbox. The software links typical defects in railway bridges with appropriate methods. The link leads to the one page information, which can be printed, if necessary.

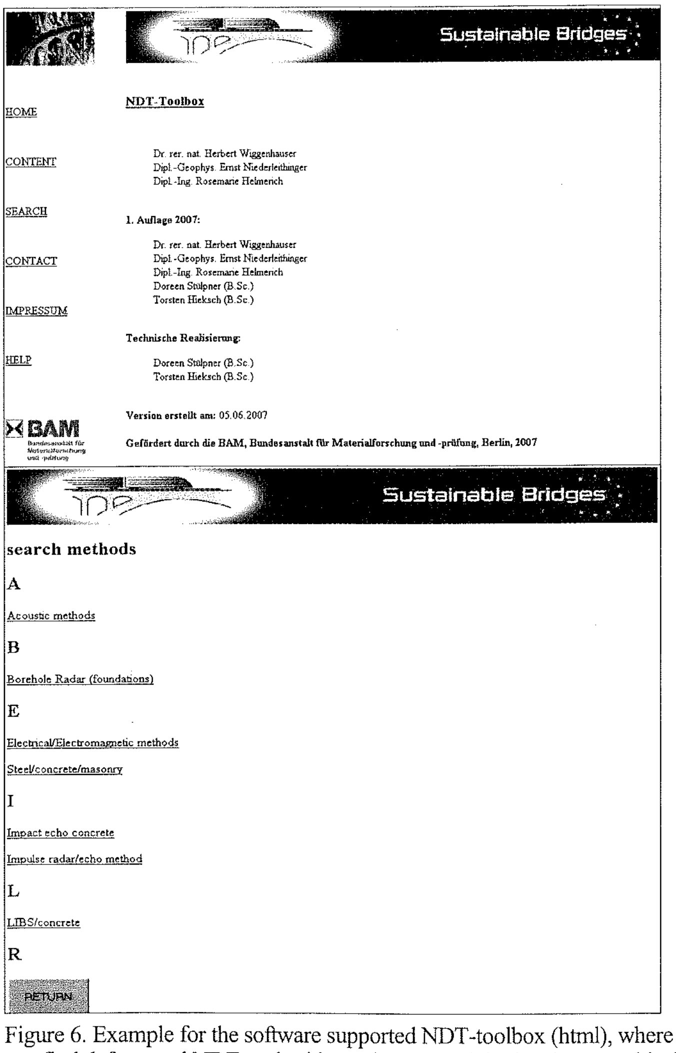
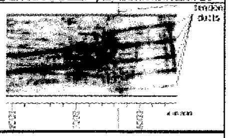


Figure 6. Example for the software supported NDT-toolbox (html), where inspectors can find defects and NDT-tools either using a search by levels or graphical index

Ultrasonic(US) echo RC, PTC	Sustainable Bridges
Field of application	Inspection of the inner structure of structural elements made of reinforced or post-tensioned concrete: rebar + tendon location, compaction faults, voids
Description	US-pulses are transmitted into concrete and their reflections are analysed with respect to reflections at interfaces and internal reflectors. Several point measurements are combined to visualise the reflection along a line or parallel to the surface in images. Dry coupling of arrays is possible (point contact transducers)
Physical principle	Broadband pulses are generated in the frequency range of 50 to 150 kHz. With a known wave-propagation velocity (calibrated at a point with known thickness), the depth of the reflectors can be evaluated from the measured pulse transit time. In most cases the measured data is evaluated with reconstruction calculation (3D-SAFT). The relative intensity of the reflected waves give information about the boundary condition of different layers and presence of air inclusions.
Limitation	The propagation of ultrasonic waves is limited by layers containing air, e.g. concrete with large amount of air pores and by very dense reinforcing rebars.
Characterisation	
Physical principle	☐ Visual ☐ Electrical/Electromagnetic ☒ Acoustic ☐ Chemical ☐ Other
NDT/ destructive	☒ Non-Destructive ☐ Minor destructive ☐ Destructive
Type of test	☒ Single test ☐ Monitoring
Equipment Cost	☒ High ☐ Medium ☐ Low
Required education	☒ High ☐ Medium ☐ Low
Examination level	☐ Inspector alone ☐ Inspector + specialist ☒ Specialised laboratory
Accuracy	The finding of insufficient grouting is under research with good results in laboratory applying reconstruction calculation. The accuracy is depending on the choice of emitted wave length (depends on size of aggregates) ½ λ ~ 2cm
Required equipment	Transducer arrays with point contact transducers, which don't require coupling agent (producer: ACSYS, Moscow). Large data sets have to be stored for later evaluation. Automated measurement applying scanners is recommended.
Advantages	Accessability only from one side, no safety restrictions (as for X-ray)
Disadvantages	Difficult coupling of planar ultrasonic transducers to rough concrete surfaces, even for point contact transducers the unevenness has to be < 5 mm.
Time consumption	For 1 m² with 5 cm-grid: 44 min per 1 m² (automated scanning, 6 s per point). Data preprocessing and reconstruction of data: ~ 1h/ m²
Comments	Automated scanning system recommended, hand held measurement for small areas possible. Application to bridges is in research stadium, proposed for use in areas with legitimated doubts, one of the most appropriate techniques
Standardisation	None, only recommendations: e.g. BA 86/04, DGZIP (AB)-recommendation B6
Typical application: 	Typical result: 
Links, references	www.kompendium.bam.de
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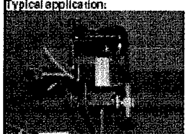
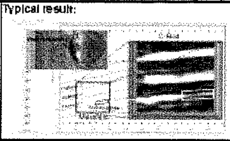
Impact Echo (IE) RC, PTC	Sustainable Bridges
Field of application	Thickness determination, localisation of delamination, voids, inhomogeneities, hollows in tendon ducts mainly in concrete structures
Description	An impactor generates an acoustic wave. Waves propagate, flaws and boundary surfaces with different acoustic impedance reflect them. Transducers record surface displacements caused by multiple reflections versus time.
Physical principle	Short mechanical impact causes stress waves. Multiple reflections between surface and reflector (boundaries: back wall or void) are recorded and their frequency spectrum is transfered from time domain to frequency domain (FFT). The depth of the target is calculated with the validated the wave speed.
Limitation	Minimum detectable target size varies according to the depth of the target. Very effective test method for a depth from 0.1 m up to about 1.2 m.
Characterisation	
Physical principle	☐ Visual ☐ Electrical/Electromagnetic ☒ Acoustic ☐ Chemical ☐ Other
NDT/ destructive	☒ Non-Destructive ☐ Minor destructive ☐ Destructive
Type of test	☒ Single test ☐ Monitoring
Equipment Cost	☐ High ☒ Medium ☐ Low
Required education	☐ High ☒ Medium ☐ Low
Examination level	☐ Inspector alone ☐ Inspector + specialist ☒ Specialised laboratory
Accuracy	Thickness of concrete slabs may be obtained to ±3% (rel. to BA 86/04), detectable size and approximate relationship between all influences: Germann
Required equipment	IE-Test equipment (commercial systems available): Electro-magnetically enhanced or ball bearing impactor, response transducer, computer
Advantages	No restriction because of risky waves (as X-ray), access only from one side of element needed, easy to handle equipment, quick results are obtained on site
Disadvantages	Uncoated surface must be directly accessible. Roughness of surface may impair the coupling of the sensor. Data need to be post-processed (3-D-image)
Time consumption	Manual measurements: high cost for small areas. Advised procedure: automated scanning system: Detailed investigation of areas, questionable after radar measurement, simultaneous IE + US: ca. 11s per point → 5 cm-grid: 80 min per 1m².
Comments	Thickness and delamination measurements are well approved. Knowledge of geometry details (shape and size of tendon ducts) is necessary to reliably model the impact echo response; method for tendon duct detection is on research level.
Standardisation	e.g. BA 86/04, RI-ZfP-TU (Tunnel-guideline, German Highway agency)
Typical application: 	Typical result: 
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Figure 7. Examples for one page information of the impact echo and ultrasonic-echo method

4. MATERIAL SPECIFIC RECOMMENDATIONS TO INSPECTION AND ASSESSMENT

4.1. General recommendations

In the presented Guideline for concrete, steel and masonry bridges as well as for foundations and transition zones the following aspects of inspection and condition assessment are described:

- characteristic degradation processes and defects,
- typical weak elements and connections,
- inspection procedures,
- recommended testing methods.

Main attention is paid to NDT techniques and special requirements for their application are described. Even well developed NDT-methods need a two-step validation procedure for the estimation of the accuracy. Reference specimens can be used for the validation of the method itself in a first step in the laboratory or by applying standardised validation specimens taken on-site, e.g. for application of ultrasonic-echo or radiography to steel bridges. For some methods, the wave propagation in air can be used for calibration. Certain accuracy with standard deviation is received to characterise the method.

In a second step, the influence of the material characteristic, given by the physical parameters of the material in this special bridge, its age and deterioration has to be estimated on site. For the purpose of calibration e.g. of ultrasonic wave propagation, electric characteristics or electromagnetic parameters, minor destructive tests can be carried out, such as coring, drilling or use of spectroscopic methods. The validation and calibration is highly dependent on the materials quality.

4.2. Reinforced concrete bridges

Defects in concrete bridges are characterised by their age, execution quality environmental conditions and deterioration processes. New scanning techniques developed at BAM (see also Figure 4) during the last years allow superpositioning of several measured data sets with high geometrical correlation (data fusion.) to reach much higher accuracy, than expected only a few years before. Figure 8 shows results from a demonstration measurement at a box girder bridge of the German railways. During this measurement the new techniques were presented.

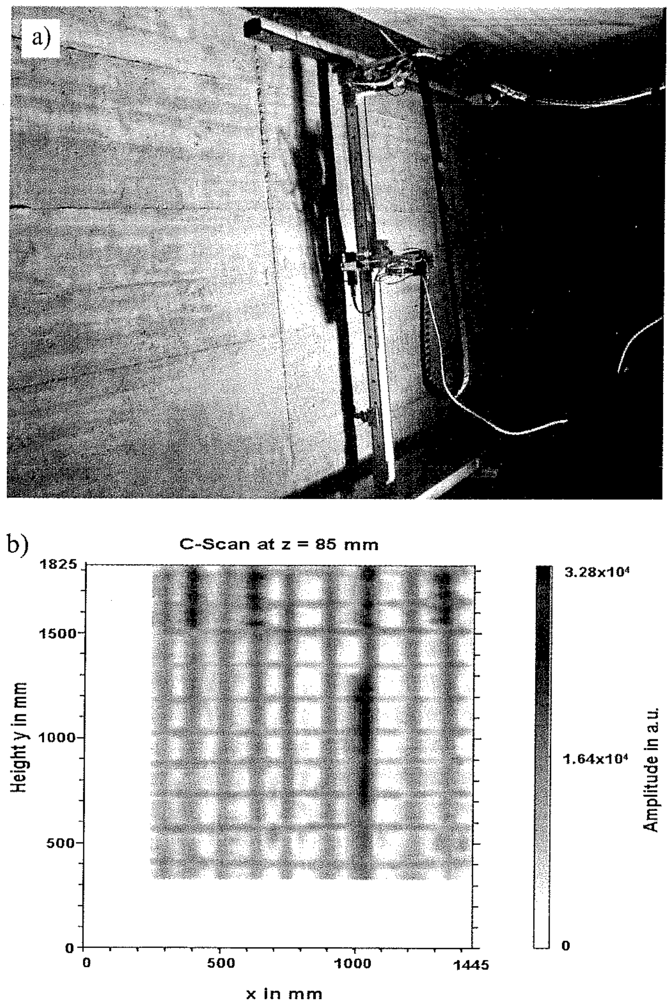

Figure 8. Automated scanner setup of the automated scanning equipment for impulse radar, ultrasonic echo and impact echo measurement (a) and the result of SAFT reconstructed radar data for a depth of 8 cm (b), inside a box girder (Streicher, 2006)

More detailed information about special inspection of reinforced concrete bridges with focus on the corrosion level by potential field measurement (see Figure 3) is given in (Buhr et al., 2007).

4.3. Steel bridges

The durability of steel bridges is mainly affected by corrosion and fatigue. That's why the inspector has to care for hidden corrosion and fatigue critical details. In case of doubts a special inspection can be called in. Non-destructive testing for steel bridges is well developed in other industries. Many experiences can be transferred from pipeline or pressure vessel testing or aeronautics to steel bridges. Inspection requirements for steel bridges, estimation of inspection intervals and the acceptability of flaws in steel structures are described in the paper (Kammel et al., 2007).

4.4. Masonry arch bridges

The application of non-destructive testing to a masonry arch bridge was carried out as part of the bridge testing in WP7. The guideline presents both, traditional testing and latest research results as feasibility tests with radar tomography (Cruz and Topczewski, 2007). Time consuming and cost intensive NDT would be carried out only during special inspections, called in in case of doubts or during reassessment. Special inspections can than be accompanied by displacement measurements for calibration of the static system.

4.5. Subsoil and foundation

Foundations are important elements of bridge structure. Failure of a foundation system may lead to failure of the bridge. The behaviour of the transition zone is also vital for the performance of the whole bridge system. Defects or insufficiencies in bridge foundations, embankment foundations, fill and subsoil can often not be inspected visually without excavation. However, settlements, twist and cracks in the superstructure are indicators of problems and should be regarded during inspection. Scour and other erosion problems as well as differential settlements between bridge abutments and transition zones are often more obvious. They can and should be regarded during visual inspection (Holm, 2006).

Methods for the investigation of foundation were enhanced within the EU-project RUFUS. These results were incorporated into the Guideline and NDT Toolbox (Niederleithinger, 2005).

4.6. Proposals for railway bridge owners

The future way for inspections should be based on flexible planning of inspection intervals. Among other parameters, these flexible intervals shall be based on parameters referring to the age, bridge type and deterioration level of a bridge. The importance of the bridge in the railway traffic network and the type of traffic crossing and under passing the bridge should be taken into account. For this structure, a classification of lines can be of help. At the moment the European network is not ready to apply flexible inspection, since the preconditions in the national organisations are too different.

Furthermore, the training level of inspectors should be comparable. Specialised laboratories can perform tests or training courses or workshops for inspectors. Completing the training or workshops for inspectors, e.g. disseminating the results of the project Sustainable Bridges, specialists, can be called in for special tasks to any bridge of the European Union.

5. CONCLUSIONS

The SB-guideline for inspection and condition assessment summarises the latest level of research in the field of non-destructive testing and presents data processing tools. Hints for application by owners or specialised laboratories are given for use in inspection and bridge condition assessment. Annexes to the guideline and background documents give detailed information. Since all non-destructive testing methods have to fulfil special requirements for the application to the special material of the bridge in service, training courses for bridge inspectors are highly recommended. Training courses can contain information on the bridge inventory, material specific deterioration processes and defects, fatigue critical details and special inspections including non-destructive testing for super and substructure.

ACKNOWLEDGEMENTS

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