Condition Evaluation of Bridge Deck Surface Structure by Using State of the Art NDT- Techniques

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Abstract

This paper introduces recent experience of Ramboll Finland bridge inspectors and NDT- experts in condition evaluation of road bridges deck surface structure by using state of the art NDT- techniques. This paper focuses on possible benefits of applying NDT- techniques in condition evaluation of road bridge deck surface structures. In addition, examples from several actual test cases are reviewed. Only a simplified description concerning the technical properties of the used NDT- techniques will be given here.

Keywords: Bridges, bridge deck surface structure, NDT, Impulse-Response, Impact-Echo, bridge special inspection, quality assurance, bridge repair

1. Main Terms

In this section definitions of the most relevant terms related to this paper are given.

Bridge deck: this paper refers to concrete deck slab of a road bridges. The main function of a bridge deck slab is to support the vehicular loads and to distribute these loads to the bridge superstructure main supports (girder bridges). In case of slab bridge type the deck has also the main vehicular loads carrying role. In addition to the vehicular loads a bridge deck carries other loads (wind, snow, dead load etc.). The mentioned bridge types are the most common road bridge types in use today.

Bridge deck surface structures: refers to the different layers applied on top of a bridge deck slab. The surface structures in Finland are usually composed of asphalt layers (wearing course and base course), protective layer (asphalt mass or concrete) and waterproofing layers (sheet membranes, epoxy treatment, asphalt mastic etc.). The bridge deck surface structure layers must meet different requirements such as evenness, resistance to aging and deformations etc. The surface structure layers have to be well bonded to each other in order to ensure long term functionality and intactness. The waterproofing (sealing) layer must be water tight and well bonded to its substrate, the bridge deck upper surface. The upper part of the bridge deck slab concrete is also considered to be part of the bridge deck surface structures, as it functions as the base layer of the surface structures. The upper part in generally means several cm of the concrete top.

Well functioning surface structures will ensure road users safety, good distribution of loads and long term durability of the structure.

A typical bridge deck surface structure used in Finland is shown in figure no. 1 taken from the Finnish Transport Agency (NCCI 1, guide no. 24/2014).
2. Introduction to the NDT- Techniques

This section shortly introduces the NDT- techniques used by Ramboll engineers in condition evaluation of road bridges deck surface structures. More elaborate introductions to the NDT-systems can be found in different professional publications.

2.1 The Impulse–Response (IR) System (s’MASH, Germann Instruments)

The Impulse-Response s’MASH test system is suitable for quick NDT screening of a plate-like structures aiming to evaluate the structure integrity and to identify suspicious areas for subsequent detailed analysis for example by the NDT Impact-Echo system and/or by invasive inspection (drilled cores).

In recent years Ramboll’s engineers in Denmark and Finland have proven the system suitability for evaluation of bridge deck slab surface structure also when testing on top surface of pavements. The system is also suitable for detecting in concrete structures delaminations, honeycombing and damages due to freeze-thaw or ASR, for detecting de-bonding of overlays and repair patches from concrete substrates etc. The IR testing method requires access to only one surface of the test object.

The IR testing method is introduced in ASTM C1740-10 “Standard Practice for Evaluating the Condition of Concrete Plates Using the Impulse-Response Method”.

- The Impulse-Response system components (figure 2):
  
  - Hard rubber tipped hammer (tip d=50mm, weight 1 kg) with a built-in load cell capable of measuring dynamic forces up to 20 kN.
  - Velocity transducer for 360° testing (geophone) that responds to normal surface motion and with constant sensitivity over the range 15-1000 Hz
  - Laptop with the s’MASH software, Windows®, and Excel®. The laptop and the s’MASH software are responsible for data acquisition, data storage and signal analysis. The Excel software is responsible for graphical presentation of the screening data (contour plots).
Figure 2. The Impulse-Response s’MASH system.

- Principle of the Impulse - Response system technique and the system operation:

The IR s’MASH system uses a low-strain impact, produced by a load cell instrumented hard rubber tipped hammer, to send stress waves through the tested element. The impact causes the element to vibrate in a bending mode (flexural vibration) and a velocity transducer, placed adjacent to the impact point, measures the resulting motion of the test element, i.e. the amplitude of the response. The hammer load cell and the velocity transducer are linked to a laptop as previously explained.

The time histories of the hammer force and the measured response velocity are transformed into the frequency domain using the fast Fourier transform (FFT) algorithm. The resultant velocity spectrum is divided by the force spectrum, to obtain the mobility as a function of frequency. The s’MASH calculates the mobility spectrum which is analyzed to obtain parameters representing the element’s response to the impact.

The screening by the IR system is done in a grid form (usually 0.5-1 m intervals). Test influence depth up to 0.3-0.5 m from test surface, depending upon the tested object.

The available parameters from the mobility plot are:

**The Average Mobility** \( \text{[(m/s)/N]} \): average of the mobility values from the frequency domain in the frequency range 100-800 Hz.

Indication => enable to compare differences in overall mobility among test points and by that gives indication of suspicious areas. This is the most important value to be taken into consideration when performing evaluation of bridge deck slab surface structures, especially when testing is performed from top surface of the pavement.

The IR presents also the **Mobility Slope** value (best-fit line to mobility values between 100-800 Hz, indication => location of poorly consolidated concrete / honeycombing), The **Voids Index** value (the ratio of the peak mobility value between 0-100 Hz to the Average Mobility between 100-800 Hz, indication => locations of poor support conditions) and the Dynamic Stiffness (the inverse of the initial slope of the mobility spectrum from 0-40 Hz; used mostly for relatively thin structures). Mobility Slope, Voids Index and Dynamic Stiffness usually are not taken into consideration in valuation of bridge deck slab surface structures.
- The Impulse – Response s’MASH data presentation:

Figure 3 (left) shows a typical data presentation available during and after testing. The s’MASH presents for each testing point the Force Waveform (up left), the Velocity Waveform (up right) and the Mobility Spectrum (down) as well as numerical values of the above mentioned parameters.

Figures 3.1 and 3.2. Left (3.1): the Impulse – Response data presentation of a test point (yellow dot). Right (3.2): the Average Mobility counter map. Test case: evaluation of bridge deck surface structure, test zone consist of 4x10 points.

At the end of screening a test zone the data is transferred to Excel for graphic presentation in shape of contour maps and numerical data for further analysis. In figure 3 (right) the counter map of the Average Mobility of the figure 3 (left) test zone is presented.

The interpretation of Impulse response Average Mobility testing results is based on a comparative principle when taking into consideration the tested structure properties (geometry, stiffness) and according to the NDT- experts experience with the IR.

2.2 The Impact–Echo (IE) system (DOCter, Germann Instruments)

The impact-echo method is based on monitoring the periodic arrival of reflected stress waves and is able to obtain information on the depth of internal reflecting interfaces or on the thickness of a solid member.

In condition evaluation of road bridges deck surface structures the IE system is usually used when testing directly on a concrete surface, e.g. on the bridge deck upper surface. IE testing on an asphalt surface is proven to be uncertain and slow.

The IE system is suitable for detecting the presence and depth of voids, delaminations and honeycomb in concrete structures, for evaluating grout injection in post-tensioning tendon ducts, detecting of ASR and freeze-thaw damages in concrete and for measuring the thickness of pavements, asphalt overlays, slabs-on-ground and walls (ASTM C1383). IE testing requires access to only one surface of the test object.

- The Impact-Echo system components (figure 4):
  - Mechanical spherical impactor source, i.e. the generator of the short duration pulses, normally in the range from 3 to 15 mm in diameter.
  - High fidelity displacement transducer for measuring the surface displacement
  - P-wave propagation speed measuring test set
  - Laptop with the Impact-Echo software. The laptop and the software are responsible for data acquisition, data storage and signal analysis.
- Principle of the Impact - Echo system technique and the system operation:

Figure 5 shows a sketch of the IE system setup and the operation principle.

The impactor generates a short-duration (<100 µs) pressure wave, which travels into the concrete and is reflected from the backside of a solid test object or from an internal anomaly (e.g. void / defect). The P-wave is reflected several times and the arrivals of the reflected P-wave are detected by the displacement transducer on the test object surface. The impactor contact time is a function of the impactor diameter and is influencing the frequency domain.

The time-displacement response (time domain waveform) is converted to a frequency response (amplitude spectrum) using a fast Fourier transform (FFT) algorithm.

- The Impact–Echo DOCter data presentation:

In figure 6 the upper plot shows the surface displacement waveform obtained from a specific test point and the lower plot shows the amplitude spectrum obtained by transforming the waveform into the frequency domain. In the amplitude spectrum of this test point the dominant signal’s frequency peak is marked (vertical red line). The system user can examine also the other “less dominant” signal peaks.

The interpretation of IE testing results requires from the system user substantial technical understanding, understanding of principle of signal analysis including performing “forecasting” frequency calculations before actual testing, experience of using and “calibration” experience of IE testing results by invasive means.
3. Application of State Of The Art NDT- Techniques in Evaluation of Road Bridges Deck Surface Structure – Why and When

This paragraph will review the importance of using state of the art NDT- techniques in evaluation of road bridges deck surface structure, in what kind of cases we can efficiently apply NDT- techniques and what are the suitable NDT- techniques.

Condition evaluation of bridge deck surface structures is a crucial phase of bridge special inspection. The main aim of bridge special inspection is to evaluate the condition of the various structure parts including the functionality of the bridge deck surface structures, i.e. the pavement layers, protective layer, waterproofing and the deck upper surface. Usually bridge special inspections are performed when it is obvious that a bridge is in a need for renovation.

Bridge special inspection and of course the following repair works of the deck surface structure are time consuming, expensive and cause significant disturbance to road users (in renovation time for long period!). It is important to get sufficient information of the surface structures’ actual condition and as efficiently as possible, before initiating the repair work.

Traditionally evaluation of deck surface structure is based merely on visual observation of the bridge pavement top surface (looking for deformations, cracks, unraveling of the top pavement surface etc.) and of the deck under surface (looking for water leakage marks). According to the visual observation locations of invasive testing i.e. opening of the surface structure are chosen. Unfortunately this is proven to be an unreliable and insufficient method of choosing those locations, especially as only a few openings of the surface structures are usually done, usually 5 to 10 locations when the bridge surface structures area is up to several thousands of square meters. Often reviewing the deck under surface is substantially limited, for example in case of box girder bridges or in long and- or high bridges when visual walk through is difficult and time consuming. Inadequate information of the surface structures’ condition means faulty initial information for repair planning and possible expensive “surprises” to the bridge owner in connection to repair costs and timetable.

Over the years it became obvious that unreliable evaluation of the surface structures is a real problem and solutions are needed.

In the recent years Ramboll engineers have proven that a relatively reliable, fast and in situ evaluation of bridge surface structures can be performed by means of the Impulse–Response (IR) NDT technique. In some cases also the Impact–Echo NDT technique is usable, mostly when testing is performed on concrete surface.

One of the significant advantages of the IR is that testing can be performed directly from the pavement surface, also from asphaltic pavement surfaces. This is mostly limited to other NDT- methods. Ultrasound tomography has been tested on asphalt surfaces but appeared to be unclear and slow. Impact-Echo seems to be suitable in some cases also when testing on asphalt surface, yet, the testing is very point-wise and slow. As both methods are based on detection of wave reflections the uncertainty increases when applying them on surface structures as the acoustic characteristics of the different materials of the surface structure are unknown and in many cases even the actual thickness of the surface structures is unknown.

The main reason why the IR is suitable for testing also from asphalt surfaces is because we are measuring the Mobility which describes the resistance of a plate-like object to vibrate due to an impact (dynamic behavior) and not reflections of waves.
By using the IR technique on relatively extensive areas of a bridge pavement we can detect suspicious areas and pinpoint logical locations for opening of the surface structures. By that we increase substantially the reliability of the surface structure condition evaluation.

Main guidelines of applying the IR in a bridge special inspection:

When screening surface structures we will look for areas which produce relatively high Average Mobility (AM) values. In general, a loose / damaged surface structure will produce higher AM because the loose layer will be more mobile, i.e. will have a smaller resistance to vibrate in comparison to a similar intact surface structure. Based on experience even old and poor condition surface structure will have relatively areas of better condition so the relative comparison should succeed. If high AM values will appear everywhere there is anyway a serious problem with the tested deck.

When analyzing the AM values one has to estimate the general mobility of the deck structure itself. For example, the cantilever zone of a deck should produce higher mobility values than the deck zone above a girder. Also areas of different thickness of surface structures will have differences in mobility (the thicker the less mobile).

Figure 7. Example of bridge deck mobility behaviour. Green arrow = relatively lower mobility zone. Red arrow = relatively higher mobility zone.

High AM values in evaluation of surface structure usually could indicate of:
- Loose pavement / protective layers e.g. due to faulty execution or wear and tear.
- Damaged pavement / protective layer, e.g. due to traffic loads or freeze-thaw.
- Loose waterproofing from the protective layer
- Loose waterproofing from it substrate (deck top surface), e.g. due to faulty execution, wear and tear or damaged substrate. This indication is the most severe to deck structure durability because it means that moisture and possibly de-icing salts might penetrate into deck structure causing corrosion of reinforcements and thus weakens the structure. Also the repair of this kind of damage is the most time and budget consuming.

Each of the indications may be a problem as good condition bridge surface structure should be intact and its layers should be well bonded to each other.

The actual IR testing is done in a grid form, usually with intervals of 1 m from test points. The test points are marked by spray paint. Testing is performed in several investigation zones usually of 20-50m². Only rarely the whole bridge deck surface structure is screened, depending on the purpose of the test case in question.

Example of test case in the frame of a bridge special inspection, see test case 1.

In addition to the usage of the IR in bridge special inspections the system is proven to beneficial, sometimes together with the IE, in different phases of bridge deck surface
structures **repair works quality assurance** as reviewed below. The QA possibilities are of great importance in relation to rapid renovations of surface structures.

**- Evaluation of the deck top surface**: after mechanical removal of old deck surface structure layers the condition of the bridge deck top surface should be evaluated as it should function as the substrate for new waterproofing or for a surface repair cast or for a profiling concrete cast. Traditionally the exposed deck top surface is estimated by visual walk through and by performing several pull off testing (concrete tensile strength) at chosen locations. In Finland a qualified concrete substrate should produce at least value of 1.5 MPa in pull off testing. In case the top surface in inadequate usually the damaged concrete is remove by water jetting.

The problem with visual estimation is that it is too general. Hammering or dragging of chains on the surface may be considered but usually at a bridge repair site the background noises limits the possibility of hearing the sounds of those testing.

The Impulse-Response screening of the deck top surface and Average Mobility analysis can assist in pin-pointing logical locations for pull off testing and in evaluating the general condition of the top surface (approx. dimensions and locations of weak concrete). Areas of high AM are suspicious and may indicate of deteriorated concrete. Impact-Echo could be used in searching deep damages / faults or when trying to estimate the depth of damages in a suspicious zone according to IR testing.

Example of test case similar to the described above see **test case 2**.

**- Bond / delamination estimation of concrete repair casts or profiling casts**: after removal of inadequate concrete layer from a deck top surface a repair cast (in case of local damages) or a profiling cast (in case of extensive damages or when improving of the deck cross-wise inclination) will be applied on the exposed old deck surface. In some cases the repair cast has also an important structural function for example if removing concrete deeper than the depth of reinforcements above intermediate support zone of a continuous bridge.

Because during repair works the construction and environmental conditions are often difficult (weather, dust etc.), the new cast is not always well bonded to its substrate.

If debonding occurs at a substantial area of the repaired deck the whole repair work can be considered as a fiasco and it is likely that the faulty repair work has only caused more damage than benefits, wasting a great deal of budget in the process. Unfortunately, experience has already proven that substantial number of old repair works has been unsuccessful (putting it mildly).

By screening large areas by the IR system ones can identify suspicious areas for invasive testing, for example by pull off testing when drilling several centimeters into the old deck concrete. Suspicious areas according to the IR could be investigated also by the IE by searching dominant wave reflections at the depth of the bond plane.

Example of test case similar to the described above see **test case 3**.

**Condition estimation of a ready product**: when new deck surface structure is ready. In the end of a renewal of bridge deck surface structure additional quality assurance measure could be IR screening of the ready product and when necessary, if clearly suspicious areas of high AM are detected, also performing of invasive testing.
For the owner of the bridge this could mean additional quality assurance measure, i.e. additional indication that the renewed surface structure is intact. A logical time for performing this kind of testing could be just before the end of the guarantee period given by the repair work contactor for ensuring acceptance of a good quality product.

Example of test case similar to the described above see **test case 4**.

In Finland Ramboll has frequently performed quality assurance NDT tasks in relation to rapid renovations of surface structures when the assurance process should be fast and nondestructive as possible.

### 4. Example Test Cases

This paragraph will shortly review some selected test cases related to evaluation of bridge deck surface structures by the mentioned NDT- techniques.

- **Test case no. 1**

  Vuosaari bridge (Helsinki) special inspection.

  ![Figure 8.1-8.3. Vuosaari bridge general photos and the bridge deck cross-section.](image)

  Main challenge: deck surface structure area >8000m² and significant time and cost limitations for work execution. Openings of the surface structure less than 20 pcs.

  Solution: systematical IR scanning of 14 different zones each of 30m² along the deck followed by immediate opening of the surface structure according to IR results (fast scanning, fast interpretation => fast movement).

  ![Figure 9. Bridge deck surface structure IR test zones (small squares)](image)

  Figures 10.1 and 10.2. Example of IR test results, test zone 4. At low AM values area (green) the surface structure is confirmed to be in reasonable condition and well bonded. Deck upper
surface pull-off test result = 2.2 MPa, thin section examination confirms deck upper surface concrete is in fair condition.

Figures 11.1 and 11.2 Example of IR test results, test zone 14. At high AM values area (red) the surface structure is confirmed to be badly deteriorated, waterproofing is debonded, deck upper surface pull-off test result = 0.5 MPa, thin section examination confirms severe deterioration damages (freeze-thaw) of the deck concrete.

- Test case no. 2

Leppävirta bridge (Central Finland), testing during repair works.

Evaluation of deck upper surface concrete by IR after removal of deck surface structure during bridge repair work.

Figures 12.1-12.3 Bridge general photos and testing results. Scanned area by IR = 200m2. At relatively high AM value zones pull-off testing results confirm weakening of deck upper surface concrete due to freeze-thaw.

Water jetting of the scanned area confirmed damaged concrete to substantial depth, in some cases also beneath the rebars and in good correlation to the high AM testing results (yellow-red areas).

- Test case no. 3

Haaga-Metsälä bridge (Helsinki), quality assurance during repair works.

Task: integrity and bond evaluation of bridge repair cast applied on water jetted bridge surface. Main concern: debonding of the new cast from the old concrete.

Solution: IR screening of several zones of the bridge deck (175m2) followed by IE testing of several selected points. After NDT- testing core samples were extracted and pull-off testing evaluating the bond between the new and old concrete were done.
Figures 13.1 - 13.5. Bridge cross-section, example of IR and IE testing results. IR testing results indicated relatively low AM values with no clear indication of significantly suspicious zones. At cantilever AM values increases as expected (thinner and thinner structure). According to IE testing results (on right, frequency spectrums) dominant signals appear at the depth of the old concrete or at the deck under surface. No suspicious indications at depth od bond plan.

Figures 14 and 15. Core samples. Bond plan marked with red arrow. Bond plan is closed. Pull off testing results between new and old concrete= 1.64…2.04 MPa (requirement ≥ 1.5 MPa). Results support NDT.

- **Test case no. 4**
Brändöström bridge (Åland islands), quality assurance after repair work.

Task: evaluation of ready surface structures more than a year after execution of repair works. Aim is to ensure acceptable quality of the surface structure repair.

Solution: IR screening of all the bridge deck area, 530m² followed by opening of the surface structure in selected locations according to IR results.

Figures 16.1 - 16.3. Bridge general photos and cross-section with marking of test points.
5. Conclusions

The impulse-Response NDT- technique is proven to be an efficient method for condition evaluation of bridge deck surface structure, also when testing is performed from the surface of asphalt pavement. The technique enables to map and locate suspicious areas and helping in pin-pointing logical locations for further invasive measures. Together with the Impact-Echo NDT- technique it is possible also to evaluate the integrity of bridge deck upper surfaces and of concrete repair casts.

The applications of the test methods are most suitable in the frame of bridge special inspections and in different stages of bridge repair works (quality assurance) and smart usage of the systems can significantly increase the reliability of those.

References

Germann Instruments Publication and Commercial Material