Dynamic Structural Monitoring for Condition Assessment and Life-Cycle Management of Port Facility Structures

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1 Introduction

Port assets by their very nature are large, costly and for the most part unseen. When they work income is generated, if they don't, income is reduced and repairs often very costly to implement, especially if there is uncertainty about the cause and effective remediation.

The civil engineering nature of the asset implies that much is unseen; consequently, to determine its condition and ability to undertake its functions, costly inspections need to be undertaken which in many cases cannot fully appreciate the cause for any structural distress or condition. This can lead for over remediation or seriously under rectification

While there are currently in the Port market innovative non-destructive inspection systems, such as Falling Weight Reflectometer [FWD] devices for residual paving strength and condition, ground radar penetration technologies for sub surface investigations, sonar inspections, fibre optics and many others, there is nothing hereto available that can assess the actual load carrying ability nondestructively and the overall structural condition of each port asset, other than by dynamic monitoring. One is reminded of a massive Lo/Lo crane failure, resulting in total collapse, when on inspection fatigue structural cracking was hidden under skin paintwork indicating little problem. Had dynamic monitoring of that crane taken place, such an event would not have happened

The optimization of the maintenance management of built port facilities, such as wharfs and cranes, can lead to considerable cost savings. The exact knowledge of the actual structural condition and load bearing capacity allows for extended inspection intervals (less down time of facilities), minimization of direct maintenance and repair costs and considerable extension of the total lifetime.

Vienna Consulting Engineers have developed the BRIMOS® Technology based on ambient vibration monitoring. The actual load bearing capacity can be determined by measuring the dynamic characteristic of structures, which reflects their condition, together with numerical simulation. Any hidden damage which affects the structural condition can also be detected and localized.

Structural monitoring with BRIMOS® is also used to check structures for residual strength if needed for future increase of load capacity (e.g. by taller cranes).

Dynamic Monitoring with BRIMOS® has been successfully been implemented on more than 900 structures worldwide.

2 Motivation for Structural Health Monitoring of Port Facilities

All infrastructure assets have to be properly maintained by their owners and operators to ensure safe and reliable operations without interruption. Asset management and maintenance planning of port facilities requires accurate information on their actual structural conditions, as well as predicting the further lifecycle development. Therefore the condition assessment of exposed high value structures cannot rely on visual inspections alone but needs to be supplemented by sophisticated methods to assess real condition and load bearing capacity. Periodic and permanent structural health monitoring are appropriate methods.

The following figure shows the six typical stages of a structural life cycle and the differences in the cost allocation between port and offshore structures, bridges and buildings.

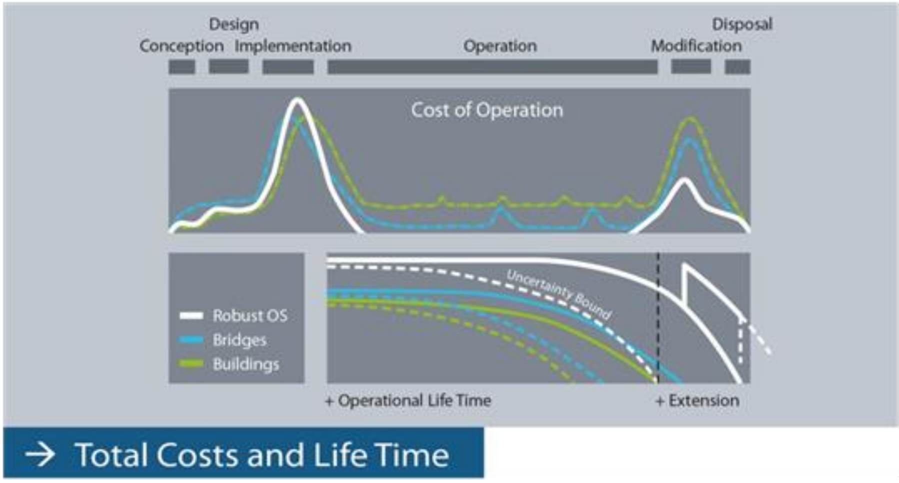

Figure 1: Compared life cycle curves

The degradation concept shows the difference between ordinary and robust structures. While the mean degradation for an ordinary structure coincides with the design life, robust structures carry additional capacity (in other words safety) which produces conditions that allow for uncertainties appearing in an empirical way without jeopardizing the safety of the structure.

In reality asset conditions cannot be inspected or tested at any time, so it is preferable to receive information on the structural condition from a permanent monitoring system. Current structural health monitoring technology is able to reliably supply this information.

3 Monitoring Technology

3.1 Dynamic Measurements and System Response

Considering the scale of robust structures it is advisable to monitor the System Response of the structure. It describes reliably how the structure behaves under actual loading. Any change in the system response over time (i.e. degradation) can be identified and compared to the pre-set target values. The monitoring system determines the condition index in real time and warns automatically when there is deviation from the target values.

The appropriate methodology to determine the system response is Ambient Vibration Monitoring (AVM). In the Ambient Vibration Measurement methodology, the vibration behaviour of a structure is recorded, evaluated and interpreted under ambient influences, i.e. without artificial excitation, by means of highly sensitive acceleration sensors. Structures show a significant vibration behaviour which may be addressed as "vibrational signature". This dynamic behaviour is typical for any structure and can be obtained by appropriate measurements and used for the assessment of the condition of a structure as well as for the detection of any changes over time. It has been applied for 25 years and is already well established.

Calculation models used for determining of stresses and consequently for measuring structures, only represent an approximation to reality and have to be calibrated. With System identification it is intended that the conformity between the calculation model and the actual load-bearing behaviour can be determined.

With ambient Vibration Monitoring, the dynamic characteristics of the structure are determined and they can be used, not only to check the calculation models, but also for understanding the chronological development of the load-bearing capacity. Estimates of the remaining service life duration are then assessed by measurements taken at certain intervals. Such measurements taken show snapshots of structural integrity and can be used in combination with parallel mathematical analyses for determining possible structural damage.

Dynamic monitoring is used to perform system identification. Statistical methods are used to build a mathematical model of the dynamic properties of the structure. This approach offers a reliably system response of the structure under real life conditions.

4 Typical Applications

4.1 Quayside Ship Container Cranes

Quayside ship to shore container cranes are large structures which can lift and move quickly up to 4 full size containers at once. These cranes are equipped with sophisticated monitoring systems for the lifting machinery (motor, winches, hoists etc.) but these systems do not cover the condition of the actual structure. Therefore additional information and monitoring of the structural integrity is required in order to determine that the structure is not overstressed or defective. The main sources of damage to crane structures are:

- ship collision
- fatigue damage
- storms
- earthquake

Periodic and permanent dynamic monitoring of the primary load bearing structure of container cranes provide:

- Integrity assessment of the load carrying structure
- Early damage detections and damage location
- Early warning and reduction of down-time.

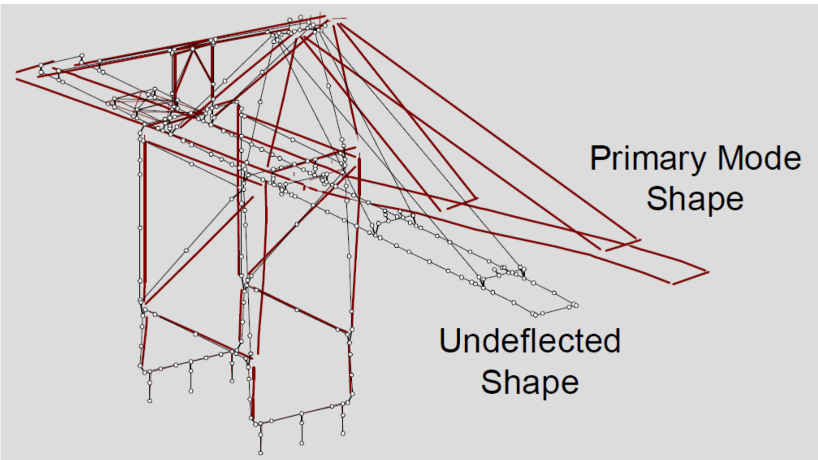

Figure 2: Dynamic behavior of container cranes

4.2 Increase of the Load Rating and Extraordinary Loading of Wharfs

Assessment of structures by dynamic monitoring is the most suitable monitoring method for the assessment of the global condition and the load bearing capacity of wharf structures.

Any modifications (e.g. strengthening) or damage affecting the load bearing capacity of the structure can be detected by changes in its dynamic behavior. Minor damage which does not affect the load bearing capacity does not influence the measurement results.

The result of the dynamic investigation is the determination of the real load bearing capacity of the structure including any hidden reserves by initial overdesign.

Following tests are typically part of the dynamic assessment

Piles:

- Test rolling of crane along wharf structure during dynamic and static measurements (acceleration and vertical deflection),
- Static test loading of selected pile-groups during dynamic and static measurements,
- Evaluation of load bearing capacity.

Deck structure, beams:

- FE-Modelling of typical / selected sections
- Dynamic measurement of selected weak / heavy loaded sections
- Test loading of selected sections
- Data analysis of modal parameters
- FE-Modell-Updating with the obtained modal parameters
- Evaluation of the load bearing capacity from the FE-Model.

4.3 Integrity and Load Bearing Capacity Assessment as Part of a Due Diligence Requirement

Technical due diligence should clearly assess whether a port's infrastructure is fit for the continued use of the site as intended and highlight key risks as to its sustainability.

The assessment of the load bearing capacity of the wharf structure by dynamic measurements supports these objectives. Measurements with BRIMOS® in combination with an updated FE-model allow for the determination of the actual load bearing capacity. This includes:

- Evaluation of the wharf loading capacity
- Evaluation of a quay wall
- Evaluation of pile loads based on crane operations as well the condition of pile fenders and ladders (corrosion, etc.)
- Review of the suspended deck including concrete condition, location of cracks if any
- Survey of bollards and curb bar, exposure of steel reinforcement and corosion
- Evaluation of the ground anchor construction (retaining wall and anchor arrangement).

5 Benefits to the Port Operators and Owners

The application and the benefits for the port industry are – like for all other industries, that use dynamic monitoring – to be able to know how safe the structure is and to have decision support as to how long the asset can be operated safely. In case of damage, these can be detected and sometimes – depending on the severity – be removed in order to increase the asset's life.

The following cost saving benefits can be achieved through a program of structural health monitoring and lifecycle engineering services:

- Assurance that the structure is safe and provides a methodology that can be monitored on a regular real time basis
- Increased assurance of avoiding environmental damage or other high impact/low probability event
- The ability to check the structure after storm, seismic, or other significant damage risk event
- Provides a basis for reducing the frequency of physical inspection (ROV or diver based)
- Provides an understanding of the condition of structure and any liabilities prior to any modifications (repair, strengthening)
- Provides a basis for rationalizing and planning life extension of the structure, with the possibility of greatly improved financial returns

5.1 Summary of Benefits of Dynamic Monitoring

Dynamic monitoring services provide the following benefits:

- Dynamic monitoring enables identification of actual condition of any structure
- The procedure is non-destructive and does not interfere with operational activities
- The technology reduces the required inspection procedure to a minimum
- The accuracy of the assessment will be considerably improved
- Subsequent lifecycle engineering enables priority ranking
- An optimal budget management for routine maintenance is feasible
- Critical structures can be monitored permanently
- Online systems issue warnings before critical situations arise

Annex: BRIMOS® Method Statement

BRIMOS® is also an assessment and judgement methodology, which enables accurate observation and assessment of the structural condition, damage detection and load bearing capacity of structures and infrastructure. This technology is constantly being modified and optimized in order to support the owner's decision process in maintenance, rehabilitation and cost planning.

It was recognized very early on in its development, that methods based on conventional visual inspection can get broadened and made more objective by incorporating the dynamic behavior of an analyzed structure. Based on the principles of structural mechanics tailored dynamic measurements are merged with numerical simulations. In the first instance structural analysis reflects experimental full scale monitoring (measured physics). Complementary Finite Element Calculations enable a deepened understanding of structural integrity leading to decisive interpretation of results.

Dynamic response due to ambient excitation like wind, traffic or micro seismic activity is fully utilized. In most of the cases structural behavior is affected by traffic and mechanical use. This dominant source of impact is evaluated to identify and localize potential weak areas in order to determine the remaining load-bearing capacity. The non-destructive measurements are performed under unrestricted operational conditions.

1. Measurement Procedure

An aerial measurement grid, which usually comprises 12 accelerometers, is distributed in pre assigned locations all over the structure, while the reference sensor remains at its fixed position.

For each sensor array at least one measurement file with a length of 22 minutes and a sample rate of 500 Hz (= 2 milliseconds) has to be recorded. The whole measurement can be supported by video-recordings which facilitate the verification of loading impact during data evaluation and data processing.

Various measurement equipment is available for dynamic measurements including wired technology as well as wireless technology.

2. BRIMOS® Sensor Layout for Structures

The appropriate sensor layout must be developed on a case by case basis. Sophisticated software called BRIMOS® Layout Creator has been developed. This guaranties the optimal sensor distribution on the structure and helps to keep the measurement efforts as practical as possible.

3. Dynamic Parameters used for Structural Sssessment

Investigations are based on measurements and numerical analysis using KPIs (KEY PERFORMANCE INDICATORS) from the field of structural dynamics (Eigen frequencies, mode shapes, damping, vibration intensity, deformations). The interpretation incorporates structural engineering experience (statement to integrity with regard to structural resistance, remaining load bearing capacity).

Figure3: KPIs for health identification

The dynamic parameters are very sensitive to changes. The analysis identifies those parameters that provide information on damage. They are then called key performance indicators, which could be followed up online if a permanent monitoring system is available.

4. Computer Simulation & FE Model Update

In general as the undamaged reference condition, in terms of a dynamic measurement, is not stated at the beginning of the asset's service life a finite element model can be very useful. The calculated parameters serve as expected values based on the undamaged condition. The comparison of the results from the model with those of the measurements supports the assessment of the structural condition.

A Finite-Element-Model-Update procedure is used to identify weak or damaged parts of a structure and to evaluate the load-bearing capacity. The procedure allows manual, semi-automated and automated model update.

5. Assessment & Rating

BRIMOS® offers a well-defined rating system for investigating structures. This classification allows early identification of the structure's integrity, as well as the corresponding risk level, based on the measured key performance indicators (Eigenfrequencies, Mode Shapes, Damping Pattern in the lengthwise direction and Vibration Intensity), an accompanying visual inspection as well as a comparison with an analytical analysis of the structure (Finite Element Model). Additionally a comparison with BRIMOS®- reference investigations, which have been administrated in a special database, is made.

BRIMOS® represents a diagnostic procedure which is based on more than 15 years of consistent development of user-oriented research. As the research project activities started in 1995, thousands of structures worldwide have already been evaluated. The gained experience has been incorporated into the assessment procedure, which makes VCE as one of the world-leading representatives in the field of applied structural dynamics.

Thus an integrated approach for infrastructure diagnosis in each relevant stage of operational service life is recommended (Life-cycle-management), which does not depend on the type of structure or the construction materials used.