Use of SHM in destructive testing of bridges

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Dad! How do they know how much a bridge can carry?

They drive larger and larger trucks over it until it fail…

…. the last truck will give way and they will built up the bridge again.

I should have understood that.

If you don’t know, so say so now!!!
Outline

- Introduction
- Monitoring principles
- Structural Assessment
- Case Studies
- Destructive testing
- Summary and Conclusions
- Acknowledgements
Introduction

The following questions must be asked:

- Do we need monitoring?

- Has monitoring become a “popular” research field because the fast development in sensor and IT technology during the last decade?

- Do we really obtain the information asked for about the structures that are monitored?

- Compared to ~20 years ago – do we get more useful information today or only more data to evaluate?
Introduction

What are the drivers for SHM?

- Increased traffic demands
- Heavier loads
- Increased traffic intensity
- New demands from owners
- Deterioration of our infrastructure
- Larger and more complex structures
- Extended residual service life for bridges
- Increased cost for inspection and maintenance

- Also the development in sensor and computer technology must be considered a driver
What is monitoring?

ISO 13822  Bases for design of structures - Assessment of existing structures

- **Inspection**
  On-site non-destructive examination to establish the present condition of the structure

- **Load testing**
  Test of the structure or part thereof by loading to evaluate its behavior or properties, or to predict its load-bearing capacity

- **Monitoring**
  Frequent or continuous, normally long-term, observation or measurement of structural conditions or actions
Why monitoring?

The main purpose for SHM must at the end be to increase the total cost benefit for the client.

This should be carried out considering the safety, durability and service life.

To able to do this we have to be sure that we monitor the “right thing” at the “right time” in the correct “state”.

State is here defined as:
- Ultimate limit state, ULS
- Service limit state, SLS
- Fatigue limit state, FLS
- Durability limit state, DLS
Why monitoring?

One reason may be if a physical phenomenon needs to be followed up or if uncertainties in calculation models exist.

But also if the strengthening effect needs to be verified and for assessment of structures.
Why monitoring?

SHM can also be very useful in relation to demolition or destructive testing of structures. This might also be denoted load testing – but contain much more than just a load test.
Monitoring Principles

Time strategies, local or global monitoring, load effects etc.

- Short- and long time monitoring
- Periodic, continuous or trigged monitoring
- Local or global monitoring
- Damage detection
- Static or dynamic monitoring
- etc.

Hejll, 2007
Monitoring Principles

Goals of monitoring – we have to have a distinct goal

- Monitoring provides reliable input (information) about an existing structure based on measurements under operational conditions. Input for
  - the condition assessment of existing structures
  - predicting the performance of existing structures under different loading conditions
  - predicting the remaining life-time of a structure (e.g. fatigue, chloride penetration and content)
  - verifying the effects and quality of strengthening
  - optimizing the inspection cycle
  - optimizing the maintenance strategy
  - verifying design models……..

- Monitoring has a benefit only in combination with an assessment or maintenance concept
Monitoring Principles

Basic Monitoring Methodology

- Monitoring objectives
- Constraints
- Design model monitoring system
  - Design of physical monitoring system
  - Installation of physical monitoring system
  - Validation of model and physical monitoring system
  - Maintenance of model and physical monitoring system

Competence of the bridge engineer
- What?
- Where?
- When?

Competence of the monitoring engineer
- How?

After Glauco Feltrin, EMPA, 2007
Monitoring Principles

Improved correlation

Interaction bridge model/monitoring

Do model results match with monitoring results?

Modification of model
Monitoring Principles

Verification by monitoring – not new

From: Mufti A. , Guidelines for Structural Health Monitoring, ISIS Canada

A steel truss for a bridge, tested before it was shipped to India and assembled on site.
Structural Assessment

Assessment procedure

Step 1
Initial assessment
- Site visit
- Study of documents
- Simple calculations

Step 2
Intermediate assessment
- Further inspections
- Material testing
- Detailed calculations

Step 3
Enhanced assessment
- Laboratory investigations
- Load Models
- Reliability based investigations
- Monitoring
- Refined calculations
- Decision analysis

Step 4
Destructive testing
- Design Models
- Ultimate Limit State
- Verification
- Detailed analysis
Case Study – Stora Höga - 1989

Background

- Stora Höga was a bridge located north of Gothenburg
- The bridge was built in 1980
- Load test up to failure
- Interest to investigate the shear force capacity. For all reasonable placements of the load – a bending failure would arise.
- The bridge was strengthened with externally bonded steel plates
- Strengthened from ca 200 tons to 600 tons in the loaded section
Case Study – Stora Höga - 1989

Background

- Approximately 2/3 of the bridge was strengthened with steel plates, $A_s = 250 \times 6 \text{ mm}$, weight per meter ca: 12 kg.

- The bridge was loaded ca 4.0 from the left (east) support

- Only loading after strengthening
Case Study – Stora Höga - 1989
Strengthening
Case Study – Stora Höga - 1989

Monitoring

Strain gauges on steel plates and on reinforcement

Deflections
Case Study – Stora Höga - 1989

Loading - monitoring

Load beams

"Monitoring central"
Case Study – Stora Höga - 1989

Loading - Monitoring

Steel stays anchored in the bedrock

Shear failure at 460 tons
Case Study – Stora Höga - 1989

Lessons learned

- Destructive testing to failure – very interesting
- Shear models used in the codes did not predict the correct load very well
- Steel Plate Bonding gave a considerably strengthening effect in ULS
- Practical expertise regarding the strengthening procedure
- The installed sensors worked as intended
- No focus on SHM – only load testing
- The test was very useful since the failure of the bridge could be compared with models used for design
Case Study – The Örnsköldsviks bridge - 2006

- A railway trough bridge – located in Örnsköldsvik
- The bridge is a traditional trough bridge built in RC
- Was demolished and removed due to the newly constructed Botnia line
- Investigation of the shear capacity
- Bending failure before shear failure – needed strengthening
- Strengthening with CFRP rods in the soffit of the beams
- Testing before and after strengthening
- Loaded with steel stays anchored in the bed-rock
Case Study – The Örnsköldsviks bridge - 2006

Built 1955
Axle Load 250 kN
Case Study – The Örnsköldsviks bridge - 2006

Assessment procedure for the bridge

Step 1
Initial assessment
- Site visits - several
- Study of documents
- Study and carried out simple calculations

Step 2
Intermediate assessment
- Further inspections
- Material testing, cores etc
- Detailed calculations
- Investigations of loading etc
- Planning for testing etc
- Simple FE-Models.

Step 3
Enhanced assessment
- Laboratory investigations
- Investigations of Load Models
- Reliability based investigations
- Strengthening calculations
- Monitoring
- Refined calculations, FE-models
- Decision analysis

Step 4
Destructive testing
- Design Models
- Ultimate Limit State
- Verification
- Detailed analysis
- Non-linear FE-Models
Case Study – The Örnsköldsviks bridge - 2006

Structural Assessment

S1: Survey
Bridge owner/Consultant

S2: Condition assessment
Visual Inspections

S2: Non destructive tests
Radar, ultrasonic tests etc.

S2: Material samples
Drilling of cores, pull-off etc.

S1: Questionnaire
Bridge owner/consultant

S2: Simple FE
Consultant

S3: Laboratory testing
Concrete, Steel etc.
Case Study – The Örnsköldsviks bridge - 2006

Structural Assessment

S3: Sensor installation
Specialist consultant

S4: Load test 1
Testing institutes

S4: Strengthening
Specialist contractors

S4: Load test 2
Testing institutes

S4: Detailed evaluation
Case Study – The Örnsköldsviks bridge - 2006

Structural Assessment

- Bridge in good condition
- Concrete $f_{cc}$ (compressive) = 68.5 MPa
- Reinforcement $f_{sv}$ (ϕ16 and ϕ25) = 411 MPa
- No corrosion
- Some impact damages and scratches under the bridge
Case Study - The Örnsköldsviks Bridge -2006

Strengthening with the NSMR Technique
Case Study - The Örnsköldsviks Bridge -2006

Strengthening with the NSMR Technique

First the strengthening design was carried out. Strain based design. Resulted in 9 bars (9x100mm²/beam). $E_f = 250$ GPa. Moment capacity of 11.6 kNm per beam.

$$M = \frac{x - d'_s}{h - x} \left( \varepsilon_f + \varepsilon_{uo} \right) A'_s E_s \left( \beta x - d'_s \right) + A_f \beta (d_s - \beta x) + \varepsilon_f E_f A_f (h - \beta x)$$
Sawing for Strengthening with NSMR (Near Surface Mounted Reinforcement) CFRP Rods

Irregularities in the sawn slots were removed by a drill hammer.

The 15 x 15 mm slots were cleaned with high pressurised water, 150 bars.

Nine bars in each beam. Type Sto FRP Bar M10C. Young's modulus: 250 GPa. Each bar had a cross sectional area of 100 mm².
Final strengthening result
Case Study - The Örnsköldsviks Bridge -2006

Strengthening - Conclusion

- The strengthening work in total took approximately 6 days, including 2 days for sawing the slots, 1 day (long) for bonding and 3 days for hardening of the adhesive.
- Five people were working with the strengthening
- In total 1800 mm$^2$ of Sto FRP bar M10C was used.
- Proper scaffolding is essential
- It is important to divide the work site into stations
- Keep the mixing station separated from the bonding area
Case Study – The Örnsköldsviks bridge - 2006

The monitoring phase was be divided into five steps

- Planning
- Analysis
- Installation
- Loading
- Evaluation

Loading is added since the intention was to do a full scale test to failure

Diagram:

- Normal state
  - Planning
  - Normal inspection
  - Protocol
  - Ok?

- Investigation state
  - Deficiencies
  - Increased inspection
  - Protocol
  - Ok?

- Monitoring state
  - Deficiencies
  - CSHM inspection
  - Diagnosis
  - Ok?

- Actions
  - Build new
  - Restrictions
  - Strengthening
  - Continuous monitoring
Case Study – The Örnsköldsviks bridge - 2006

Planning
• The monitoring goal was established
• Type of data collection and data transfer
• Acquisition systems were decided, i.e. electricity, scaffolding etc.

Analysis
• An analysis of the bridge had earlier been carried out
• The analysis is used for correct placement of the sensors
• Type of loading is decided here

Installation
• Placement of sensors and load
Case Study – The Örnsköldsviks bridge - 2006

Loading
- Installation of loading device
- The type of loading was carried out in three steps
  1. Loading of the slab up to cracking
  2. Loading of the beams up to cracking
  3. Loading of the bridge up to failure

Evaluation
- Evaluation of all test data
- Comparison with previous analyses
- Improvement of calculation models
Test of Strengthened Bridge
July 10th, 2006
Stirrup rupture after yielding
Case Study – The Örnsköldsviks bridge - 2006

Load – time curve

- Slab
- Beam-Pre
- Beam-Main
Case Study – The Örnsköldsviks bridge - 2006

Predicted Load-Carrying Capacity

- Eurocode 2, $\theta = 30^\circ$  \hspace{1cm} $P = 6.1$ MN
- Eurocode 2, $\theta = 22^\circ$  \hspace{1cm} $P = 8.8$ MN
- MCFT, Response, $\theta \approx 30^\circ$  \hspace{1cm} $P = 8.7$ MN
- 2D Non-linear, Atena, $\theta \approx 30^\circ$  \hspace{1cm} $P = 10.8$ MN
- Test, $\theta \approx 30^\circ$  \hspace{1cm} $P = 11.7$ MN
Case Study - The Örnsköldsviks Bridge -2006

Some results from monitoring

- To many sensors were installed and to many people, organisations, were involved in the work. Still we would have needed more sensors to understand the total behaviour of the bridge.

- Many different types of skills are needed.

- To decide the boundary conditions are very complicated.

- Enormous amount of data to be evaluated.

- Local behaviour, e.g. strain, was easier to monitor than global, i.e. deflections.

- The use of fibre optics minimise the amount of cabling.
Case Study – The Örnsköldsviks bridge - 2006

Conclusion from the field test

- Successfully testing of a 50 year old reinforced concrete trough bridge
  - inspection and condition assessment,
  - load carrying capacity predictions,
  - strengthening and monitoring

- A failure in combined shear, bending and torsion was reached for $P = 11.7$ MN.

- The failure was initiated by rupture of a stirrup after yielding in stirrups and longitudinal reinforcement.

- The failure load was close to non-linear FE predictions and 20 to 50% higher than common design.

- The full scale test verifies that the anticipated failure mechanism was correct. This is sometimes not the case.
Case Study – Örnsköldsviks Bridge 2006

Lessons learned

- Design models do often not correspond very well with reality, at least not in U.L.S.

- The load carrying capacity is often much higher than expected.

- A proper planning for monitoring installation, data collection and evaluation needs to be carried out early in the project phase.

- Short term destructive monitoring is very useful when it comes to the understanding of a structure behaviour in U.L.S.

- Advanced FE-analysis was needed to understand the behaviour.

- The strengthening effect in the U.L.S using NSMR was considerable.
Summary and Conclusions

- Strategies and defined goals are necessary when adopting SHM – what is the expected result and how is it going to be used?
- This is necessary for our decision makers
- Monitoring shall preferably be carried out in accordance to pre-decided goals
- Monitoring can be used to verify strengthening effects
- Unusual to verify strengthening by monitoring in the ULS – important though
- Verification of design models should be done in field – if possible
Future needs

What are the future needs for SHM:

- We have to focus on the cost benefit for the bridge owners

- Uncertainties in design models – need of verification both in S.L.S and in U.L.S

- Existing strain (stress) field affect the structure, especially for very large structures, can this be monitored

- Monitoring through the different construction processes, giving the structure a “water stamp”

- Not to do monitoring because we can, but because we need to.
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