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Lessons Learned in Structural Health Monitoring of Bridges Using Advanced Sensor Technology

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Abstract

Structural Health Monitoring (SHM) with emerging technologies like e.g. fibre optic sensors, lasers, radars, acoustic emission and Micro Electro Mechanical Systems (MEMS) made an entrance into the civil engineering field in last decades. Expansion of new technologies together with development in data communication benefited for rapid development. The author has been doing research as well as working with SHM and related tasks nearly a decade. Both theoretical knowledge and practical experience are gained in this constantly developing field.

This doctoral thesis presents lessons learned in SHM and sensory technologies when monitoring civil engineering structures, mostly bridges. Nevertheless, these techniques can also be used in most applications related to civil engineering like dams, high rise buildings, off-shore platforms, pipelines, harbour structures and historical monuments. Emerging and established technologies are presented, discussed and examples are given based on the experience achieved. A special care is given to Fibre Optic Sensor (FOS) technology and its latest approach. Results from crack detection testing, long-term monitoring, and sensor comparison and installation procedure are highlighted. The important subjects around sensory technology and SHM are discussed based on the author's experience and recommendations are given.

Applied research with empirical and experimental methods was carried out. A state-of-the art-review of SHM started the process but extensive literature studies were done continuously along the years in order to keep the knowledge up to date. Several SHM cases, both small and large scale, were carried out including sensor selection, installation planning, physical installation, data acquisition set-up, testing, monitoring, documentation and reporting. One case study also included modification and improvement of designed system and physical repair of sensors as well as two Site Acceptance Tests (SATs) and the novel crack detection system testing. Temporary measuring and testing also took place and numerous Structural Health Monitoring Systems (SHMSs) were designed for new bridges. The observed and measured data/phenomena were documented and analysed.

Engineers, researchers and owners of structures are given an essential implement in managing and maintaining structures. Long-term effects like shrinkage and creep in pre-stressed segmental build bridges were studied. Many studies show that existing model codes are not so good to predict these long-term effects. The results gained from the research study with New Årsta Railway Bridge are biased be the fact that our structure is indeed special. Anyhow, the results can be compared to other similar structures and adequately used for the maintenance planning for the case study.

A long-term effect like fatigue in steel structures is a serious issue that may lead to structural collapse. Novel crack detection and localisation system, based on development on crack identification algorithm implemented in DiTeSt system and SMARTape delamination mechanism, was developed, tested and implemented. Additionally, new methods and procedures in installing, testing, modifying and improving the installed system were developed.

There are no common procedures how to present the existing FOS techniques. It is difficult for an inexperienced person to judge and compare different systems. Experience gained when working with Fibre Optic Sensors (FOS) is collected and presented. The purpose is, firstly to give advice when judging different systems and secondly, to promote for more standardised way to present technical requirements. Furthermore, there is need to regulate the vocabulary in the field.

Finally, the general accumulated experience is gathered. It is essential to understand the complexity of the subject in order to make use of it. General trends and development are compared for different applications. As the area of research is wide, some chosen, specific issues are analysed on a more detailed level. Conclusions are drawn and recommendations are given, both specific and more general. SHMS for a complex structure requires numerous parameters to be measured. Combination of several techniques will enable all required measurements to be taken. In addition, experienced specialists need to work in collaboration with structural engineers in order to provide high-quality systems that complete the technical requirement. Smaller amount of sensors with proper data analysis is better than a complicated system with numerous sensors but with poor analysis. Basic education and continuous update for people working with emerging technologies are also obligatory.

A lot of capital can be saved if more straightforward communication and international collaboration are established: not only the advances but also the experienced problems and malfunctions need to be highlighted and discussed in order not to be repeated. Quality assurance issues need to be optimized in order to provide high quality SHMSs. Nevertheless, our structures are aging and we can be sure that the future for sensory technologies and SHM is promising.

The final conclusion is that an expert in SHM field needs wide education, understanding, experience, practical sense, curiosity and preferably investigational mind in order to solve the problems that are faced out when working with emerging technologies in the real world applications. The human factor, to be able to bind good relationship with workmanship cannot be neglected either. There is also need to be constantly updated as the field itself is in continuous development.

Keywords: Structural Health Monitoring, Structural Health Monitoring System, bridges, sensor technology, emerging technology, fibre optics, fibre optic sensors concrete, creep, shrinkage, steel, distributed sensors, crack detection.

Sammanfattning

Kontroll och övervakning av infrastrukturers hälsotillstånd (på engelska *Structural Health Monitoring, SHM*) gjorde entré inom väg- och vattenbyggnadsområdet under de senaste decennierna. Utbyggnad av ny teknik tillsammans med utvecklingen inom datakommunikation borgade för en mycket snabb utveckling. Författaren har forskat och arbetat med SHM och liknande uppgifter under nästan ett decennium och tillägnat sig både teoretiska kunskaper och praktiska erfarenheter.

Denna avhandling presenterar lärdomar i SHM och sensorteknik vid övervakning av infrastrukturkonstruktioner, främst broar. Dessa tekniker kan emellertid även användas i de flesta tillämpningar i samband med anläggningsarbeten såsom dammar, höga byggnader, offshore-plattformar, pipelines, hamnkonstruktioner och historiska monument. Nya och etablerade tekniker presenteras, diskuteras och exempel ges utifrån uppnådda erfarenheter. Särskild omsorg ges till fiberoptisk sensorteknik (FOS) och den senaste utvecklingen inom området. Resultat från sprickdetektering, testning, långsiktig övervakning, sensorjämförelse och själva installationen av givarna betonas. De viktiga frågorna kring sensorteknik och SHM diskuteras utifrån författarens erfarenhet och rekommendationer.

Tillämpad forskning med empiriska och experimentella metoder utfördes. En state-of-the art-studie av SHM inledde processen men omfattande litteraturstudier gjordes kontinuerligt under hela forskarutbildningstiden för att hålla kunskapen aktuell. Flera SHM-fall, både små- och stor-skaliga, har genomförts inklusive val av sensorer, installationsplanering, fysisk installation, datainsamling, testning, övervakning, dokumentation och rapportering. I en fallstudie ingick även förändring och förbättring av systemdesign och fysisk reparation av sensorer samt två provningar för mottagningskontroll (*Site Acceptence Tests, SATs*) och testning av det nya sprickdetekteringssystemet. Temporära mätningar och provningar ägde också rum och många övervakningssystem (på engelska *Structural Health Monitoring System, SHMS*) utformades för nya broar. De observerade och uppmätta resultaten dokumenterades och analyserades

Ingenjörer, forskare och förvaltare av anläggningskonstruktioner bereds en möjlighet till implementering vad gäller drift och underhåll av konstruktionerna. Långsiktiga effekter som krympning och krypning i segmentellt byggda spännbetongbroar studerades också. Många studier visar att befintliga beräkningsmetoder har brister när det gäller att förutsäga dessa långsiktiga effekter. De resultat som har uppnåtts vid fallstudien om den Nya Årsta Järnvägsbronkan ha begränsad generell giltighet eftersom den aktuelle konstruktionen är mycket speciell. Hur som helst, kan resultaten jämföras med resultat från andra snarlika konstruktioner och på lämpligt sätt användas för underhållsplanering för själva fallstudien.

Den långsiktiga effekten av utmattning i stålkonstruktioner kan i värsta fall leda till haveri. Med hjälp av nya sprickdetekteringssystem – som bygger på speciella algoritmer för DiTeSt systemet – kan sprickor upptäckas och lokaliseras. Sådant system vidareutvecklades, provades och användes i studien med Götaälvbron. Dessutom utvecklades nya metoder och arbetssätt i installation, testning, modifikation och förbättring av det installerade systemet.

Det finns inga allmänt vedertagna rutiner för hur man presenterar och redovisar befintlig fiberoptisk sensorteknik. Det är därför mycket svårt för en oerfaren person att bedöma och jämföra olika system. Uppnådda erfarenheterna med fiberoptiska sensorer och mätsystem har samlats in och redovisas i avhandlingen. Syftet är dels att ge råd när man bedömer olika system, dels att främja utvecklingen av ett standardiserat sätt att redovisa tekniska krav. Dessutom finns det ett behov av att reglera terminologin inom området.

Slutligen har den totala erfarenheten från projektet samlats in. Det är viktigt att förstå komplexiteten i ämnet för att kunna utnyttja det. Allmänna trender och utveckling för olika tillämpningar jämförs. Eftersom forskningsområdet är brett har vissa utvalda, särskilda frågor analyserats på en mer detaljerad nivå. Slutsatser dras och rekommendationer ges, både specifika och mer allmänna. SHM-system för en komplex konstruktion kräver att många parametrar mäts. Genom att kombinera flera olika tekniker kommer man att kunna genomföra alla nödvändiga mätningar. Dessutom måste erfarna specialister inom övervakning arbeta tillsammans med konstruktörer för att man skall kunna erbjuda högkvalitativa system som uppfyller alla tekniska krav. En mindre mängd sensorer med ordentlig analys av data är bättre än ett komplicerat system med många givare, men med en britsfällig analys. Grundläggande utbildning och kontinuerlig vidareutbildning av de människor som arbetar med de nya teknikerna borde vara obligatoriska.

Man kan spara mycket pengar genom en öppen och rättfram kommunikation och ett etablerat internationellt samarbete. Man får dock inte enbart berätta om de framsteg man nått utan man måste också diskutera de problem och de fel man stött på så att de inte upprepas. Vidare behöver man optimera kvalitetssäkringsfrågorna för att skapa högkvalitativa SHM-system. I takt med att våra konstruktioner åldras kan vi vara säkra på att behovet av övervakning ökar och att framtiden för sensorteknik därför är ljus.

Den sista slutsatsen är att en expert inom SHM-området behöver bred utbildning, kunskap, erfarenhet, praktisk handlag, nyfikenhet och helst ett innovativt synsätt för att lösa de problem som dyker upp när man arbetar med ny teknik i olika tillämpningar i den verkliga världen. Sociala egenskaper såsom att kunna knyta goda relationer till byggnadsarbetarna får heller inte försummas. Det finns slutligen ett behov av livslång kompetensutveckling eftersom hela området befinner sig i en ständig utveckling.

Nyckelord: Övervakning, övervakningssystem, broar, sensorteknik, ny teknik, fiberoptik, betong, stål, distribuerade sensorer, sprickdetektering.

Preface

This Doctoral Thesis was written at the Division of Structural Engineering and Bridges, Department of Civil and Architectural Engineering at the Royal Institute of Technology (KTH) under the supervision of Professor Johan Silfwerbrand.

I am indeed grateful to Johan Silfwerbrand for creating a positive working environment and for his superior guidance.

Thanks to personal in Structural Design and Bridges, who supported me, especially to Dr Elena Ilina for interesting discussions and for being a good and supportive friend.

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Great thanks for Mr Simon De Neumann from Flint & Neill for outstanding collaboration and fruitful discussions in Messina Bridge project.

Thanks to all my former colleagues and collaborations partners. Special thanks go to Mr Frank Myrvoll, Mr Per Dobloug and Mr Erik Lied from Norwegian Geotechnical Institute and personal from SMARTEC S/A for their enthusiasm, hard work and excellent collaboration.

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Great thanks to my dear friends for your endless support.

Greatest gratitude to my family; especially for my mother Raili Enkkelä and my sister Tuula Enckell with her family for being there and supporting me in all kind of ways you could ever imaging.

I dedicate this thesis for my beloved; Kurre, Emil and Daniel. You are always there and provide me with your affection. I love you.

I also love bridges, firstly because they are landmarks and symbols of places and let us pass to the other side with dry feet, and secondly, because they are symbols of connection, teamwork, hope and peace. Ultimately, lets us all be bridges in our environments; to reach out to the other side with a positive outlook and build connections with sincerity, tolerance and acceptance for a better world.

Copenhagen, October 2011

Merit Enckell

List of Publication

This thesis consists of a comprehensive summary and four appended papers.

Paper A

Evaluation of a Large-Scale Bridge Strain, Temperature and Crack Monitoring with Distributed Fibre Optic Sensors, Journal of Civil Structural Health Monitoring. Published first online, 3rd March 2011. Volume 1, Numbers 1-2, 37-46, DOI: 10.1007/s13349-011-0004-x.

Authors: Merit Enckell, Branko Glisic, Frank Myrvoll and Benny Bergstrand.

Paper B

New and Emerging Technologies in Structural Health Monitoring. Accepted for publication on March 2011. This paper is part of a book *"Handbook of Engineering Measurements"* that will be published by Wiley, New Jersey in 2012. Only the most relevant chapters 1, 4 and 11-13 and 15 are published here.

Authors: Merit Enckell, Jacob Egede Andersen, Branko Glisic and Johan Silfwerbrand

Paper C

Gathered Knowledge of Structural Health Monitoring of Bridges with Fibre Optic Sensors. Submitted to Proceedings of the ICE - Bridge Engineering on 13 October 2011.

Authors: Merit Enckell and Johan Silfwerbrand

Paper D

New Årsta Railway Bridge – A Long Term SHM Case Study with Fibre Optic Sensors. Submitted to Nordic Concrete Research on 30 September 2011.

Author: Merit Enckell

Three papers were prepared in collaboration with co-authors. The author of this thesis took the following responsibility for the work in those papers:

Paper A Made a literature study. Took part in the initial field testing in order to verify the function and suitability of the monitoring equipment. Took part in the installation planning and physical installation. Made individual tests with malfunction of sensors and suggested and tested modifications to the designed system with malfunctions. Repaired sensors and developed new strategies in reparation and re-installation. Took part in two Site Acceptance Tests (SAT) including additional testing of crack detection system. Documented all testing and installation with daily diary, photographs and weekly reports. Wrote the paper.

Paper B Made a literature study. Designed several SHM systems for various bridges. Took part of the installation planning and installation. Collected information about latest news in emerging technologies, met people from the field and discussed ideas and analysed results from different monitoring techniques. Talked to clients and asked for their opinions. Documented all data, testing and installation results with photographs and reports. Wrote the paper in collaboration with the others.

Paper C Made a literature study about FOS. Wrote the initials reports with recommendations and installation planning for new Årsta Railway Bridge. Installed sensors and data acquisition systems in collaboration with SMARTEC SA. BBK AB and BEMEK AB. Installed the sensor system, analysed the results during re-furbishing of the Traneberg Bridge, wrote daily and monthly reports about the bridge condition. Designed several SHMSs for various bridges. Collected information about latest news in emerging technologies, met people from the field and discussed ideas and analysed results from different monitoring techniques. Documented all data, testing and installation results with photographs and reports and suggested recommendation. Wrote the paper.

Paper D Made a literature study about SHM and FOS. Wrote the initials research reports. Made installation planning, installed sensors and data acquisition systems for New Årsta Railway Bridge in collaboration with SMARTEC SA, BBK AB and BEMEK AB. Made rough analysis about the results during construction. Wrote daily diary and photographed the installation procedure, reported about malfunctions and found solutions. Documented all data, testing and installation results with photographs and reports and suggested recommendations. Performed testing of the built bridge and analysed the results. Studied long-term effects like shrinkage and creep and existing models. Wrote the paper.

Additional Relevant Publication

Enckell-El Jemli M, Karoumi R and Lanaro F, 2003. Monitoring of the New Årsta Railway Bridge using traditional and fibre optic sensors. In Proceedings of the SPIE, Smart Structures and Materials, NDE for Health Monitoring & Diagnostics. V 5057: 279-288.

Enckell-El Jemli M, Karoumi R and Wiberg J, 2003. Structural Health Monitoring for an optimized pre-stressed concrete bridge. In Proceedings of the ISHMII-1V 2: 993-996.

Enckell M and Wiberg J, 2005. Monitoring of the New Årsta Railway Bridge. Instrumentation and preliminary results from the construction phase. Technical report 2005:8. Royal Institute of Technology (KTH). Department of Civil and Architectural Engineering.

Enckell M and Larsson H, 2005. Monitoring the behaviour of the Traneberg Bridge during retrofitting. In Proceedings of the ISHMII-2, V P2: 1631-1635.

Enckell M, 2006. Structural Health Monitoring using Modern Sensor Technology –Long-term Monitoring of the New Årsta Railway Bridge. Licentiate thesis, Royal Institute of Technology, KTH.

Enckell M, 2007. Structural Health Monitoring of Bridges in Sweden. On proceedings CD of the 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure - SHMII-3. Paper No: 117.

Glisic B, Posenato D, Persson F, Myrvoll F, Enckell M and Inaudi D, 2007. Integrity Monitoring of Old Steel Bridge Using Fiber Optic Distributed Sensors Based on Brillouin Scattering . On proceedings CD of the ISHMII-3, paper No.112.

Wiberg J. and Enckell M, 2008. Monitoring of the New Arsta Railway Bridge. Presentation of measured data and report on the monitoring system over the period 2003-2007. Technical report 2008:14. Royal Institute of Technology (KTH). Department of Civil and Architectural Engineering.

Glisic B, Enckell M, Myrvoll F and Bergstrand B, 2009. Distributed sensors for damage detection and localization. On Proceedings CD of the 4th International Conference on Structural Health Monitoring on Intelligent Infrastructure-SHMII-4, paper No.393.

Myrvoll F, Bergstrand B, Glisic B and Enckell M, 2009. Extended operational time for an old bridge in Sweden using instrumented integrity monitoring. In proceedings of the Fifth Symposium on Strait Crossings: 397-401.

De Neumann S, Andersen J E, Enckell M and Vullo E (2011). Messina Bridge - Structural Health Monitoring System. On proceeding CD of the IABSE-IASS 2011 Conference, ref nr. 0939.

Contents

Appended Papers

Chapter 1 Introduction

1.1 General

New and emerging sensory technologies, sophisticated data acquisition systems and automated analysis tools are present. Great benefits and capital savings can be done with monitoring and Structural Health Monitoring Systems (SHMS) do provide guidance for civil engineers in decision making. A structure can be monitored during its whole lifetime, from construction to operation and finally to demolition. Bridges, dams, nuclear power plants, geotechnical structures, historical buildings, offshore platforms, pipelines, ocean structures, roads, pavements, airplanes and turbine blades may be objects for monitoring, just to mention some. SHMS can be incorporated into a new structure when integrated prior to construction or added afterwards to existing structure.

This thesis deals with numerous Structural Health Monitoring (SHM) activities; emerging and established sensory technology, design of SHMSs, concrete research, long-term monitoring, fatigue effects in steel bridges, installation issues, testing like Factory Acceptance Test (FAT), Site Acceptance Test (SAT) and load testing. A special attention is directed against Fibre Optic Sensor (FOS) technology including crack detection systems, gathered knowledge in order to give recommendation and long-term effects like creep and shrinkage in pre-stressed segmental built concrete girder bridges.

1.2 Background

Several factors benefited for intense development in Structural Health Monitoring (SHM) and sensory technology. Shortened construction periods, increased traffic loads, new high speed trains causing new dynamic and fatigue problems, increased traffic loads and quantities, new materials, new construction solutions, slender structures, limited economy, need for timesaving etc. are factors that demand better control and makes SHM as a necessary tool in order to manage, maintain and also be able to guarantee the quality and safety for end-users.

The author has been doing research and working with SHM for nearly a decade. Various projects are completed, from design of Structural Health Monitoring Systems (SHMSs) for new and existing structures to planning, installation, testing and monitoring. Working with emerging as well as now established technologies in the field has brought up a huge amount of heuristic knowledge and the most important issues are now presented and evaluated here. Some recommendations are also given.

The following four projects are presented shortly in order to give the reader a picture about different aspects of SHM projects and related advantages as well as challenges:

- The New Årsta Railway Bridge is a unique pre-stressed concrete girder bridge with slender and optimised design. SHMSs were installed on one chosen characteristic span of the bridge during construction in 2003. Two doctoral theses were connected to the project in order to learn about the bridge as well as the new sensory technologies. This thesis presents the FOS system including thermocouples; and their long-term function. Strain and temperature data are collected from first casting up to date.
- The Traneberg Bridge consists of three single concrete arch bridges for road and suburban railway bridge. SHM project of Traneberg Suburban Bridge under retrofitting and strengthening show an ideal way to verify and control the behaviour of the bridge.

The concrete samples taken from the old arch from 1934 arch confirmed high values of Young's modulus. It was decided to keep the old arch and reconstruct the pillars and the deck. Monitoring the old arch was significant in order to control the behaviour of the arch during reconstruction. The monitoring system consisted of seven fibre optic SOFO sensors and five thermocouples.

- Steel girders of Götaälvbridge suffer from fatigue and mediocre steel quality and some severe cracking and also a minor structural element collapse has taken place. The SHMS for Götaälv Bridge is a large monitoring project with novel technology of distributed FOS based on Brillouin scattering. The installed system measures strain profiles along the whole length of the bridge and detects cracks that are wider than 0.5 mm. Innovative technology was developed, tested and applied and knowledge was collected; conclusions are presented and discussed.
- The planned Messina Strait Bridge will connect the coasts of Sicilia and Calabria in southern Italy. The bridge will carry a four lane highway with emergency lanes and a dual railway line. The bridge is a suspension bridge with a world record breaking 3300 m main span with a design life of 200 years. Over 3000 sensors are included in a designed innovative SHMS that will take SHM into a new level.

1.3 Outline

The thesis consists of chapters 1-9 and appended papers A, B, C and D.

Chapter one is a general introduction.

Chapter two discusses methodology used in the research.

Chapter three describes components of a SHMS.

Chapter four presents emerging technology.

Chapter five describes FOS Technology.

Chapter six gives a brief introduction to some chosen applications and approached results.

Chapter seven concludes the general results and provides recommendations.

Chapter eight is the discussion.

Chapter nine gives conclusions and recommendation for future research.

1.4 Aim and Scope of the Thesis

The general aim of this thesis is to study SHM in long-term with a specific focus on fibre optic sensor technology: existing SHMSs are analysed in order to develop improvement and give recommendations.

The specific aims of this thesis are to:

- Present a realistic state-of-the-art report on recent SHM activities, both advances and disadvantages need to be high-lighted.
- Present and increase the knowledge around emerging and established sensor technology with a special focus on FOS Technology.
- Highlight the plentiful possibilities FOS monitoring do provide and to capture lessons learned in order to develop best practices and successful criteria for future projects.

- Show applications in order to give a clear picture of the complexity of the subject and highlight the numerous results that were achieved so far.
- Analyse the performance of the SHMSs on some selected bridges.
- Use the results achieved so far in the SHM of the New Årsta Railway Bridge in future maintenance planning of the bridge
- Highlight the general results and give recommendations
- Discuss and conclude the general knowledge: give advice for future projects while working with advance sensor technology and SHM in order to save money and increase efficiency as well as increase the understanding for SHM and advocate open communication in the field of SHM.

1.5 Limitation

When managing with applied research the most difficult task has been to limit the subject and try to draw conclusions that are applicable for more general projects. Case studies were also unique and it was difficult though important to find general conclusions that were applicable for all the projects.

As there was no experience at the beginning of the project concerning the SHM of the New Årsta Railway Bridge, several fatal errors were made and these errors affected the quality of data and therefore complicated the analysis.

1.6 Abbreviations

Acoustic Emission	AE
American Society for Photogrammetry and Remote Sensing	ASPRS
Analogue-to-Digital Converter	ADC
Bridge weigh-in-motion	B-WIM
Central Mainframe Server	MFS
Digital Signal Processor	DSP
Data Acquisition System	DAS
Data Acquisition Unit	DAU
Digital Signal Process	DSP
Factory Acceptance Tests	FAT
Fibre Bragg Grating	FBG
Fibre Optic Sensor	FOS
Finite Element	FE
Geographic Information Systems	GIS
Ground Penetrating Radar	GPR
Local Area Network	LAN
Long-Gauge	LG
Micro Electro Mechanical Systems	MEMS

Non-Destructive testing	NDT
Optical Backscatter Reflectometer	OBR
Optical Frequency Domain Reflectometry	OFDR
Optical Time-Domain Reflectometer	OTDR
Plastic Optical Fibres	POF
RAdio Detection And Ranging	RADAR
Railway Weigh-In-Motion	R-WIM
Short-Gauge	SG
Site Acceptance Tests	SAT
Structural Health Monitoring	SHM
Structural Health Monitoring Systems	SHMS
Supervisory Control And Data Acquisition system	SCADA
The International Society of Photogrammetry and Remote Sensing	ISPRS
Uninterruptable Power Supply	UPS
Weigh-in-motion or Weighing in Motion	WIM
Wide Area Network including Bridge Area Network	WAN

Chapter 2 Methodology

2.1 Applied Research

SHM is a large subject bending over several fields of engineering, these fields needed to be examined in order to have a comprehensive understanding for this complex subject. The research started with a literature study including detailed aspects of SHM, sensor technology, FOS, concrete research and measuring techniques. Monitoring activities around the world were also looked over in order to be collected and summarised.

The objectives of the research were defined and some predictions were made. The research was defined mostly as applied and experimental research involving the practical application of science. A systematic investigation using knowledge, theories, methods, and techniques was defined. Empirical methodologies based on observations and testing were planned to be used as well.

Applied research deals with solving practical problems and because it exists in the real world, simplicity in the methodology is vital. Strict procedures how to document experiments and observations was decided in order to be able to compare the results afterwards. An implication for interpretation of results was seen from wide prospect in order to be able to see general conclusions. Induction, observations under different circumstances, was also used in some specific cases when out in the field and solving problems with emerging technology.

Data from New Årsta Railway Bridge SHMS research project were downloaded manually from the site during the construction period. After the broadband connection was established, the data were downloaded every two weeks to once a month depending on measuring frequency.

Data from Traneberg Suburban Bridge were downloaded manually from the site via a modem connection.

As the author was also working beside the research in the same subject, a lot of material and observations were also collected from other real non-research projects in order to get more data. This data were collected, analysed and included in the population and general conclusions were drawn.

2.2 Documentation

Careful documentation in a systematic matter is essential and was performed in every single project and testing procedure. Installations were generally documented in a daily installation diary and photographs were taken if possible. Every single deviation was reported in a separate report and the report was also distributed to all stakeholders in order to understand the reason for deviation and also to find ways to avoid it in the next step. General methods for data quality assurance, analysis, processing and storage were implemented. Also the data back-up was planned.

2.3 Concrete Research

As the monitoring started from the first pour of the concrete to the formwork, concrete behaviour models were studied at very early age, early age and also long-term effects in concrete constructions were mapped. To comprehend the behaviour of the sensors in the fresh concrete was also significant.

Long-term effects like shrinkage and creep may cause severe malfunction if not calculated correctly. In the worst case, these phenomena may also leads to structural collapse. Different international codes like CEB-*fib*, ACI-209, AS 3600 and RILEM-B3 as well as the research around their function and verification were studied.

FE modelling of concrete from the first pour to loading process with Young's Module growth is an interesting subject but beyond the aim of this thesis

2.4 Crack Detection

Steel structures do suffer from fatigue effects. Old steel structures might also suffer from mediocre quality of steel. Fatigue is the progressive and localised structural damage when a material is subjected to repeated cyclic loading. Microscopic cracks will begin to form at the surface and sooner or later a threshold value will be reached and the structure will fracture. The process is stochastic, significant scatter takes place even in controlled environments and increases with the age of material.

Different methods to test crack occurrence and location identification were investigated. There are several crack detection systems in the market but many of these systems are not fully developed and continuous updating in the subject is necessary. A system that can detect, measure and localise cracks is optimal.

2.5 Testing and Trouble Shooting

Many kind of short-term and long-term experiments and tests have taken place in the various projects and helped in decision making as well in verifying products and procedures. An experiment is a methodical procedure and its goal is to verify, falsify or establish the validity of a defined hypothesis. It is important that the test or experiment can be repeated and the results can analysed logically.

A load test is often included in new structures as well as in verification of a SHMS. These activities are cautiously planned and scheduled in detail beforehand. Several load tests were performed in the various projects.

A short feasibility study including a test installation of selected FOS technology was prepared at the early stage of the SHMS project of the Götaälv Bridge. The purpose of the test was to confirm the most suitable installation procedure as well as to verify the performance of the sensors and data acquisition system. Some characteristic I-beams of the bridge were installed with sensors and a load test was performed. Different installation methods like clamping and gluing of the sensor to different positions of the beam were tested.

SHMS project of the Götaälv Bridge also included gluing around 5 km of sensors to the steel beam. In order to find the most suitable glue with excellent long-term qualifications, three different kinds of glues were tested. The tests also included testing the adhesion of the glue to the sensor, to the painted surface and even to the clean steel surface. Diverse issues were also carefully discussed with the glue producer before making the final decision.

Trouble shooting is performed in complex systems to repair or modify products or processes. It is logical and systematic form of problem solving. The acknowledged problem may have different causes and in order to fix the malfunction the problem needs to be identified. If there are several causes, there is need for elimination. Sometimes it is impossible to solve the problem with the original solution but a modification is needed. Nevertheless, the final solution needs to be verified and should assure the original technical requirements.

2.6 Appended papers

Brief summary over papers is given in the following:

Paper A

Brillouin based distributed fibre optic system was installed on Götaälv Bridge for integrity monitoring. The project is large; totally around 5 km of the bridge girders are installed with sensors. The installation procedure for that kind of large application is really challenging as experience from the past does not exist. The installation issues are brought up and discussed. Several full-scale and small-scale tests were performed during the process before operation period.

The Götaälv Bridge is monitored continuously for cracks bigger than 0.5 mm and high strain occurrence. The system sends warnings to the traffic authorities if defined limits are exceeded. As some inconvenience occurred in the operation period, modification to the system was done in order to improve the quality and reliability of the system.

This paper presents implementation, installation and operation of a large-scale Structural Health Monitoring (SHM) project based on stimulated Brillouin scattering in optical fibres for an old steel girder bridge. Procedures around different task that were experienced in the project are presented, discussed and analysed. Results of improvements after an operation period are highlighted; conclusions are drawn in order to give a reader a truthful image of a large scale SHM project in its different stages.

Paper B

Paper B is part of the book (*"Handbook of Engineering Measurements"* that will be published by Wiley, New Jersey in 2012) and too large to be included in whole. Only the most relevant, chosen chapters are presented.

Measuring and testing activities have been performed from the beginning of the 20th century within engineering. Early activities in SHM were damage identification in aerospace and mechanical engineering. Aircrafts and military vehicles needed monitoring and a lot of sensors were developed for these purposes. Today, also many civil engineering structures are monitored continuously and provide true real time information of these structures.

Technical development of sensory technology has been rapid and is still ongoing. This paper presents new and emerging technologies and new areas of usage; mostly for the civil engineering structures. It highlights their advantages and also brings up with challenges. Some real applications are presented in order to give a true picture about SHM with new and emerging technologies and complexity of the subject.

Paper C

SHM of civil engineering structures has developed rapidly in recent decades. Different kinds of projects took place; both large and small scale and with various equipment. Fibre optic sensory technology made a serious entry into monitoring field. However, as the subject was new and also spreading over several fields of engineering, the lack of regulation, policies, guidelines, knowledge and educated personal was large at the beginning.

This paper presents the experiences gathered with common FOS, data acquisition systems and tools required when working with fibre optic sensors aimed mostly for civil engineering structures, especially bridges. Some primary projects are shortly introduced. The advantages, disadvantages and malfunctions are gathered, reported and discussed in order to underline recommendations. Special attention is paid to summarise and discuss the general experience gathered from these different applications and recommendations and conclusions are provided.

Paper D

The New Årsta Railway Bridge was built in 2000-2005. The structure is a unique pre-stressed concrete girder bridge with slender and optimised design. SHMS was installed on the bridge during construction. One characteristic span is mainly instrumented with several sensors and monitoring is still ongoing.

This paper presents the Fibre Optic Sensor (FOS) system including thermocouples; and their function. Observations, malfunctions and inconvenience during construction, testing and operation are collected, carefully documented and analysed. Strain and temperature data are collected from first casting up to date.

Results are highlighted and conclusions are drawn. Recommendations are given, based on the experience gained so far. Furthermore, general, accumulated knowledge about monitoring is given.

Chapter 3 Structural Health Monitoring System

3.1 Introduction

SHM of a structure performs structural characterization and damage detection over time in order to provide reliable information regarding the integrity of the structure. SHMS for a structure consists of sensors and transmission cables, data acquisition systems, data transfer and storage systems, data management that normally includes data analysis as well as presentation, and data interpretation. It is a valuable implement, in general a permanent system that can provide many different solutions and outputs depending on the monitored structure and requirements based on the system itself. Larger projects also have a Control Room with permanent crew in order to take actions if needed. More info about SHM and monitoring concepts can be seen in [Aktan et al. 2001, Bergmeister &Santa 2001, Brownjohn 2007, Enckell 2006, Mufti 2001].

3.2 SHMS Design and Implementation

It is a standard procedure to design a SHMS for new large scale or complex bridge structures in these days. Organisational issues and responsibilities and documentation procedures are clearly stated at the beginning of the project.

Engineers designing SHMSs need to be specially educated in numerous aspects of SHM. A monitoring project is a delicate matter and the following items need to be taken into account for the planned system; existing standards and codes including units to be specified, environmental conditions, design life, it- structure of the system and different interfaces if any. Initially, desired parameters to be monitored are identified together with structural engineers. Secondly, other indirect parameters like environmental parameters that might be needed in the analysis process are also identified and technical requirements are established.

Sensor technologies that will fulfil the requirements are chosen. A Factory Acceptance Test (FAT) is prepared in order to verify that the specified technical requirements can be fulfilled with the chosen system if there are any emerging technologies and developments involved. Data acquisitions and data analysis tools and methods are also chosen and finally a detailed installation and monitoring plan is prepared.

Database requirements are stated and procedures for data handling are described in detail in order to optimise the monitoring system's long-term function and redundancy.

Installation is carried out by experienced personal. Installation diary is written and completed with photos. All employees at the building site are informed about the SHMS activities and a positive working environment is created. These simple facts help to guarantee better sensor survival rate and both money and time are saved. Any malfunction or deviations are reported immediately to stakeholders and solutions are found.

A Site Acceptance Test (SAT) is performed after complete installation at the presence of stakeholders; sensors, database tools and analysis methods are tested and verified. Long-term function of the SHMS is also tested and verified. The first period of monitoring, a few months up to a year is also a running-in period: structural behaviour of the monitored structure due to environmental effects and loading is studied and adjustments and refinements are concluded in order to optimise the system. Alarms and warnings are set up if necessary.

If handling with an existing structure, a lot more information is present: drawings, technical reports, previous testing, inspection protocols, maintenance actions, retrofitting/strengthening of the structure, noted problems, concerns or verified structural weakness. There is also need to discuss with operation and maintenance personal in order to bring up with any relevant information about existing uncertainties, malfunctions or problems. A site visit to the structure is essential on early stage of the project in order to make a visual inspection. At the same time, identification and accessibility to the structure is also carefully examined. The structure can also be tested and classified in order to find the most relevant features for monitoring.

3.3 Components of SHMS

3.3.1 Sensory System

The sensory system consists of permanently installed sensors and sometimes of a set of portable sensors. Permanent sensors are installed on the structure and portable set can be taken around on the structure to measure if uncertainties would come up.

A sensor is a type of transducer that converts a physical property into a corresponding electrical or optical signal. This signal is in its transferred into a digital signal that can be processed further. Commercially available sensors that are well proven in similar circumstances as the intended structure are preferably and it is good to keep in mind that if emerging technologies are involved special expertise is a requirement.

Every SHMS does require metrological sensors, in other words a weather station. A basic weather station is used to monitor air temperature and relative humidity, wind speeds and wind direction. More sophisticated weather station can also include a barometer, a rain gauge and a pyradometer.

Table 1 gives an example what kind of sensors and methods can be required for a minimal, general and a complex SHMS for a bridge structure.

Table 1 Example of sensors for a minimal, general and complex SHMS

Minimal	General	Complex
Weather station	Same as in minimal + following:	Same as in general + following:
Temperature sensor	Laser displacement sensor	Road wear sensor
Fibre Optic Sensor, strain	Global Positioning System (GPS)	Microwave interferometric radar
Inclinometer	Weigh-In Motion (WIM) station	Acoustic emission sensor
Corrosion cell	Triaxial accelerometer	Pyradometer
Biaxial accelerometer	Anemometer	Photogrammetry
	Humidity sensor	Hydraulic pressure sensor
	Ground water pressure	
	Seismic accelerometer	Ground penetrating radar
		Bridge WIM station
		Thermography

3.3.2 Data Acquisition System

The Data Acquisition System (DAS) consists of sensors, Data Acquisition Units (DAUs), interrogators and/or Main Computer that also can work as a server. Sensors send either electrical or optical signals that are converted to digital numeric values that can be processed by a computer. Different systems on the market do require different components and solutions are multiple.

DAUs are local servers located in chosen locations on the structure and sensors can be connected to them. Each DAU can be equipped with a time synchronisation device and may have some data processing and data storage facilities if needed.

A typical Data Interrogator is an electronic device that records data: the received signal from the sensor is processed and converted into engineering units and can be seen on a display to view the measurements. Interrogators for optical devices have complicated design compared with electrical devices and are therefore generally more expensive. Some interrogators have a local interface device and can be used individually while others need an external computer with utilized software to activate the interrogator, as well as to view, store and analyze the collected data. Large projects have many sensors and if the number of the channels is exceeded there is a need for a switch that will host additional channels.

Output signal of a sensor is either analogue or digital. The conversion of an analogue to a digital signal is performed by an Analogue-to-Digital Converter (ADC). Signal conditioning and filtering might be needed, especially for electrical sensors in order to allow for transmission and post-processing of the signal.

All data on the SHMS need to be synchronised. The suitable data communication system needs to be decided. Typical SHMS do have either a Wide Area Network (WAN) or Local Area Network (LAN). Large systems do operate with backbone Fibre Optic networks that allow for redundant systems with no data loss.

A data communication system transfers the collected signals to a remote Main Computer or to an Interrogator. Some Interrogators do data processing and are able to work independently without an external computer. DASs can be located either on the structure or in a main control room. Sensors can be connected via DAUs to interrogators or directly to interrogator. There are many different solutions depending on the technical requirements of the chosen systems.

Figure 3.1 highlights the different possibilities for Data Acquisition Systems:

- Sensors are connected directly to an Interrogator that is able to perform data processing
- Sensors are connected via an DAU to an Interrogator that in its turn is connected to Main Computer that performs data processing
- Sensors are connected via an DAU to Main Computer that performs data processing

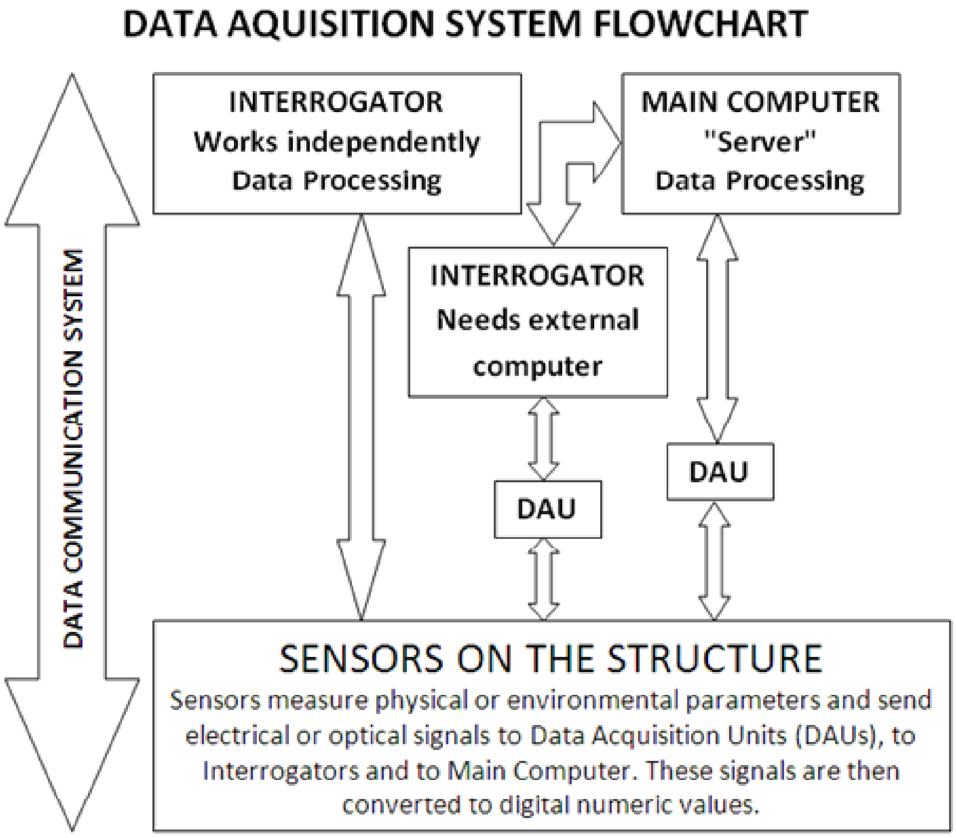

Figure 3.1 Flowchart for Data Acquisition System highlights the various possibilities transporting and processing signal from sensors to data processing.

3.3.3 Control Room

Small SHMS that do not have a control room may operate via a broadband connection from the office. Larger SHMSs do have a control room where Supervisory Control And Data Acquisition (SCADA) are normally located. The SCADA system normally includes all existing operation systems. SHMS can be an individual system that operates independently of other operation systems or it can interface with operation systems if needed. Control room can be located on the structure or some other chosen location that can be distant from the actual structure.

The master screen in a control room can be either a desktop display with the ability to transfer data between different functions quickly and easily, or a large display wall. This wall can be divided into various monitoring areas with different functions.

The system will visualize in real time all collected information, in the most suitable way for an immediate and efficient representation (graphs, tables, videos) and will allow the search, visualization, and elaboration related to user specified periods.

3.3.4 Cabling

Appropriate transmission and connection cables from sensors to the interrogator are also of high importance when working with fibre optic applications. Different circumstances like people walking on the cables and rodents eating cables may take place. Cable selection is challenging and requires thoughtful consideration as utilising an improper cable may jeopardise the function of the whole system. Different kinds of standards exist for various cables and need to be matched with installation requirements, as well as with environment circumstances.

3.3.5 Other issues

Other important issues that also need to be considered are the following:

- Fastening for sensors and DAS components on the structure
- Spare parts for the SHMS, if any.
- Manuals for SHMS and its components. Language of the manuals needs to be specified.
- Tools that are needed when working with SHMS components
- Power delivery during construction and operation. Uninterruptable Power Supply (UPS) for DAS.
- Cable ladders for passive cables.
- Physical protection for sensors, components and DAUs.

3.4 Data processing

Data processing encompasses automatic conversion of the raw data into useable information. It consists of data collection, transmission, pre-processing, analysis, post-processing, and storage and archival of the data in a format that is easy to access and present.

Comprehensive data analysis is a key issue to successful application of a SHM. The main goals of data interpretation in connection to the monitored structure are; structural identification during construction, operation and demolition, FE model updating, condition assessment, alarm configuration if required, service life prediction and maintenance planning. Data analysis may allow for damage location and quantification as well as for condition assessment.

Data mining is the process of extracting patterns from large data sets by combining methods from statistics (e.g. statistical pattern recognition) and artificial intelligence.

Data can be displayed and reports can be generated, all depending on technical requirements in a project.

Data storage and backup is planned carefully and often tailor made to fit the SHMS purposes. A lot of efforts and capital can be saved with cautiously planned procedures. If possible, all raw data are stored and later archived as it is uncertain what types of information will be needed or are useful in the future. Data archival is essential in large projects and inactive or non-critical data will be transferred to a particular type of long-term storage media. Archived data generally consist of primary copies of the data being stored.

Accessibility and easy localisation of data are an important challenge in large projects, because the size of the collected raw data can be up to terabytes. In order to design an efficient platform for all stakeholders, all specific needs are collected and evaluated. Technical requirements are established and procedures for different groups are defined.

3.5 System procurement and installation

Installation procedures that are described in the literature seem often to point out that the installation is an easy process. Nevertheless, in the practical case it is often the opposite. Installation is a complex matter and need careful planning and expertise.

Commissioning assures that all subsystems and components of a SHMS are designed, installed, tested, operated, and maintained in accordance to the technical requirements of the owner.

Many companies that are inventing new products in the field are concentrated on one or few type of products and do often lack the understanding that is needed in a complex projects. Nearly every company seems also to be convinced that their own products are the best even though there is not proper practice of the product in long term. Many complex SHM projects do need several kinds of technologies in order to be able to monitor large amount of parameters. This can be achieved by combining products from several companies for the different tasks. There is a need for outstanding expert to check these products and their functionality with critical attitude so that no money is wasted on non proven products that might jeopardise the whole project in large.

3.6 Management and maintenance of SHMS

Management system of SHMS should check function of the system in general and also the function of the system in delivering the monitoring requirements. A "watch-dog" function for sensors itself is also recommended.

Maintenance cannot be avoided and it is important to schedule a time line for maintenance activities. As the design life of many electrical, optical and mechanical components may undertake the planned design life of the whole system, it is important to plan how to maintain individual components without causing disturbances or loss of data in the system.

Maintenance tools are required for the inspection and maintenance purposes of the whole SHMS. A portable inspection and maintenance system can be located on the structure and used if problems should occur. Emerging technologies may need some special tooling and furthermore training in trouble shooting

Management and maintenance of the SHMS are described in detailed manuals that are established in the project. These manuals shall illustrate the complete management and maintenance procedures and possible interfaces with other systems that need to be taken into consideration.

3.7 Adaptability

A modern approach to monitoring takes into consideration the provision of the flexibility for future expansion or rearrangement. Complex SHMSs shall be developed in such a way that future expansion, modification or rearrangement can be easily facilitated. As the sensor and DAS technology is in constant development, it would be dense to design systems that are not adaptable.

SHMS software and hardware of the DAUs should also be developed in a flexible way. Each DAU should be capable of receiving all sensor types that are included in the SHMS and it is recommended to provide free slots for additional data acquisition cards so that the expansion, if any is straight forward and does not require too many efforts

3.8 Dismantling and environmental effects

A plan for dismantling and waist collection needs also have to be established. The materials used should be environment friendly and chemicals used in the installation procedures tested and safety regulations need to be followed.

Safety instructions to the work force need to be clearly stated and the work force need to be informed and educated if any risks are present.

Chapter 4 Emerging Technologies

4.1 Introduction

The market of sensory technologies as well as data acquisition system is in accelerating change. Emerging technologies are science based innovations that have the potential to create a new industry or transform an existing one [Day et al. 2000]. New kind of thinking is needed in order to work and prevail with them. They are characterized with certain ambiguity and complexity but in addition with high accuracy, straightforward usage and data-collecting concept.

FOS, Micro Electro Mechanical Systems (MEMS), optical distance measurement techniques, acoustic emission and different type of lasers and radars are now available on the market. Remote sensing is the technology of obtaining reliable information on a given object or area either wireless, or elsewhere without physical or intimate contact with the object. Any form of non-contact observation can be regarded as remote sensing. Microwave Interferometry and photogrammetry are good examples of remote sensing and presented latter.

Nearly any preferred parameter can be measured nowadays and existing systems also perform automatic data processing and analysis in real time and with remote access. New challenges are faced when working with emerging technologies but with correct procedures it is possible to accomplish sustainable SHMSs with new and emerging technologies. People working with new and emerging technologies need to be open for new ideas, ways of thinking and able to have an idea about the future development in order to find flexible, adaptable solutions that will meet the requirement not only now but also in the future. Following subchapters present some emerging technologies and areas that the author find interesting and relevant for civil engineering structures. FOSs are presented in separate Chapter 5 and more information concerning emerging as well as established technologies can be seen in Paper B.

4.2 Acoustic emission

A structure starts to deform elastically when it is applied to a load; either by internal pressure or by external mechanical loading. In this manner, the stress distribution and storage of elastic strain energy in the structure changes. Acoustic Emission (AE) [Jaffrey, 1982] technology was born in the early 1960s when it was recognized that growing cracks and discontinuities in fibre reinforced plastic tanks and pressure vessels could be detected by monitoring their acoustic emission signals. AE is a naturally occurring phenomenon that takes place and generates elastic waves with these before mentioned loading conditions that relate to rapid release of energy. Acoustic emission monitors electronically ultra-high frequency sounds that stressed materials release and it is classified as a passive non-destructive testing method. AE tests can be used to evaluate the structural integrity of a component or a structure, structural damage diagnosis, life-time assessment and SHM.

AE monitoring detects and locates defects in real time while the phenomenon is taking place and following can be monitored with AE: corrosion, occurrence and extension of fatigue cracks, fibre breakages in composite materials or fibre breakages in bridge main cables, stay cables or pre-stressed cables as well as cracking in concrete or reinforced concrete members.

AE sensors are piezoelectric crystals that convert movement (a variation of pressure) into an electrical voltage. The sensors must all have an identical response and they should be calibrated annually. They are normally held in place using metallic clamps for steel structures or bonded to concrete. These are connected to the AE system using coaxial cables with shielding to prevent electro-magnetic interference. A resonant frequency of 30-100 kHz is typical for concrete applications; whereas 100 and 200 kHz is used for metallic structures. Higher frequency sensors can be used in high noise environments but only for local monitoring due to the higher attenuation at these frequencies.

A typical AE system comprises a high speed Digital Signal Processor (DSP), AE processing boards with individual processing channels for each sensor (i.e. a non multiplexing system) and the ability to program the settings for signal thresholds and frequency range to enable the AE signal to be filtered. It should also have software for source location in both one two and three dimensions, feature extraction capability to allow characterization of the signals and stable software for long-term monitoring.

Numerous codes, standards and recommended practice are already present for Acoustic Emission Monitoring.

4.3 Radar technology

4.3.1 General

RADAR is an acronym for RAdio Detection And Ranging [Buderi, 1996] and invented in 1934. The first ground penetrating radar survey was performed in Austria in 1929 to sound the depth of a glacier [Stern, 1929, 1930]. The technology was largely forgotten until the late 1950's when U.S. Air Force started investigations into the ability of radar to see into the subsurface. A similar equipment as Stern's original glacier sounder was planned, built and sent on Apollo 17 to the Moon [Simmons et al., 1972] in 1972 and the electrical and geological properties of the crust were studied.

4.3.2 Ground-penetrating radar

Ground Penetrating Radar (GPR) is one of the most inclusive archaeological geophysical methods. GPR uses electromagnetic waves to collects large amounts of reflection data to map the spatial extent of near-surface objects, interfaces or changes in soil media and produces massive 3D databases as well as images of those attributes.

A surface antenna of a GPR propagates radar waves in distinct pulses that are reflected off buried objects in the ground, and detected back at the source by a receiving antenna. When radar pulses are being transmitted through various materials on their way to the buried object, their velocity changes, depending on the physical and chemical properties of the material through which they are travelling. If the travel times of the energy pulses are measured and velocity through the ground is known, distance can be correctly measured and a 3D data set can be produced.

Various equipment are commercially available in the market [Conyers, 2002] and numerous areas are e.g. non-destructive surveys of structures and buildings, utility detection and mapping, geology, geophysics, geotechnics and environment, archaeological and cultural heritage, forensic and security.

In the GPR method, radar antennas are moved along the ground in transects, and two-dimensional profiles of a large number of periodic reflections are created. Set-ups for bridge pavement measurements and set up for soil measurement with several units connected together can be seen in Figure 4.1.

Figure 4.1 Right: set-ups for bridge pavement measurements. Left: Set up for soil measurement with several units connected together (Courtesy of Ingegneria Dei Sistemi S.p.A , IDS)

4.3.3 Interferometric radar

Interferometric radar is a pioneering ground-breaking technology in the domain of geodetic measurements that is now spreading out to civil engineering field. The measurement device is coherent radar. The instrument generates, transmits and receives the electromagnetic signals to be processed to provide movement and deformation measurements [Gentile 2010]. Both static and dynamic measurements of structures can be performed. This non contact method to measure objects distances up to kilometres is convenient for many applications like stay cables and main cables in bridges. No instrumentation is needed, traffic can continue and the method saves time, money and resources.

Interferometric Radar can be seen in front of the Manhattan Bridge in Figure 4.2. Manhattan Bridge is from 1909 and suffered of fatigue cracks. Monitoring of the vertical and torsional displacements of the mid-span using Interferometric Radar and GPS can be seen in [Mayer et al. 2010].

Figure 4.2 Interferometric Radar Equipment in front of the Manhattan Bridge (Courtesy of Ingegneria Dei Sistemi S.p.A, IDS)

4.4 Photogrammetry

The practise where geometric properties of object can be determined from photographic images is called photogrammetry [Mikhail et al. 2001]. The American Society for Photogrammetry and Remote Sensing (ASPRS) is a scientific association founded in 1934. Their mission is to advance knowledge and improve understanding of mapping sciences to promote the responsible applications of photogrammetry, remote sensing, Geographic Information Systems (GIS), and supporting technologies. Photogrammetry is defined as follows [http://www.asprs.org]:

> *"Photogrammetry is the art, science, and technology of obtaining reliable information about physical objects and the environment, through processes of recording, measuring, and interpreting images and patterns of electromagnetic radiant energy and other phenomena."*

Photogrammetry can be divided to aerial photogrammetry, close -range photogrammetry or Stereophotogrammetry. It is used in topographic mapping, architecture, engineering, manufacturing, quality control, archaeology, meteorology and geology. Photogrammetry enables producing plans of large or complex sites efficiently. Monitoring of crack origin and evolution with photogrammetry can be seen in [Benning et al., 2004].

A camera installed on an aircraft and taking multiple overlapping photos of the ground is used in aerial photogrammetry. 2D or 3D models are then created from these aerial photographs. Close-range photogrammetry cameras are used to model buildings, engineering structures, vehicles, forensic and accident scenes. Typically, a camera is hand held or set on a tripod close to the subject and 3D model or a drawing is produced. Stereophotogrammetry estimates three-dimensional coordinates of points on an object and requires two or more photographic images taken from different locations. Common points are identified on each image and a line of sight can be constructed from the camera location to these points on the object. 3D locations of the points are established by triangulation [Ackermann, 1984]. More information about photogrammetry can be found on the website of The International Society of Photogrammetry and Remote Sensing (ISPRS) (http://www.isprs.org/).

4.5 Corrosion monitoring

Water and consequently corrosion is present in civil engineering applications and the loss of capital caused by premature deterioration is vast. Reinforced Concrete structures and steel structures in aggressive environments are exposed to chemical attacks. SHM techniques for evaluating the condition of these structures are indispensable. If errors can be identified at an early stage of their occurrence a lot of capital can be saved as maintenance and repair may be costly. Parameters to be measured in reinforced concrete structures are; chloride concentration, resistivity and temperature.

Corrosion monitoring has many applications in the construction and maintenance of civil engineering structures: high-rise buildings, bridges, dams, spillways, flood control channels, tunnels, piers, pylons and harbour constructions. Numerous FOS and AE techniques for corrosion and humidity measuring purposes exist in the market. Many of these sensors are aimed at reinforced concrete measurement and a lot of research in ongoing [Sirinivasan et al. 2009].

Cathodic Protection prevents deterioration in reinforced concrete infrastructure: it controls the corrosion of a metal surface by making it the cathode of an electrochemical cell. The most common methods to protect steel constructions are coating, painting and weathering steel. Steel with special chemical constellation forming a protective layer on steel surface under the influence of the weather is used in weathering steel. A dense and tightly adherent oxide barrier is formed at the steel surface and the atmosphere is sealed out and additional corrosion is retarded [Roberge, 2006].

4.6 Weigh-In-Motion systems

Weigh-In-Motion or Weighing In Motion (WIM) devices capture detailed data for each individual vehicle as vehicles drive over a measurement location: dynamic weights of all axles, gross vehicle weights, axle spacing, vehicles distance and speed, vehicle classification according to various schemes and statistic representations for all types of traffic parameters.

Modern WIM systems are efficient as they are capable of measuring at normal traffic speeds. Many heavy vehicles are weighty and legal limits are exceeded. Severe damage can be caused to roads and bridges and accurate information about vehicle axle loads is important in order to make prognoses for traffic development as well as in construction and maintenance planning [Quilligan, 2003].

Bridge weigh-in-motion (B-WIM) is the process by which axle and gross vehicle weights of trucks travelling at highway speeds can be determined from instrumented bridges. Strain transducers are installed to the soffit of a bridge for detecting axles in order to provide information on vehicle velocity, axle spacing and position of each vehicle. B-WIM system and a wide range of field trials have been completed in recent years. These systems are becoming gradually more accurate and they are remarkably durable as no contact with tires is required [Obrien et al. 2008].

Railway Weigh-In-Motion (R-WIM) market is under development. Though, emerging in-line wheel load weighing systems are already available and can detect overloaded wagons as well as damaged wheels and flat spots. Railroad companies check the operational safety and identify possible unsafe wagons with R-WIM.as a system that has minimal impact on the railways and there is no need to lower down the speed.

4.7 Infrared thermography

An interesting and safe non-contact and remote measurement method that can be used on both still standing and moving objects is called infrared thermography or thermal imaging. It is example of infrared imaging science and allows fast scanning of objects and produces immediate images in real time. Thermal images produced by infrared thermography are visual displays of the amount of infrared energy emitted, transmitted, and reflected by an object.

Camera and software technology improvements have made this technology common and areas of usage are e.g. construction industry, condition monitoring and predictive maintenance industry. Detection of hidden structures, deterioration, moisture, and heat losses can be investigated quickly, remotely and cost effectively.

Emitted invisible infrared energy from an object is processed and images of that radiation, called thermograms with variations in temperature can be produced and plotted. However, in order to perform proper analysis of the information gathered, the personal working with infrared thermography needs education and experience

More information about Infrared Thermography can be seen in the website of the Institute of Infrared Thermography (http://www.infraredinstitute.co.uk/index.html).

4.8 Smart technical textiles

Technical textiles are commonly used in civil engineering and geotechnical applications for reinforcing, repairing, or retrofitting purposes [Veldhuijzen Van Zanten 1986]. Characteristic applications in civil engineering domain include repair of damaged parts of structures and retrofitting of seismically weak structures. Characteristic geotechnical applications include reinforcing bearing capacity of soils beneath foundations and stabilisation of land masses prone to subsidence or sliding. There is a need to evaluate the performance of the smart textile as well as the performance of the host structure in long term, to assess efficiency of the technical textile application and the upgrading made to the host structure. Deterioration in the performances needs to be identified, since it may lead to failure of the structure. Two parameters that are of particular interest for assessment the condition of civil engineering structures are strain and temperature. In geo-technical applications, besides these two parameters, monitoring water pressure and leakage is important for assessment of condition of reinforced soils and foundations.

Technical textile is transformed into an innovative intelligent multifunctional material when a monitoring system is embedded into it. This "smart textile" provides both reinforcing and monitoring capabilities at the same time. The sensors provide with assessment of performances of the technical textile, while the latter provides for protection and an easy and practically inexpensive installation of the sensors, because they were integrated in the technical textile during the production.

Various sensing technologies can be embedded in the technical textile; however the FOSs seem to provide the most promising results. Sensors based Fibre Bragg Gratings (FBG) and Distributed sensing technologies based on Raman and Brillouin scattering are particularly suitable for embedding in layers of technical textiles used to repair and retrofit civil structures [Messervay et al., 2010]. There are several applications commercially available on the market.

Research is also ongoing in domain of plastic optical fibre based sensors. Plastic optical fibres are highly deformable and therefore extremely suitable for monitoring large deformations.

Chapter 5 Fibre Optic Technologies

5.1 General

Telecommunication systems have made fibre optics familiar to one and all. The development that made optical communication possible was firstly, the invention of the laser in 1960 and secondly, the invention of optical fibre itself.

The use of fibre optic applications in different kinds of engineering fields made also a vast expansion in the last decades, especially in communications. The market is massive. There are numerous different techniques and various kinds of sensors that also can be modified for unique monitoring needs for a particular structure [Udd 1991, 1995, 2006]. FOS allow for measurements that have been unpractical or too costly with the traditional sensor technology. Hundreds measuring points along the same fibre, as well as distributed sensing, versatility, insensitivity for electromagnetic fields, operability under extreme climate conditions and also the fact that there is no need for protection against lightning are some of the advantages over the electrical-based counterparts [Ross & Matthews 1995].

An optical fibre is a thin transparent fibre, with the diameter of a human hair. The core serves to guide the light along the length of the optical fibre and it is surrounded by cladding with slightly lower index of refraction than the core. Cladding minimise the losses as the light propagates in the fibre but also physically supports the core region. Optical fibres for FOS are usually made of very pure glass i.e. fused silica but Plastic Optical Fibres (POFs) are also entering the market. Silica based optical fibres transmit light over large distances with very little losses while POF suffer from attenuation and distortion characteristics.

Area of usage is wide and it can be really confusing to general public to comprehend the various concepts. Fibre optic sensors are either intrinsic or extrinsic: optical fibre itself can be an intrinsic sensor, part of the optical fibre can be an intrinsic sensor or the optical fibre can be used to connect a non-fibre optic extrinsic sensor to a measurement system. Different parts of the optical fibre can also be used to measure different parameters e. g strain and temperature. If the sensors are divided by the transduction mechanism affecting the property of light, the categories are the following; intensiometric, interferometric, polarimetric, modalmetric and spectrometric [Measures 2001]. FOSs used in civil engineering applications are in common spectrometric and interferometric. Fibre Bragg Gratings (FBG), sensors based on Brillouin, Raman and Rayleigh scatterings are spectrometric and Fabry-Perot, Michelson and Mach-Zehnder Interferometer sensors are interferometric.

The monitoring of the structure can be either local, concentrating on the material behaviour or global, concentrating on the whole structural performance. Fibre optic technologies offer a wide variety of sensors for SG length, LG length as well as distributed and environmental parameter monitoring. FOSs in civil engineering can be used to measure strains, structural displacements, vibrations frequencies, acceleration, spatial modes, pressure, temperature, humidity and so on. The list is long and the techniques are innovative and in the explosive stage of development.

FOS can be measured and tested in many ways. The most simply way of checking is connecting a laser pen to the sensor coupler and see if the light travels trough the sensor. Demodulators for LG sensors are e.g. the Optical Time Domain Reflectometer, OTDR; low coherence interferometer and tunable laser demodulator. Demodulators for SG sensors are, for example the passive spectral ratiometric demodulator, tunable narrowband filter demodulator, laser sensor demodulator as well as the interferometric-based demodulator.

Recent significant developments in the optical telecommunications market helped reduce the cost of the FOS. The cost might still be higher compared to conventional sensors, but by some means reasonable when taking into consideration the outstanding long-term performance. Following sub chapters present typical FOSs. Many sensors like the ones based on fluorescence are mostly used for medical and chemical applications and are beyond the scope of this thesis.

5.2 Sensors

5.2.1 Fibre Bragg Grating

A FBG sensor consists of a single mode optical fibre that contains a region of periodic variation in the index of the fibre core, the so called “grating”. When intense light is exposed to the core of the optical fibre, this light wave propagates within the fibre. The wavelength corresponding to the grating field will be reflected and all the other wavelengths will pass by the grating uninterrupted. The reflected light is lead back and the analysis of the spectrum is performed and converted into engineering units. FBG sensors for strain measurements exists both in SG and LG versions and both static and dynamic monitoring is possible. Most FBG sensors nowadays are also provided with temperature compensation. The versatility of FBGs is dominating compared to other fibre optic sensors and a lot of qualified products are already available commercially. A wide-ranging study of present status as well as of the applications can be seen in [Majumder et.al., 2008] that also discusses issues like interrogators and encapsulation techniques.

5.2.2 Distributed sensors

Distributed sensor can replace large number of discrete sensors as a single cable is sensitive at every point along its length. Distributed sensor conveys measurements at discrete points that are spaced along the fibre by a constant value, called the sampling interval. Only a single connection cable to transmit the data to the interrogator is required. Various techniques for distributed sensing with FOSs exist and are based on FBG and Raman, Brillouin and Rayleigh scattering in optical fibres. These sensors can use thousands of discrete FBG points in a same fibre or simply a standard single mode optical fibre. The advantage with sensors based on FBG is that they can perform dynamic measurements while other techniques measure the static behaviour of the structure. The disadvantage with sensors based on FBG is the short measuring length, up to 70 meters while other distributed techniques can measure up to tens of kilometres.

Distributed systems based with discrete FBG point sensors use Optical Frequency Domain Reflectometry (OFDR) technique with swept-wavelength interferometry to spectrally and simultaneously interrogate thousands of sensors in a single fibre. FBG point sensors that are able to reflect at the same nominal wavelength are used in order to simplify the production process [http://www.lunatechnologies.com/products/DSS/files/DSS-4300_Data_Sheet_2009.pdf]. This system can perform static measurements to distances up to 70 meters and dynamic measurements up to 7 metres.

Another distributed sensing system uses a standard single mode optical fibre and the Optical Backscatter Reflectometer (OBR) [Lanticq V et al., (2009)]. An OBR with swept-wavelength interferometry measures the Rayleigh backscatter as a function of the length of optical fibre. An OBR is able to interrogate thousands of points in a single fibre; it simply transforms a standard telecom fibre into a strain and temperature sensor.

These two systems provide distributed measurements of temperature or strain with up to 10 millimetre spatial resolution along the length of the fibre. Resolution of ± 0.1°C, ±1 microstrain over the spatial resolution of 10 millimetres is also achieved.

Distributed sensing based on Brillouin scattering [Measures, 2001, Inaudi & Glisic, 2007] commonly consists of a single optical fibre which can be used to measure either strain and temperature or both along the fibre, for distances up to tens of kilometres. Brillouin scattering takes place due to interaction of light with phonons in optical fibres. The phonons will shift the frequency of the light in order to the acoustic velocity of the phonons. The acoustic velocity consecutively is dependent on the density of the glass and material temperature. As the Brillouin frequency varies linearly with applied strain and temperature makes it possible to measure both parameters simultaneously along an optical fibre. The scattering phenomenon can be either spontaneous or stimulated. The spontaneous process requires only an extremely low level of the detected signal but sophisticated signal processing while the stimulated phenomenon have a relatively stronger signal [Enckell et al., 2011]. Monitoring based on Brillouin technique can be seen in [Nikles et al., 2004, Inaudi & Glisic, 2005, 2006].

Raman scattering is the result of a non-linear interaction of the light travelling in the silica fibre core and based on the change in amplitude of Raman scattered light which is dependent only on temperature. Therefore, distributed sensing based on Raman scattering is used for temperature measurements. Insensitivity to strain is actually a benefit since no particular packaging of the sensor is needed. Typical spatial resolution of Raman systems is 1 m, and typical resolution is better than 1°C. Raman based systems are used for leakage monitoring in large structures like leakage of pipelines, dykes and dams.

5.2.3 Fabry-Perot sensors

There are three types of Fabry-Perot sensors; intrinsic, extrinsic and in-line fibre etalon versions [Measures, 2001]. [Chen et al., 2006] describes micro-air-gap based intrinsic Fabry-Perot sensors as well as their recent progress. The extrinsic Fabry-Perot sensor is easy to build; it consists of two optical fibres with a cavity, an air-gap of a few microns or tens of microns and can be seen in [Clark et al., 2001; Geib, 2003]. The mirror-tipped optical fibres are supported within a micro capillary alignment tube. The sensor needs to be carefully calibrated in order to determine the gauge length of the sensor. Fabry-Perot sensors are able to measure a number of parameters; strain, displacement, pressure and temperature. Many sensors are also temperature compensated. They can be manufactured as strain rosettes meaning a sensor with several measuring points near each other; often in different directions like traditional strain rosettes based on strain gauge technology.

5.2.4 Michelson and Mach Zehnder interferometers

Michelson and Mach Zehnder interferometers are easy to understand and manufacture. The Michelson interferometer is more widely used. The sensor consists of two single mode optical fibres and has chemical mirrors in end parts; first fibre, the sensing fibre is fixed in definite points and the other fibre, the reference fibre is loose in order to keep a zero strain level [Measures, 2001]. This loose fibre compensates thermal influences to the sensor. Data acquisition system sends the optical signal through a coupler to the sensor, mirrors placed at the end of each fibre reflect the signal back to the data acquisition unit that convert the measurement into engineering units. Since the sensor is pre-tensioned it is possible to measure both elongation and compression.

A well proven Michelson interferometer is called SOFO (French acronym for Structural Monitoring using FOS) [Inaudi, 1997]. The standard SOFO sensor is composed of two zones, the active zone which measures the deformations, and the passive zone transmitting data between the active zone and the interrogator. The SOFO sensor is a true LG sensor, with a typical gauge length between 20 centimetres and 10 meters. Large number of projects are installed with SOFO sensors and their long-term performance is good [Glisic et al., 2010, Enckell & Larsson, 2005, Enckell, 2006]

5.3 Crack detection

Monitoring strain and crack width with traditional strain gauges, crack gauges and displacement transducers is a general practise. Anyhow, FOSs are entering the field of crack detection and development is ongoing. Some commercial applications are already in the market but data acquisition systems for these techniques are still pretty costly

A lot of research is concentrated on techniques based on Brillouin scattering. Brillouin based sensors can also be used for crack detection and localisation as well as crack width estimation [Imai et al., 2009, Zhang and Wu, 2008].

[Enckell et al., 2011] present a novel SHMS for a large bridge structure with a crack detection and localisation system. Cracks bigger than 0.5 mm with a system based on Brillouin scattering are detected. The stress created by a crack is transferred to the longer section of the sensor in order to prevent the breakage of the optical fibre. Minimum 100 mm of delamination of the sensor from the surface should take place in order not to damage the sensor. The crack is the event that occurs on very short length, smaller than spatial resolution of the system. For that reason, a special detection scheme to detect the cracks was developed.

Brillouin sensing technology is a powerful candidate for SHM of the structures where crack detection, localisation and crack width estimation is required. .

5.4 FOS technology equipment

Optical fibres operate over a range of wavelengths but the 1550 nanometre wavelength is standard for minimal losses. They are generally divided into two kinds; single mode and multimode. Many applications for FOSs use single mode fibres with the core diameter of 5 to 10 micrometers.

Optical connectors are normally used in sensor applications to connect the sensors to transmitting cables, interrogators or to each others. The market is full of various types of connectors but many commercial sensor manufacturers generally use E-2000 and FC/APC connectors.

Many fibre optic sensors are ready for installation and delivered with transmission cables connecting to the data acquisition units, connectors and connector protection. However, when working with large and complicated applications, as well as problem localisation and repairing; it is necessary to have both knowledge and practical experience about related tools and equipment.

A special laser pointer or a laser pen is a simple and useful tool to control the function of sensors and cables. The pen sends light into the system and the sensors and cables can be visually checked for light losses and eventual fibre breakages. A typical fibre breakage in an installed tape sensor can be seen in Figure 5.1.

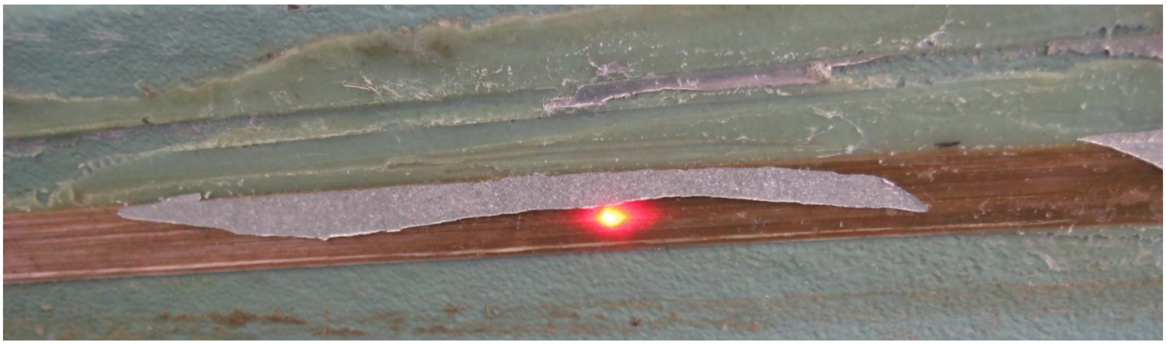

Figure 5.1 A luminous spot telling about a fibre breakage in an installed tape sensor.

An Optical Time-Domain Reflectometer (OTDR) is an optoelectronic instrument that is used to characterise an optical fibre. An OTDR inserts a series of optical pulses into the fibre during testing and extracts back scattered light from points in the fibre where the index of refraction changes. The strength of the return pulses is measured and integrated as a function of time. An OTDR allows measuring fibre length, attenuation and optical return losses and also helps to localize breakages. An OTDR measurement can be seen in Figure 5.2. The measurements show some reflections peaks at the beginning followed by nearly 300 meters of transmission cable. A reflection can be seen just before 300 m, probably a bad splice or a dirty connection. After the reflection there is some additional transmitting cable followed by a sensor with high losses.

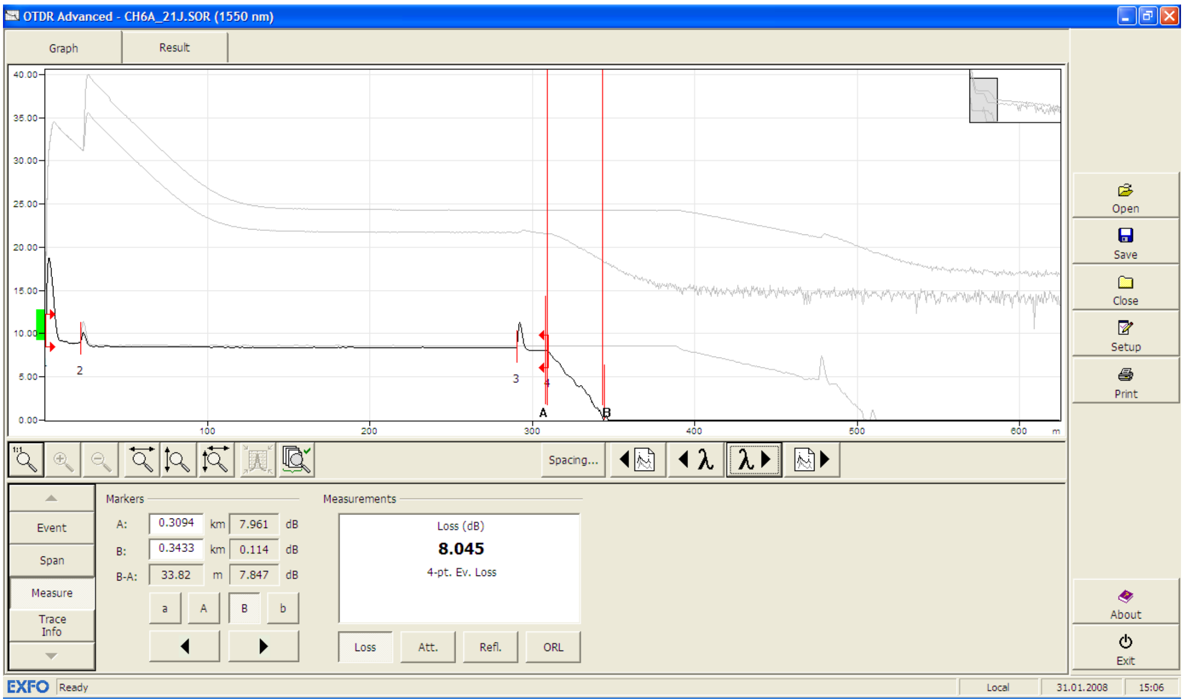

Figure 5.2 OTDR measurement checking losses of the optical signal in a tape sensor.

Optical fibres can be connected to each other by connectors or by splicing. Two fibres are joined together to form a continuous optical waveguide by splicing. Fusion splicing or mechanical splicing is used to physically join together two optical fibres. Mechanical splicing is used for temporary connections and fusion splicing is used for permanent connections. A fusion splicer is a machine that uses an electrical arc to weld/fuse two pieces of optical fibre together and the process of welding the cables together is called splicing. Other tools needed are; a stripper, alcohol, cleaver and splice protection. Firstly, the plastic cover and coating are stripped of the fibres followed by wiping with cotton dropped in isopropyl alcohol to remove any remaining material. Fibre ends are cut by a cleaver as perpendicularly as possible in order to avoid attenuation. Secondly, the fibres are placed into the fusion splicer which aligns the two fibre ends together, checks and splices them together. After fusing, the splice is covered by splice protection and other protection if required. Many fusion splicers have an active core aligning mechanism, a controllable electric arc to melt the fibre cores and join them together as well as a mechanism to melt the primary fibre protection.

Figure 5.3 show display of a Fusion Splicer. A successful splicing with 0 dB loss and perfect alignment of the core and cladding of the optic fibre can be seen on the left while some imperfections can be seen on the figure to the right: a thin line in the core and some twisting of the cladding

Figure 5.3 Display of a Splicing Machine after fibre fusion. Perfect results with 0 dB loss can be seen to the left and poor outcome with 0.8 dB loss to the right.

Some DASs use lasers that send harmful light and can damage eyes. It is very important to use safety glasses if there is a risk of damaging radiation. It is also important to set warning signs at the structure if there is any risk that personal or visitors may have a risk to injure their eyes.

5.5 Suitability

SG FOSs are suitable to measure local material behaviour while LG FOS are suitable to measure global behaviour of the structure. SG sensors are also good to measure crack widths of existing cracks. Some FOSs also exist in train rosettes that are useful when there is need to measure in several directions.

LG FOSs are suitable to either cast in concrete or to be mounted on the concrete surface as long as they are not in direct sunlight that might affect the measurements. These sensors provide measurements of concrete from early age to long-term measurements with excellent long-term stability but are also suitable for steel and composite materials.

Distributed FOSs are suitable for large structures like bridges, pipelines, dams, roads, pavements and also various geotechnical applications, just to mention a few. They measure distributed strain, temperature and can also be used for crack detection, localisation and crack width measurements. More information can be found in Paper 3 and in Paper 2, Chapter 4.

Chapter 6 Chosen Applications

6.1 General

As the author of this thesis has been involved in numerous SHM projects, both working as well doing the research, a lot of experience is gained. A short description about a few chosen projects is given in this chapter. Monitoring of the New Årsta Railway Bridge highlights the unique structure and doctoral projects connected to it. The monitoring of the Traneberg Bridge highlights the historical aspects of monitoring in Sweden and benefits of temporary monitoring with small amount of sensors. The SHM of the Götaälvbridge is a large project with novel technology. A detailed description about the installation is given in order to describe challenges when working with the new, innovative technique in the field. SHMS for Messina Bridge highlights groundbreaking challenge, designing a SHMS for the biggest ever planned bridge in the world. This project aims to adopt the latest available technologies as well as advanced existing technology in order to provide a redundant, sophisticated system that will meet the qualification of the 21st century.

6.2 New Årsta Railway Bridge

6.2.1 Introduction

The New Årsta Railway Bridge in Stockholm was built in 2000-2005. The bridge is an optimised, slender and complex ten span pre-stressed concrete structure. The total length of the New Årsta Railway Bridge is 833 m and it is 19.5 m wide. The northern and southern spans, closest to the abutments, are 48 and 65m respectively, while the main nine spans are 78 mm each. The distance between the new and the old bridge is 45 meters. The bridge accommodates two tracks for railway traffic, a service road and a pedestrian and cycle road.

A SHMS was installed on the bridge due the unique design. The monitoring is ongoing and the aims of the study are to check both static and dynamic behaviour of the structure both during construction period, load testing and in long-term. The dynamic study can be seen in [Wiberg, 2006, 2010].

This thesis highlights the static study and monitoring with FOS and thermocouples. Furthermore, the aims are also to learn about fibre optic sensors and compare them with the traditional transducers, to accumulate knowledge about SHM, sensory systems, monitoring procedures and practical point of views like installation, when working in the field.

One characteristic span, P8 to P9, of the bridge is mostly instrumented with both longitudinal and transversal LG FOSs as well as thermocouples. Monitoring sections are called A, B, C, D and E Figure 6.1.

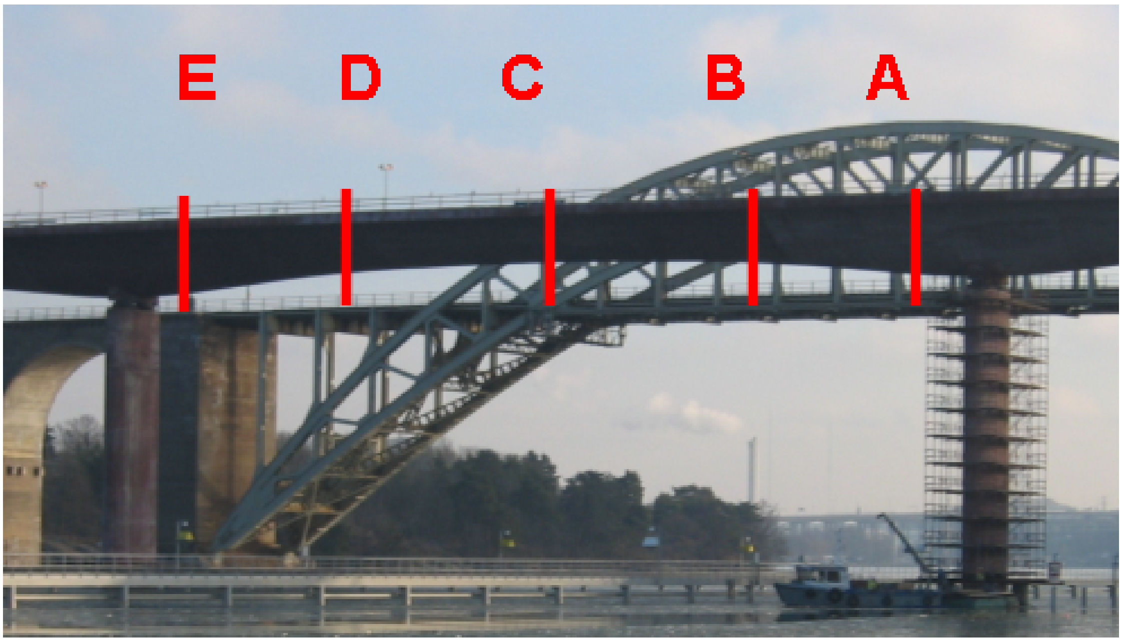

Figure 6.1 The picture shows monitored sections in the span between pier 8 and pier 9. Point A is close to pier 9. The old Årsta Bridge can be seen in the background.

6.2.1 Results

The New Årsta Railway Bridge is not only a challenging structure but also a large research project and huge amount of data and experience are gathered over the years. SHMS of the New Årsta Bridge highlights the plentiful possibilities FOS monitoring do provide. Fibre Optic LG sensors were shown optimal to cast in concrete and do measure early age concrete behaviour, construction stage behaviour, testing of the bridge and long-term behaviour efficiently. Sensor survival rate for cast in SOFO sensors was 84 %.

Applied research with novel technology and without previous experience is really challenging and many mistakes have been made. Successful SHMS includes following; clearly stated responsibilities, careful planning at the presence of an SHM expert, fewer sensors but adequate data analysis, appropriate database handling and intense study of the monitored structure at the beginning of the project in order to optimise and refine the procedures used in monitoring.

On the other hand, a lot can be learned and it is essential to capture lessons learned in order to develop best practices and successful criteria for future projects. Results from this study are influence by the fact that New Årsta Railway Bridge is a unique structure and it is complicated to draw general conclusions. Alternatively, a huge amount of general knowledge is gained and the results can be compared to other similar structures. Results are also fundamental in the future maintenance of the New Årsta Railway Bridge

Cracking in the concrete was revealed by monitoring that was also confirmed by crack mapping. SOFO sensors do show stable long-term behaviour compared to traditional strain transducers that do drift, malfunction or stop working. A lot of data lost was caused by modest memory capacity on the SOFO interrogator. Long-term function of SOFO sensors is excellent. Long-term effects like shrinkage and creep were studied. A simplified calculation can give a better estimate than a large FE model. The existing codes and models are inaccurate and need to be revised. More investigation is needed. Some recommendations are given latter and in Paper D and can guide the reader to build better SHMSs. Previous research can be seen in [Enckell & Wiberg, 2005, Enckell, 2006, Wiberg & Enckell 2008].

6.3 Traneberg Bridge

6.3.1 Introduction

Traneberg Bridge was built in 1934, and consisted of two parallel arch bridges, one for road traffic and one for the subway. The arch with 191 meters main span was the largest and longest ever built, at the time of its completion. Test samples of the concrete shrinkage were continuously monitored during several years in order to ensure the high quality of the concrete and verify the theory against the reality, see Figure 6.2 left. Additional testing like formwork pressure and stress in concrete in critical parts of the construction took also place, see Figure 6.2 right.

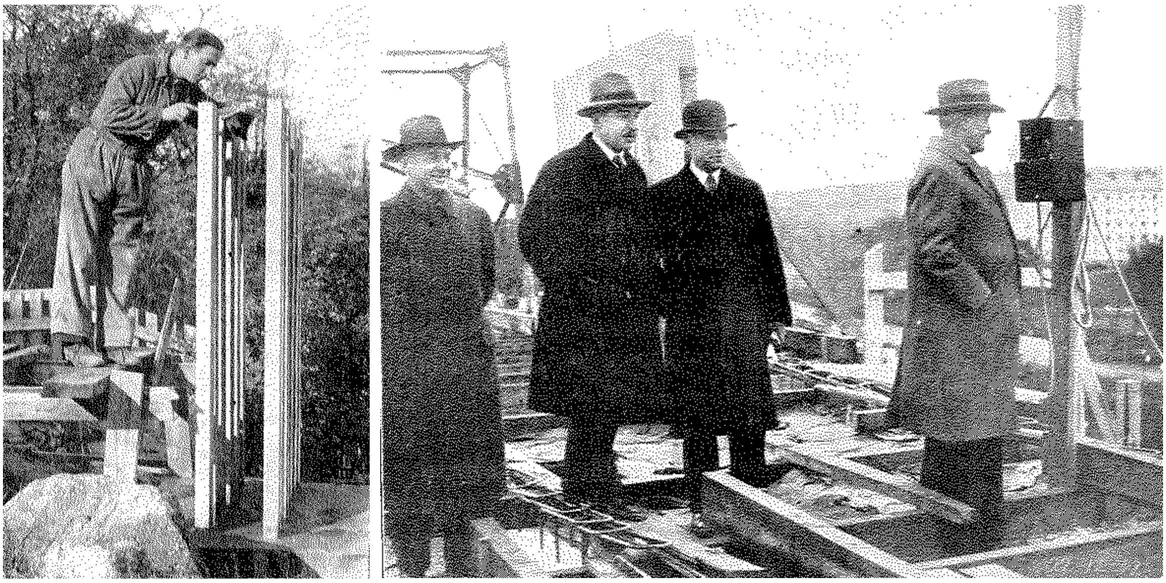

Figure 6.2. History of monitoring: Testing activities in Traneberg Bridge in 1930ies [Anger 1935].

The increased traffic and deteriorated concrete condition of the road bridge resulted that a third bridge was built south of the old road bridge in 2002. The old bridges were retrofitted by keeping the arches and reconstructing the pillars and the deck [Enckell and Larsson, 2005]. The project was completed at the beginning of 2005. All the three bridges are now in use and are able to support the new traffic demands.

The Traneberg subway bridge is a reinforced concrete structure. The supporting girders of the floor structure are made of steel [Nilsson, 1938]. The vertical clearance is 26 meters. The hollow arch is provided with three cavities and it is 9 meter wide. The height of the arch is 3 meters at the crown and 5 meters at the abutments. The structure is indeterminate as the arch is fixed in the abutments and there is no hinge on the crown. The reinforced concrete deck rests on plate shaped pillars by means of welded plate girders and lies above the crown over the length of 54 meters.

SL Infrateknik AB ordered a monitoring system for the bridge to control the behaviour of the arch under retrofitting. The old arch of the bridge was continuously monitored during retrofitting using seven fibre optic SOFO sensors and five thermocouples. The length of the fibre optic sensors is four meters and they are installed on the concrete surface in the longitudinal direction in the central cavity of the arch with L-brackets. The sensors are permanently installed on the bridge. Automatic measurements were performed and the data were downloaded to the office on a weekly basis. The data was briefly analysed and reported on a weekly and monthly basis. Peab

AB, the contactor continuously reported activities from the building site and these activities were included in these reports

6.3.2 Results

Historically, old reports showed that monitoring was used when building the bridge in 30's. Monitoring activity of e.g. shrinkage behaviour was performed during several years and it increased the understanding, verified the uncertainties and helped the engineers to make decisions concerning material properties and construction techniques in design stage.

The temporary monitoring was carried out during re-construction and about one month of operation until February 2005. A new measuring period of few weeks was done in May 2006 in order to control the condition of the structure in connection with a Master thesis study.

Short weekly and monthly reports were performed under the retrofitting and controlled by the owner: monitoring with small amount of sensors and thermocouples provided interesting information during the retrofitting progress. The contractor was very co-operative and helped the monitoring staff in various ways and benefited to better quality for the SHMS and its function [Enckell and Larsson, 2005].

After retrofitting, the service life of the structure is extended and this is a great economic benefit for the society and also a confirmation of the exceptionally good engineering work from 1934. 70 years old concrete arc was is still in good condition and could be reused. Additionally, a short study was done about temperature effects and reconstruction on the bridge [Miranda, 2006]. As the sensors are also permanently installed, the monitoring can be performed in the future to control the integrity of the structure, if the need would arise.

6.4 Götaälvbridge

6.4.1 Introduction

Götaälvbridge, built in 1939, is a large steel beam, concrete deck structure with combined road and light-rail. The bridge also accommodates a pedestrian-and bicycle road on the sides. The bridge is opening-able as a lot of boat traffic transit every day to Gothenburg harbour. Navigation channel is 20 meter wide and has a vertical clearance of 30 m. The total length is 950 m. It is the most important connection between the Gothenburg City and Hisingen for the city traffic. The dense light-rail traffic causes dynamic effects and bridge openings cause static loads as queues are built up on the bridge. Steel girders suffer from fatigue and mediocre steel quality and some severe cracking and also a minor structural element collapse have taken place.

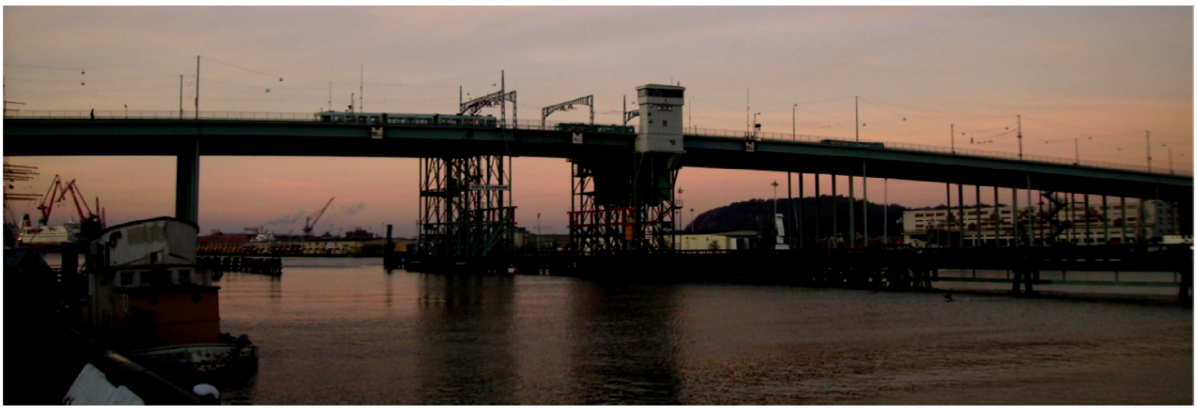

Figure 6.3 Götaälvbridge with the navigation channel in the middle.

NGI (Norwegian Geotechnical Institute) investigated the existing SHMSs and suggested a SHMS based on distributed FOSs [Myrvoll et al., 2008]. A small scale test installation of chosen fibre optic sensors called SmarTape took place in 2005; it also included testing the adhesion of the glue to the SmarTape, paint and to steel clean surface. The strengthening of the bridge took place in 2006 and the SHMS was also installed on the bridge. The chosen system is called DiTest and it is based on stimulated Brillouin scattering. The system consists of five longitudinal fibre optic arrays along the whole bridge, connection boxes, temperature cables, three interrogators, broadband connection and a control room. The system monitors strain continuously and has an inbuilt crack detection system that generates warnings so that the needed measures can be taken if needed. The system was planned to work for next 10 years which set very high demands for the selected system [Glisic et al. 2007].

6.4.2 Installation

The primary installation of the sensors started in June 2006 and was finished in October 2006.

The installation procedure on Götabridge is explained as follows. The tape sensor is slowly pulled trough the openings in the crossbeams and fixed loose with supports of tape bridges. This part of the work is really cautious in order not to damage the sensor that is normally 90 meters. After that, the surface and the sensor are cleaned with alcohol. Glue is set to a few meters piece of the sensor the sensor is pulled cautiously in order to prevent bending and fixed to the surface. After the sensor is covered with aluminium tape that will protect the sensors against water, dust etc. and prevent foreign particles to reach the glue. The procedure is repeated until the whole length of the sensor is glued to the beam as well as protected with the aluminium tape. The transmission cables are protected if needed and fixed on the web of the beam. Subsequently the sensors are spliced together to build loops and connected to the interrogator.

Installation procedure was really complicated as there was no experience from the past. Some of the beams suffered from harsh corrosion that has to be removed before the actual installation. Other beams were difficult to access and temporary scaffolding had to be built, some transversal beams had no passage so that holes were drilled in order to let the sensors to pass by. Special kind of small bridges were glued to these holes in order to allow the sensor to follow the bridge structure and transfer the real strain profile. As the south side of the bridge is located in Gothenburg city, the bridge is crossing several heavily trafficked roads and installation demanded careful planning [Enckell, 2006].

6.4.3 Results

Distributed strain and temperature monitoring for long-term monitoring was implemented for the very first time on a large bridge structure. Novel crack detection and localisation system, based on development on crack identification algorithm implemented in DiTeSt system and SMARTape delamination mechanism, was developed, tested and implemented. Also new methods and procedures in installing, testing, modifying and improving a SHMS were developed, tested and proven, both in laboratory and on-site. The data management system is able to perform analysis and send warning messages.

The designed system was also modified during the process. Due to lack of experience, contractor did not thoroughly train the personnel on installation which led to errors and delays in installation. A lot of heuristic knowledge was gathered; crack detection system that can detect, measure and localise cracks is optimal [Enckell et al. 2011].

6.5 Messina Bridge

6.5.1 Introduction

The planned Messina Bridge crossing Strait of Messina will connect the coasts of Sicilia and Calabria in southern Italy. The length of the main span will be 3300 m, the total length of the bridge 3666 m and it is planned to carry a four lane highway with emergency lanes and a dual railway line. The bridge will have steel towers, three steel girders, double main cables consisting of twin cables spaced 1.75 m - i.e. a total of four cables are required for the bridge. The suspended deck is arranged with the cross girders spaced at 30 m as the main elements whereas the two roadway girders and the central railway girder are taken as secondary elements spanning between the cross girders. In this manner the Messina Strait Bridge will be the first bridge in the World to adopt the triple box concept for the deck, which is 68 m wide. The design life of the bridge is 200 years.

Figure 6.4 Illustration of the planned Messina Bridge (Courtesy of Stretto di Messina)

The SHMS has been developed in parallel to the design of the bridge in collaboration with the structural designers. The SHMS will facilitate a variety of tasks including construction monitoring, operation monitoring, design validation and maintenance planning. The SHMS will be integrated into a Management and Control System for the bridge and approach networks. SHMS data will also be used for updating service life calculation and point ranking assessment of structural components of the bridge to assist with long-term maintenance planning.

The SHMS will consist of a central Mainframe Server (MFS) that is located in the operation control centre, fifteen DAUs, and a network of sensors. The SHMS will consist of about 3000 measurement locations and portable sensors, of which 90% will be integrated into the permanent SHMS data-stream [De Neumann et al. 2011].

6.5.2 Future challenges

The SHMS will be part of the Supervisory Control and Data Acquisition (SCADA) system but will operate independently of the other sub-systems. Database for storing data will be common for all sub-systems. An extensive dehumidification system to control the internal environment of the bridge boxes, towers as well as main-cables will be provided.

It would be optimal to monitor strain, temperature as well as humidity inside the main cables. Further development of fibre-optic sensor technology for installation within the main-cables presents one of the most important development challenges. Strain sensors are the most challenging part as they need a proper bonding over the whole length of the cable or at least some chosen discrete points that are to be measured. SG FBGs can be used to measure strain in discrete point or distributed sensors if the whole length of the cable is to be measured.

Temperature and humidity sensors do not require bonding to the main-cable and therefore the implementation of a full-length fibre-optic cable is less demanding. Distributed sensors based on Raman scattering can be adopted for measurement of the temperature of the main-cables. Raman sensors have been applied successfully on large structural projects, for example for dam monitoring [Aufleger, 1998]. Feasibility of FOS installation as well as functionality of the sensors needs to be carefully tested and verified. Testing will prove feasibility of the installation as well as verify functionality of the sensors. Testing will be judges by qualified experts that will also establish the requirements of testing. Some trials have been made so far but there is need for more appropriate procedures in order to guarantee the high quality required.

Chapter 7 Results and Recommendation

7.1 General

Large number of SHMSs are designed and numerous installations and testing campaigns are completed. Massive amounts of measured data have been collected and also various skills and practices are gained. Some complicated installations took place and new and emerging sensors and systems were installed and new techniques were proven to be useful. Some issues are highlighted in this chapter and additional information can be seen in previous reports and author's Licentiate Thesis [Enckell and Wiberg, 2003, Enckell and Larsson, 2005, Enckell 2006, Wiberg and Enckell, 2007, Enckell, 2007, Glisic et al., 2009, Myrvoll et al. 2009, Enckell et al., 2011].

The following recommendations are given based on the experience so far:

- SHMS design is performed in collaboration with SHM experts and structural engineers. It is important to take into consideration various needs that different stakeholders may have. Common system requirements need to be ensured and if there are any special requirements present, more expertise is needed, e.g. cable manufacturer when finding new methods in cable installation.
- The database where statistical studies of parameters are easily done is preferred. The statistical methods are a good tool in revealing malfunctions in long-term monitoring. Simply checking the daily variation of FOS and their changes in time revealed cracking in The New Årsta Railway Bridge and in Traneberg Bridge.
- If sensors are installed on the surface of the measured structure, they should not be in the solar radiation or covered with a material that will raise the local temperature and give biased readings
- There is a need for common programming platform/environment in large projects. All sensors and devices need to be commercially available, proven and able to connect to the chosen general platform in order to simplify the data processing including analysis.
- Data should be storied in compatible format for end users; this can decrease the cost of analysis fundamentally. DAS need a proper memory capacity so no data are lost
- Less is more: simple system with proper analysis gives more value than large system with poor analysis.

7.2 FOS Related Issues

FOSs are still today quit unfamiliar to general public yet they have many advantages compared to electrical transducers. The latest advancement has pushed the price down but the equipment is still expensive. On the other hand, FOS does not need expensive amplifiers, the installation time is reduced and the long-term function is good and the initial cost is saved in the long run.

Working with novel technology set new requests on the people working with it. Experienced staff, that like challenges, is open for new ideas, have practical sense and preferably investigational mind in order to solve the problems that are faced out when working with real world applications, is needed.

The following recommendations are given based on the experience so far:

- Use of FOSs is straightforward if some education and training is given. It is essential to understand sensor performances and to comprehend with given technical requirements and specifications. Guidelines help to understand different issues around sensor technology and need to be studied carefully if any knowledge is lacking. Companies selling FOS do also have education and courses that can be attended in order to be able to work with FOS technology.
- Cabling issues are important when handling with FOSs. All cables, both for sensors and transmission purposes need to be with adequate protection. Some telecommunication cables may have lower quality and high attenuation, use of proper cable that are recommended by the manufacturer of the sensors is crucial. It needs to be checked that cables copy with standards e.g. IP standard and other requirements of the SHMS if any.
- Interrogators and DAUs should be adaptable and with appropriate size of internal memory and also with possibility to connect external switch if more channels are needed. Memory requirements are checked based on monitoring plan.
- If having problems with dirty connectors and light losses in a harsh environment with a lot of dust, it is better to splice the connections in order to minimise losses.
- Technical specifications for FOS are not standardised and therefore complex to comprehend and compare. Attention is paid to details and the manufacturer is asked for more details to solve uncertainties.

7.3 Concrete Monitoring

Concrete is a complex material that takes time to form. Some measurements made at the New Årsta Railway Bridge were not ongoing long enough in order to catch the basic behaviour of the sensor and the concrete and it is impossible to find the "exact" zero level that is needed in comparison with other sensors. The projects also had only one portable interrogator to measure several sections and several interesting phenomena were not measured. As there was no experience from the past, it was difficult the judge the amount of measurements needed but also witch location that was the most critical to measure.

In order to obtain proper measurements and data that can be analysed, the following is recommended:

- Measurement should start when pouring the concrete to formwork and go on at least 28 days.
- Strain measurements need to be performed frequently meaning minimum every hour but preferably more frequently and do measure temperature of the concrete at the same frequency.
- Environmental parameters like temperature and air humidity need to be measured continuously. If solar radiation is suspected to give even just a moderate contribution to structural behaviour, it needs to be monitored or the daily pattern needs to be recognised.
- Every construction step like pre-stressing and removal of the formwork is measured. If having several separated sections and only one portable interrogator, it is recommended to rent another interrogator or several units in order to measure all activities as this will help a lot when analysing the data. If that is not possible, it is important to evaluate the most important event to be monitored.

Chapter 8 Discussion

8.1 SHM in general

This research work has been ongoing since 2003 side by side with an employment as civil engineer. Working with applied research and emerging technologies without previous experience was once in a while indeed challenging. Many lessons were learned; huge amount of experience and knowledge are gathered and still, a lot of work remains. In general, collection, storage and especially analyses of the collected data need to be organised in a more systematic way and more investigations are needed.

"Health Monitoring" was defined by Aktan et al. in 2000 [Aktan et al. 2000]. They also published the report "Development of a Model health Monitoring Guide for major Bridges" [Aktan et al.2001]. ISIS Canada Research Network was established in 1995. ISIS published a report "Guidelines for Structural health Monitoring" in 2001 [Mufti A, 2001] and several others design manuals and reports are published up today. International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII), a non-profit organization was founded in 2003. ISHMII also publish a paper called "*The Journal of Civil Structural Health Monitoring (JCSHM)*". The European Union project, Sustainable Bridges also started to work with functional requirements for railway bridges in 2003. The goal was to achieve increased capacities required to meet future demands for increased traffic levels and heavier axle loads.

[Farrar et al. 2007] gives an introduction into SHM. [Brownjohn, 2007] presents a comprehensible and extensive paper about SHM of civil infrastructure that illustrates the different topics of SHM of dams, bridges, offshore, buildings, towers, nuclear installations, tunnels and excavations Problems, challenges and limitation of development of SHM are brought up in these two papers, the subject that is very important but still left out completely by many other authors.

SHMSs help engineers to make decisions during construction and operation and provide help for management and maintenance procedures. Data interpretation for a complex structure needs to by tailor-maid as even two similar structures could have built in problems from the construction period. A trial period after completing the installation of a SHMS is crucial. Structural behaviour related to daily and annual variations, loading conditions and environmental effects is carefully studied and SHMS is calibrated to fit the defined requirements and also possible alarms and warning systems are set up and tuned.

Harmonisation of the vocabulary in the field is needed. Different manufacturers use different words for same equipment, many abbreviations are used and universities and researchers find their own ways of expressing and illustrating things. All this is confusing for a person who is new in the subject and there is need to describe some standards to be used.

8.2 Distributed FOS and crack detection techniques

Cracking may cause serious damage to the structure and weaken its performance and safety. Methods based on distributed FOS for detection and localisation of cracks in large structures and different materials like concrete, steel and composite were studied. [Bao et al., 2005] tested non-linear strain response of the concrete columns to detect the de-bonding and cracks under loading and rotation conditions. This study concluded that distributed Brillouin sensing technology is a powerful candidate to monitor the health of the structures and offers both local and global strain distribution. [Shi et al., 2005] and [Nöther et al., 2009] studied Brillouin based distributed sensing systems for geotechnical engineering structures like tunnels, slopes, piles, permafrost roadbeds for railway, roads, river and coastal dikes, dams, and landfills. These studies verify the suitability and potential of distributed FOS based on Brillouin scattering in optical fibres for geotechnical applications. [Imai et al., 2009] and [Zhang & Wu, 2008] tested and discussed crack detection and even crack width estimation and/or measurement with distributed technology.

Paper A presents SHMS for Götaälvbridge. The process started with a feasibility study with a test installation in order to evaluate the functionality of the system as well as to test the installation procedure on the bridge, in real conditions. Furthermore, a distributed strain and temperature monitoring system for long-term monitoring was implemented for the very first time on a large bridge structure. Novel crack detection and localisation system, based on development on crack identification algorithm implemented in DiTeSt system and SMARTape delamination mechanism, was developed, tested and implemented. Also new methods and procedures in installing, testing, modifying and improving a SHMS were developed, tested and proven, both in laboratory and on-site. Distributed sensing technologies has a unique capacity of monitoring thousands of points in one go. Several studies show promising results and more attention and research is needed.

8.3 Emerging technologies

Established technologies are well known and have a proper long-term experience. Emerging technologies, on the other hand, are science based innovations that have the potential to create a new industry or transform an existing one [Day et al. 2000]. They are also characterized with certain ambiguity and complexity as they are in accelerating change.

Emerging technologies do provide various advantages. Distributed fibre optic sensors are able to perform distributed dynamic measurements. Interferometric radars, photogrammetry and thermography do not need sensors or traffic to be stopped and the equipment is portable. These mentioned techniques and other emerging techniques are in expansion and do have ground-breaking potential and will provide us with even better systems and methods in the near future. The obligation is that we keep us updated continuously in order to understand and copy with this progress and therefore be able to judge the maturity of the existing as well as new products that appear on the market. Generally speaking, many studies in this field tend to talk only about advantages and are overoptimistic and more critical thinking is needed.

As emerging technologies present completely new advantages and challenges to civil engineering society, they demand for new kind of thinking in order to prevail and copy with them. Even if there is a lot of literature about sensor technology, SHM and SHMS design, the engineering society seems not able to apply this information and only the experience brings up with deeper understanding for the complexity of the subject. Many problems and malfunction are repeated unnecessarily. It is frustrating as an engineer and researcher to see the same mistakes to be repeated time and again. More sustainable systems can be built and solutions provided with a bit more self-effacing outlook.

8.4 FOS in general

FOS technology entered into the civil engineering area and its contribution is numerous. New sensors and methods are available and provide new possibilities. Nevertheless, new sensors and methods need to be proven in different conditions so that general rules can be established. Some presented case studies confirmed the good stability of the FOS. Though, many malfunctions were experienced, especially in installation planning and physical installation but can be avoided in the future and given recommendations will also help others to carry out better procedures.

Interrogators for optical devices have complicated design compared with electrical devices and are therefore generally more expensive. Some interrogators have a local interface device and can be used individually while others need an external computer with utilised software to activate the interrogator, as well as to view, store and analyze the collected data. Diverse FOSs also require different data acquisition systems so it is complicated to give general guiding principles. Technical specifications from different manufacturers also show a great variety and it is not easy to judge the suitability of the system or compare systems to each other. New stakeholders need a lot of education in order to be able to judge systems. More equivalent technical specifications would simplify the process and many mistakes could be avoided.

New challenges for fibre optic sensors lie on cable applications like: pre-stressed or post-stressed cables in various applications; stay cables and main cable applications in bridges. It would be convenient to install these cables with embedded sensors; either discrete or distributed sensors that do measure humidity, strain and temperature as the inspection of these cables afterwards is indeed complicated. Distributed FOSs need packaging improvements that will make them easier to install on the surfaces of large structures.

8.5 Concrete Monitoring

[Glisic et al. 2003, 2005] describe long-term monitoring of high-rise buildings over four years. The LG FOSs were embedded in the ground-level columns during the construction and the monitoring started with the birth of the structure. [Robertson, 2005] presents results of a long-span pre-stressed bridge monitoring program after nine years of data collection. Short-term and long-term responses of the structure were monitored and analysed. Creep and shrinkage testing with associated strength testing was performed beforehand and these test results were used for long-term creep and shrinkage predictions.

The New Årsta Railway Bridge, one of the case studies, provides a lot of interesting results. Though, the bridge structure is unique and it is difficult to analyse some results as some information is missing. Portable systems had no capacity to measure all installed sensors during the construction period and as there was no experience, it was difficult to judge the period that monitoring should take place as well as which sequences that should be prioritised. In order to avoid similar mistakes in the future projects, special recommendations are given concerning concrete monitoring.

Some primary results in New Årsta Railway Bridge as well as in Traneberg Bridge show that statistical methods can reveal cracking in concrete structures and it would be suitable to make a deeper study into the subject.

Also the long-term effects in concrete structures were studied. Long term creep and shrinkage studies are ongoing and the subject is eagerly discussed [Bažant et al. 2008, 2010, Wu and Yao, 2011]. Different codes like CEB-fib, ACI-209, GL, JSCE and RILEM-B3 were compared and checked and measured data for 56 pre-stressed segmental built box girder bridges was investigated and results are highlighted in [Bažant et al. 2011]. Shrinkage and creep long-time effects seem to be difficult to calculate, [Gilbert, 2001] illustrates that shrinkage strain models have huge error margins up to 30-40 % of the measured ones. Gilbert also demonstrates a simplified theory calculating common concrete shrinkage.

Long-term results from the New Årsta Railway Bridge are somehow comparable to study presented by [Robertson, 2005]. As many mistakes were made at the beginning of the project of the New Årsta Railway Bridge some measurements are insecure and difficult to analyse. These malfunctions could have been avoided with better planning at the early stage of the project. It would also have been preferable to work full time at the beginning of the project as the task was really demanding and time taking and no experience existed.

8.6 Installation issues and practical problems

Practical problems are often experienced when working in the field and ability to understand and rapidly find solutions is needed in order to avoid disturbances or stops in the projects. Many professionals have good theoretical skills but lack the practical experience that is gained when working in the field with real life applications. Many stakeholders neglect simple problems and in addition, belittle their effects. Therefore, many practical as well as organisational problems are repeated and the capital is wasted, time and again.

Many technical specifications, manufactures and even researchers state that the installation is a simple process. Anyhow, that was nearly never the case in the real world with real world applications. The author of the thesis has been involved in many practical applications and has therefore genuine knowledge that many other researchers lack. Certainly, there were some good days but many times there were some unexpected circumstances that took place on the bridge or the construction site independently and changed the planning or procedure. Real life applications require adaptable solutions and staff that can make quick decisions and solve practical problems on site in order not to slow down the ongoing project.

8.7 Contribution

Last decade was full of SHM activities: many structures were instrumented and one and all were enthusiastic to test their own solutions and not a lot attention was paid that several similar studies were performed side by side and collaboration was lacking. A huge amount of capital is invested in these SHMSs all over the world and it is complicated to judge the meaningfulness, significance and contribution of these systems. Anyhow, engineering society should be more critical to its own actions: better planning, well defined organisational responsibilities, straightforward systems without over ambitions, redundancy and quality assurance are needed for more sustainable solutions that will in fact save capital and contribute to a positive image of SHM.

Lack of understanding from different stakeholders, economical limitations as well as political decisions can sometimes be a hinder for emerging technologies. The experts are hindered by decision makers that are conservative and do prefer to stuck to old, conventional techniques. In addition, new and emerging technologies are also rejected by civil engineers as the general public is still not familiar with them and do lack understanding of variability and advantages that these techniques can offer. The importance of international collaboration cannot be neglected: this thesis advocates for open communication in the field of SHM. The general public needs better information for faster development. Harmonisation of vocabulary and standardisation need also to get started in order to avoid misunderstandings and to be able to talk same language around the world.

This thesis aims to help the reader to cope with different aspects around SHM and brings up various practical aspects and critical thoughts that are left out in many other reports in the field. Without previous experience many mistakes were made and that complicated the whole process: lessons learned are presented here in order to overcome the obstacles in the future projects. This thesis contributes for better understanding and gives recommendation. The aim of the recommendations is to advise for better utilizing as well as research in the SHM field: capital can be saved and effectiveness can be increased.

Chapter 9 Conclusions and Further R&D

9.1 Conclusions

Major conclusions based on continuous literature surveys, research, design work on major international bridges, long-term experience of practical use of FOS and other emerging technologies, feasibility studies, various kinds of temporary testing and measuring activities with various methods as well as continuous dialog with various experts are presented here:

1) Emerging technologies do provide high precision, high accuracy, stability and redundancy. On the other hand, emerging technologies do require a new kind of philosophy as they are characterized with certain uncertainty and intricacy. Interpretation of results is not always as easy as described in literature and experienced staff is essential for successful SHM.
2) Design of SHMS is a delicate process. A general procedure is presented.
3) Complex SHMS require combination of several techniques in order to be able to measure all desired parameters. Expertise is also needed in order to judge the reliability and thereby provide sustainable systems that fulfil the initial technical requirement.
4) A novel crack detection and localisation system based on Brillouin scattering was developed, tested and implemented on the Götaälvbridge. Also new methods and procedures in installing, testing, modifying and improving a SHMS were developed, tested and proven.
5) Fibre Optic LG sensors were shown optimal to cast in concrete and do measure early age concrete behaviour, construction stage behaviour, testing of the bridge and long-term behaviour efficiently. Sensor survival rate for cast in SOFO sensors was 84 % and their long-term behaviour was excellent.
6) Monitoring revealed cracking at the deck of the New Årsta Railway Bridge: change in daily variation was noted and cracks were confirmed at the bridge. Statistical studies can reveal interesting information of the changes in a structure and more analysis in this area is recommended.
7) Long-term effects like shrinkage and creep were studied in SHMS of the New Årsta Railway Bridge. The existing codes and models are inaccurate and need to be revised. The achieved results need to be compared with similar studies and more investigation is needed. Anyhow, these results are fundamental for future maintenance of the bridge.
8) SHMS at The Traneberg Suburban Bridge show that temporary monitoring with small amount of sensors and thermocouples can be a valuable tool during the retrofitting progress. The service life of the structure was extended with great economic benefit for the society. 70 years old concrete arc was reused and confirm remarkably good engineering work from 1934.
9) Sensor production needs better quality assurance. Also technical requirements given by manufacturer need more general form in order to be comparable so it will be easier for stakeholders to judge the function and reliability of these systems.

10) An advanced SHMS has been developed for planned Messina Bridge. The SHMS will be integrated into a Management and Control System for the bridge and approach networks.

As the world is full of deteriorated, malfunctioning structures, our infrastructures are aging and even newly built structures show malfunction; there is an accelerating need for SHM. The final conclusion is that an expert in SHM field needs wide education, understanding, experience, practical sense, curiosity and preferably investigational mind in order to solve the problems that are faced out when working with emerging technologies in the real world applications. The human factor, to be able to bind good relationship with workmanship cannot be neglected either. There is also need to be constantly updated as the field itself is in continuous development.

9.2 Further Research & Development

The following subjects are recommended for future research:

1) Research early age effects of concrete: Development of strength, Young's Modulus, shrinkage and creep from pour of the concrete to loading and how stresses are developing in a structure.
2) The behaviour of the shrinkage and creep in long-term pre-stress concrete structures need to be studied. Existing codes contain shortcomings and need to be revised.
3) Statistical methods were used successfully to locate cracks and more investigation is needed if these methods can be used to control crack propagation as well. The bridge deck of the New Årsta Railway Bridge should be installed with thermocouples so that the temperature evaluation of the deck can be performed and included in the future maintenance of the bridge.
4) Compare the results from SHMS of the New Årsta Railway Bridge with other similar structures.
5) Development of general platforms for data processing including analysis should be investigated. Many existing analysis programs are too general and immature and cannot tackle the amount of data and complexity that is needed in data analysis.
6) International collaboration and openness are needed for faster development: both advantages and disadvantages need to be presented and highlighted in truthful manner to avoid repetition of mistakes. Harmonisation of vocabulary is also relevant, engineers around the world should speak the same language and use same terms for same equipment.

Bibliography

Ackermann F, 1984. Digital image correlation: Performance and Potential application in Photogrammetry. The Photogrammetric Record, 11: 429–439. doi: 10.1111/j.1477-9730.1984.tb00505.x.

Aktan A E, Catbas F N, Grimmelsman K A & Tsikos C J, 2000. Issues in Infrastructure Health Monitoring for Management, ASCE, J. of Eng. Me., V126:711-724.

Aktan A E, Catbas F N, Grimmelsman K A & Pervizpour M, 2001. Development of a Model Health Monitoring Guide for Major Bridges. (Report, 2001) Drexel Intelligent Infrastructure and Transportation Safety Institute, USA

Anger D, 1935. *Tranebergbron*. Offprint from *Cement och Betong* 1932-1934, Stockholm:Tryckeri Aktiebolaget Thule, 341092.(In Swedish)

Aufleger M, 1998. Innovative dam monitoring systems. Dam safety: proceedings of the international symposium on new trends. ISBN 9054109742.

Bao X Y, Ravet F& Zou L F, 2005. Non linear strain response of the concrete column to detect the de-bonding and cracks using distributed Brillouin sensor. In Proceedings of the ISHMII-2, V 1: 235-242.

Bažant Z P & Li G-H, 2008. Comprehensive database on concrete creep and shrinkage. ACI Materials Journal. 106: 635-638.

Bažant Z P, Yu Q, Li G-H, Klein GJ & Křístek V, 2010. Excessive deflections of record-span prestressed box girder: Lessons learned from the collapse of the Koror-Babeldaob Bridge in Palau. ACI Concrete International 32 (6): 44-52.

Bazant Z P, Yu Q, Hubler M H, Kristek V & Bittnar Z, 2011. Wake-up call for creep, myth about size effect and black holes in safety: what to improve in fib model code draft, fib Symposium Prague, pp. 731-746.

Benning W, Lange J, Schwermann R, Effkemann C & Görtz S, 2004.Monitoring crack origin and evolution at concrete elements using photogrammetry. In proceedings of XXth congress of ISPRS ISPRS XXXV Part B, pp. 678-683.

Bergmeister K & Santa U, 2001. *Global monitoring concepts for bridges.* Structural Concrete 2001, Vol.2;1;29-39.

Brownjohn J M W, 2007. Structural health monitoring of civil infrastructure. Phil. Trans. R. Soc. A. 365, 589–622

Buderi R, 1996. The Invention That Changed the World. Simon & Schuster, New York.

Chen X, Shen F, Wang Z, Huang Z & Wang A, 2006. Micro-air-gap based intrinsic Fabry-Perot interferometric fiber-optic sensor. Appl. Optics, V 45:7760-7766 doi:10.1364/AO.45.007760

Clark P, Boriniski J, Gunther M, Poland S, Wigent D & Watkins S, 2001. Modern fibre optic sensors. Smart Mater. Bull. V 2001:6: 8-11.

Conyers L B, 2002. Ground Penetrating radar Published Online: 15th of Jan 2002. DOI: 10.1002/0471443395.img026

Day G S, Schoemaker P J H & Gunther R E, 2000. Wharton on Managing Emerging Technologies. Wiley, New Jersey. ISBN: 978-0-471-68939-3.

De Neumann S, Andersen J E, Enckell M and Vullo E, 2011. Messina Bridge - Structural Health Monitoring System. On proceeding CD of the IABSE-IASS 2011 Conference, ref nr. 0939.

Enckell M &Wiberg J, 2005. Monitoring of the New Årsta Railway Bridge. Instrumentation and preliminary results from the construction phase. Tec. Rep. Royal Institute of Technology, KTH.

Enckell M and Larsson H, 2005. Monitoring the behaviour of the Traneberg Bridge during retrofitting. In Proceedings of the ISHMII-2, V P2: 1631-1635.

Enckell M, 2006. Structural Health Monitoring using Modern Sensor Technology –Long-term Monitoring of the New Årsta Railway Bridge. Licentiate thesis, Royal Institute of Technology, KTH.

Enckell M, Glisic B, Myrvoll F & Bergstrand B., 2011. Evaluation of a large-scale bridge strain, temperature and crack monitoring with distributed fibre optic sensors. Journal of Civil Structural Health Monitoring. DOI: 10.1007/s13349-011-0004-x.

Farrar C & Worden K, 2007. An introduction to structural health monitoring. Phil. Trans. R. Soc. A V 365;303–315doi:10.1098/rsta.2006.1928

Geib D (2003) Multiplexing of Extrinsic Fabry-Perot Optical Fibre Sensors for Strain Measurements. M.S. Thesis, Virginia Polytechnic Institute and State University, pp.12-16.

Gentile C, 2010. Deflection measurement on vibrating stay cables by non-contact microwave interferometer. NDT&E International 43:231–240.

Gilbert R I, 2001. Shrinkage, Cracking and Deflection - the Serviceability of Concrete Structures. Electronic Journal of Structural Engineering, 1, pp.15-37.

Glisic B, 2000. Fibre optic sensors and behaviour in concrete at early age. Dissertation. Ecole Polytechnique Federale de Lausanne (EPFL).

Glisic B, Enckell M, Myrvoll F, Bergstrand B, 2009. Distributed sensors for damage detection and localization. On proceedings of the ISHMII-4, paper No.393.

Glisic, B., Inaudi, D., Hoong, K. C. and Lau, J. M., 2003, Monitoring of building columns during construction. 5th Asia Pacific Structural Engineering & Construction Conference, pp. 593-606.

Glisic, B., Inaudi, D., Lau, J. M, Mok Y C and Ng C T., 2005. Long-term monitoring of high-rise buildings using long-gage fiber optic sensors", 7th International conference on multi-purpose high-rise towers and tall buildings, Dubai.

Glisic B & Inaudi D, 2007. Fibre Optic Methods for Structural Health Monitoring. Wiley, Chichester, England.

Glisic B, Inaudi D, Lau J M & Fong C C, 2010. Real strain evolution in concrete columns, monitoring results and CEB-FIP Model Code 1990, 3rd fib International Congress - 2010, Washington D.C., USA.

Glisic B, Posenato D, Persson F, Myrvoll F, Enckell M, Inaudi D, 2007. Integrity Monitoring of Old Steel Bridge Using Fiber Optic Distributed Sensors Based on Brillouin Scattering . On proceedings CD of the ISHMII-3, paper No.112.

Imai M, Nakano R, Kono T, Ichinomiya T, Miura S, Mure M (2009). Crack detection application for fiber reinforced concrete using BOCDA-based optical fiber strain sensor. On Proceedings CD of the ISHMII-4, paper no. 509

Inaudi D, 1997. Fibre optic sensors network for the monitoring of civil engineering structures. Dissertation, Ecole Polytechnique Federale de Lausanne (EPFL).

Inaudi D & Glisic B, 2005. Application of distributed Fiber Optic Sensory for SHM. In proceedings of the ISHMII-2. V.1: 163-169.

Inaudi D & Glisic B, 2006. Fiber Optic Sensing for Innovative Oil & Gas Production and Transport Systems. 18th International Conference on Optical Fiber Sensors, paper No: 14.

Inaudi D & Glisic B, 2007. Distributed Fibre Optic Sensing for long range monitoring of pipelines. On proceedings CD of the ISHMII-3, paper No.56

Jaffrey D, 1982. Acoustic Emission Monitoring. Met. Forum. V 5: 154-157. Winter.

Lanticq V et al., 2009. Soil-embedded optical fiber sensing cable interrogated by Brillouin optical time-domain reflectometry (B-OTDR) and optical frequency-domain reflectometry (OFDR) for embedded cavity detection and sinkhole warning system. Meas. Sci. Technol. 20 034018 doi: 10.1088/0957-0233/20/3/034018

Majumder M, Gangopadhyaya T K, Chakrabortya A K, Dasguptaa K, Bhattacharya D K, 2008. Fibre Bragg gratings in structural health monitoring—Present status and applications. Sens. and Actuators A: Phys. V 147: 150-164 doi:10.1016/j.sna.2008.04.008

Mayer L, Yanev B, Olson L D, and Smyth A, 2010. Monitoring of the Manhattan Bridge for Vertical and Torsional Performance with GPS and Interferometric Radar Systems. Transportation Research Board Annual Meeting 2010. Paper #10-3183.

Measures M R, 2001. Structural monitoring with fibre optic technology. Academic Press, San Diego.

Messervey T B, Zangani D & Withiam J L, 2010. Smart textiles and their application in bridge engineeringIn proceedings of the IABMAS2010 - The Fifth International Conference on Bridge Maintenance, Safety and Management, Philadelphia, PA, USA., pp. 2135-2139.

Mikhail E M, Bethel J & McGlone J C, 2001. Introduction to Modern Photogrammetry. Wiley. ISBN: 978-0-471-30924-6

Miranda P, 2006. Evaluation of the structural behaviour during retrofitting of the Traneberg Bridge by monitoring. M.S. Thesis, Royal Institute of Technology (KTH).

Mufti A, 2001. Guidelines for structural health monitoring. ISIS Design Manual No. 2. ISIS Canada.www.isiscanada.com.

Myrvoll F, Bergstrand B, Glisic B, Enckell M, 2009. Extended operational time for an old bridge in Sweden using instrumented integrity monitoring. In proceedings of the Fifth Symposium on Strait Crossings: 397-401.

Nikles M, Vogel B, Briffod F, Sauser F, Luebbecke S, Bals A & Pfeiffer Th, 2004. Leakage detection using fiber optics distributed temperature monitoring. In proceedings of the11th SPIE's Annual International Symposium on Smart Structures and Materials, March 14-18, San Diego, USA, Vol. 5384, 18-25.

Nilsson E, 1938. *Modern Bridges in Stockholm.* Technical notices from the harbour board of Stockholm, 1938:1

Nöther N, Wosniok A, Krebber K & Thiele E, 2009. A distributed fiber-optic sensing system for monitoring geotechnical structures. On Proceedings of the ISHMII-4, paper No: 509.

Obrien E, Žnidaric A and Ojio T, 2008. Bridge Weight- In-Motion-Latest developments and applications world wide. Proceedings of the International Conference on Heavy Vehicles, pp: 25-38.

Quilligan M, 2003. Bridge Weigh-in-Motion - Development of a 2-D Multi-Vehicle Algorithm. Licentiate thesis, Royal Institute of Technology, KTH.

Roberge P R, 2006. Corrosion Basics: An Introduction, 2nd Edition. ISBN: 1-57590-198-0

Robertson I. N., 2005 Prediction of vertical deflections for a long-span pre-stressed concrete bridge structure, Engineering structures N.27,pp.1820-1827

Ross R M & Matthews S L, 1995. In-service structural monitoring—a state of the art review. Struct. Eng. V 73:23–31.

Shi B, Sui HB, Liu J, Zhang D, Zhang W, Suo WB, 2005. Applications of distributed fiber optic sensing technologies in geotechnical engineering monitoring. In: Proceedings of the ISHMII-2, V 1: 299–305.

Simmons G, Strangway D W, Bannister L, Baker R, Cubley D, La Torraca G and Watts R, 1972. The surface electrical properties experiment: in Lunar Geophysics, Z. Kopal and D. W. Strangway, eds., Dordrecht, D. Reidel, pp. 258-271.

Srinivasan S, Taylor S E, Basheer P A M, Smith B J, Sun T& Grattan K T V, 2009. Fibre Optic Relative Humidity Sensors for Long-Term Monitoring of Concrete Structures. In proceedings 4th International Conference on Structural Health Monitoring on Intelligent Infrastructure (SHMII-4).

Stern W, 1929. Versuch einer elektrodynamischen Dickenmessung von Gletschereis. Gerlands Beitrage zur Geophysik 23:292–333.

Stern W, 1930. Uber Grundlagen, Methodik und bisherige Ergebnisse elektrodynamischer Dickenmessung von Gletschereis: Z. Gletscherkunde, V 15: 24-42.

Udd E, 1991. Fiber Optic Sensors. Wiley, New York.

Udd E, 1995. Fiber optic smart structures. Wiley, New York.

Udd E, 2006. Fiber Optic Sensors: An Introduction for Engineers and Scientists. Wiley, New York.

Veldhuijzen Van Zanten R. (Editor), 1986. Geotextiles and Geomembranes in Civil Engineering, Balkema, Rotterdam, the Netherlands.

Wiberg J, 2006. Bridge Monitoring to Allow for Reliable Dynamic FE Modelling: A Case Study of the New Årsta Railway Bridge. Licentiate thesis, Royal Institute of Technology, KTH.

Wiberg J, 2009. Railway bridge response to passing trains. Measurements and FE model updating. Dissertation, Royal Institute of Technology (KTH).

Wiberg J & Enckell M, 2008. Monitoring of the New Årsta Railway Bridge. Presentation of measured data and report on the monitoring system over the period 2003-2007. Tec. Rep. Royal Institute of Technology, KTH.

Wu, X. and Yao, K. 2011, "The effect analysis about creep and shrinkage for long-term deflection of long-span continuous rigid frame bridge". Electric Technology and Civil Engineering (ICETCE), International Conference. pp 2730 - 2733. Doi.10.1109/ICETCE.2011.5774695

Zhang H & Wu Z, 2008. Performance evaluation of BOTDR-based Distributed Fiber Optic Sensors for crack monitoring. Structural Health Monitoring. Vol. 7:143-156.

Websites

http://www.infraredinstitute.co.uk/index.html Accessed 1 March 2011.

http://www.isprs.org/ Accessed 1 March 2011.

http://www.asprs.org/ Accessed 1 March 2011

http://www.lunatechnologies.com/products/DSS/files/DSS-4300_Data_Sheet_2009.pdf
Accessed 1 March 2011