STRUCTURAL HEALTH MONITORING WITH THE GENESI SYSTEM

WHITE PAPER

Summary:

This white paper introduces structural health monitoring (SHM), explaining the reason why we need in situ continuous monitoring, current methodology and limits of existing systems. It then describes why and how GENESI developed technologies meet the needs of long lasting robust reliable structural health monitoring and discusses how GENESI system can bring a revolution to this emerging market and related application domains.

Structural health in civil engineering

Our daily life is strongly affected by modern civil structures. In growing cities, most of us live in apartment houses and work in tall office buildings or factory halls. On the way between home and our work place we are using roads and railways which are crossing each other with large bridges or we travel below populated areas in tunnel constructions. Free spaces in the cities are used to make up new buildings with underground car parks. Many cities lie close to rivers and the coast and are protected against flooding by large dams.

On the week-ends and holidays, many people leave the cities and go out to nature. Once again they are using infrastructures like bridges crossing rivers or mountain valleys, tunnels and scenic roads along the coast side hills.

And even if we stay at home we get our electric energy from large power plants, transmitted via long electric lines with high masts. Our water supply comes from a reservoir outside of the city in long water lines buried in the ground.

Thus it is clear: Civil engineering structures are of high importance to our daily life and in growing and more mobile societies they are becoming more and more important and – due to urbanization and shrinking space – more and more complex. The value of this infrastructure is rising every year. The OECD estimates the investment sum for new infrastructure worldwide until 2030 at 70.000 billion USD.

Of course it is wished that these structures have a long lifetime -over several decades-, that they sustain outer impacts in their long lifetime (environmental influences due to weather and climate, hazards like earthquakes or accidents in traffic or fire) and that they can be adapted and rebuilt to new requirements. All this demands for intact structures.

If the structures do fail without prior notice a loss of several people lives is likely to happen. Sudden failure may refer to a collapsing building or structure, but it can also mean a rockfall on the road or a breaking dam.

Ensure intact structures

Various incidents can damage a structure. Besides the normal loads and the aging, loss of structural integrity is often due to outer impacts, which are hard to foresee. Natural hazards cannot be prevented. An earthquake cannot be predicted and also a storm, a blizzard or a flood can only be forecasted a few days before. Also, other impacts like accidents and fire cannot be predicted.

Of course there are methods to prepare a structure to the most likely events. For example in most countries maps exist to evaluate the risk of an earthquake and its strength for a region. The same is true for the risks of flooding, heavy snowfall or storms. In a tunnel or a skyscraper, a fire is much more destructive than in a small building, resulting in higher demands on the fire prevention. All these risks can be evaluated and regulations and standards describe the requirements and how structures have to be built to sustain these impacts without major damage.

However during the long lifetime of a structure things can evolve differently than as anticipated in the first design. Even during construction risks may be overseen or underestimated, parts of the structure may be dimensioned in a wrong way (e.g. due to unknown factors in the underground) or the quality of some materials may be lower than expected. Then during operation, the outer conditions or demands may change. Traffic and loads can rise higher than first expected; a building could be rebuilt to satisfy the demands of a new owner. There is a potential that critical risks might not be completely covered for the new dimensions.

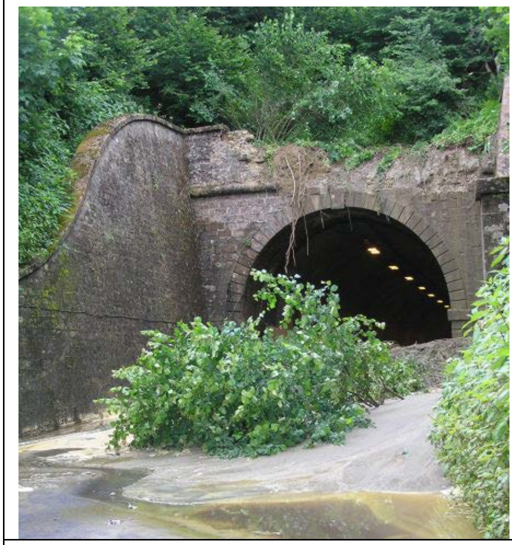
Last but not least, the construction is getting older and materials do age: Concrete can get fissures, steel will corrode. Chemicals in the air or in the rain can be the driving force for these damages. Earth dams erode as plant roots moulder and animals dig holes on the slopes or core. It also can happen that structures do survive a first heavy impact without showing major damage at first sight. These factors reduce the integrity of a structure.

It is obvious that an intact structure is much more likely to sustain extraordinary loads and events. This makes it important to be prepared and have intact structures before the impact occurs. Furthermore if a failure is detected early, an immediate repair or improvement is often easier and less costly than when structural problems can only be detected after long time. Keeping structures in good health is consequently also more economic.

Usually there are 3 main risks in a lifetime of a structure:

- During or directly after the construction or reconstruction (design failures, quality problems, uncertain or unknown outer parameters, e.g. geology)
- Due to or after an outer impact (possibly repeated)
- When the structure gets old and maintenance is inadequate

The following table gives some examples of structures that have collapsed due to an outer impact, although it was expected that they were safe. The examples emphasize that it is most important to have infrastructure in good health to sustain extraordinary outer impacts.

<table>
<tr><th>Scenario and picture</th><th>Text (Quotations/Excerpts from Wikipedia-Articles, date December 2012)</th></tr>
<tr><td>England - Beaminster tunnel
</td><td>Beaminster Tunnel is a 345-foot (105 m) long road tunnel on the A3066 road between Beaminster and Mosterton in Dorset, England. The tunnel was constructed between 1830–1832; it is notable for being one of the first road tunnels built in Britain and the only pre-railway road tunnel in the country still in use. It was built to take a toll road underneath a steep hill to the north of Beaminster and make it easier for horse-drawn traffic to travel from the coast to the hinterland of Dorset. It underwent significant repairs in 1968 and again in 2009, but in 2012 a torrential rainstorm caused a landslide that resulted in the partial collapse of the tunnel's north entrance and the deaths of two people.</td></tr>
<tr><td>New Orleans - Hurricane Katrina levee breaks
</td><td>In 29 August 2005 there were over 50 failures of the levees and flood walls protecting New Orleans, Louisiana, and its suburbs following passage of Hurricane Katrina and landfall in Mississippi. The levee and flood wall failures caused flooding in 80% of New Orleans and all of St. Bernard Parish. Tens of billions of gallons of water spilled into vast areas of New Orleans, flooding over 100,000 homes and businesses. Responsibility for the design and construction of the levee system belongs to the United States Army Corps of Engineers; the responsibility of maintenance belongs to the local levee boards. The Corps hands components of the system over to the local levee boards upon completion. When Katrina struck in 2005, the project was between 60-90% complete. Five investigations (three major and two minor) were conducted by civil engineers and other experts, in an attempt to identify the underlying reasons for the failure of the federal flood protection system. All concur that the primary cause of the flooding was inadequate design and construction by the Corps of Engineers.</td></tr>
<tr><td>CTV Building, Christchurch NZ</td><td>The CTV Building was the headquarters of Canterbury Television (locally known as CTV) and other companies. Located in the Christchurch Central City on the corner of Cashel and Madras Streets, it became one of the symbols of the February 2011 Christchurch earthquake. 115</td></tr>
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	*people lost their lives when the CTV Building collapsed during the 2011 earthquake; more than half of the earthquake's total fatalities.* *The CTV Building was inspected by engineers after the 4 September 2010 Canterbury earthquake and after the 26 December 2010 4.9 magnitude aftershock. On both occasions, the building was declared safe, having suffered only superficial damage. The building collapsed in the 22 February 2011 earthquake and due to its high death toll of over 100 people has become one of the symbols of the earthquake.*

See critical situations arising

Of course it still can happen that critical situations to a structure occur more rapidly than could be detected by regular inspection intervals. Or that the impact is stronger to whatever was expected by the dimension rules. But even then, usually the probability of a failure of the structure can be detected some minutes or seconds before it comes to the total collapse. Time that can be enough to warn people and evacuate endangered zones. Or even in case of the worst scenario that the structure has already been collapsing a warning signal can prevent people moving towards the dangerous zones (broken bridge, collapsing tunnel). On the other hand to know about the structures' health (or its remaining) can help rescue times to evaluate their risks to get to injured people.

When a tunnel is partly collapsing, usually it can be seen before that strains and stresses in the structure change. Or the deflection of parts of the structure is slowly rising, over some hours, minutes or seconds. This time can be critical - time to react and to warn the users.
Then, when the collapse has started it comes to a series of reactions that other parts receive higher loads and also fail. But when rescue teams want to get close to the collapsed part, they cannot be sure if they are safe themselves, as long as they do not know the new –partly stable - state of the structure. This can result in time lost to rescue injured people.

In the next examples we show failing structures that were in normal operation.

Scenario and picture (from wikipedia)	***Text (Quotations/Excerpts from Wikipedia-Articles, date December 2012)***
Sasago Tunnel, Japan 	*The Sasago Tunnel (笹子トンネル) is a Japanese twin-bore motorway tunnel on the Chūō Expressway. It was built in 1977. On December 2, 2012, nearly 150 concrete ceiling panels inside the Tokyo-bound tunnel collapsed, crushing three vehicles, including a van carrying six persons that caught fire. Nine people are confirmed dead. The tunnel remains closed indefinitely.*
Minneapolis- Mississippi River bridge 	*The I-35W Mississippi River bridge (officially known as Bridge 9340) was an eight-lane, steel truss arch bridge that carried Interstate 35W across the Mississippi River in Minneapolis, Minnesota, United States. During the evening rush hour on August 1, 2007, it suddenly collapsed, killing 13 people and injuring 145. The bridge was Minnesota's fifth busiest, carrying 140,000 vehicles daily. The NTSB cited a design flaw as the likely cause of the collapse, and asserted that additional weight on the bridge at the time of the collapse contributed to the catastrophic failure.*

Structural health monitoring (SHM)

What has been shown above makes clear why it is highly relevant to have methods that ensure the integrity of a structure. Therefore trained persons and experts have to inspect civil engineered structures regularly (e.g. every 5 years) or after strong impacts or changes have happened.

Most countries do have regulations defining who is responsible to maintain and check the structures and what exactly has to be done. **These experts need data they can relay on.**

Most often they do visual inspections, take samples for laboratory (e.g. of the concrete) or make experiments. Geodetic measurements are also very common to survey larger structures.

With better sensor techniques and automated data acquisition in the last 20 years also structural health monitoring with sensor networks has become established in this market. It is a very powerful method that experts often apply during the most critical phases in the structure’s lifetime.

The clear advantage of these automated SHM systems is that one can get continuous data of parts of the structure and that an alarming can be implemented. Data from automated sensors is less operator-dependent (more objective) and can more accurately and faster detect critical situations as measurements are more frequent than hand-measured data. Automated SHM works also in operation phases, when manual measurements cannot be taken (all daytimes, all seasons, during or immediately before and after an impact). In the long term it is usually very economic, because less field visits are necessary.

This makes automated SHM very valuable in evaluating the structures health. It can help save costs with better health interpretation and more focused maintenance and repair measures. This can also be emphasized in a risk diagram as shown below: The residual risk of the users of a structure to get harmed in case of a failure is minimized in this way. They can trust on more integrity of the structure and may even be warned in abnormal situations.

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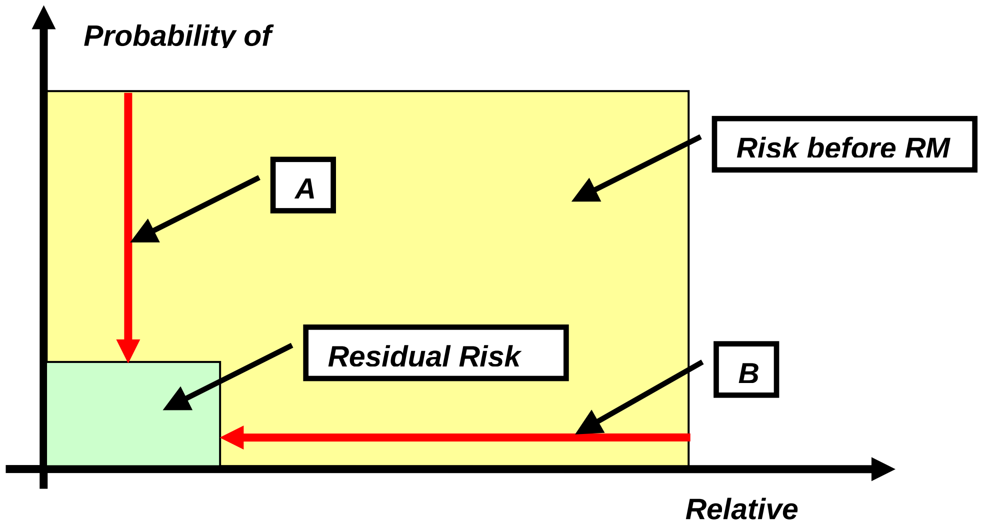

A: Structural Health Monitoring as early warning system can alert to improve structure stability and thus prevents structure damage or collapse.
B: Structural Health Monitoring can alert to evacuate building on time before collapse

GENESI - Next generation of SHM

GENESI (**G**reen s**e**nsor **ne**tworks for **s**tructural mon**i**toring) is a newly developed SHM monitoring system by leading companies in the geotechnical Structural Health market and by reputable research partners from universities and research institutes. It is a wireless sensor network with low power demands, energy harvesting and wake up radio capabilities, able to support reliable monitoring and control of infrastructures, in an energy neutral way, for very long periods of time. The project has also developed tools supporting deployments of WSNs, adaptive data sampling and outlier detection techniques to increase reliability and further reduce energy consumption of the deployed technology.

With GENESI we drive the automated SHM to a new level. One of the main ideas of GENESI is that the SHM is not only done during phases like the construction or when already first damages to the structure have occurred. GENESI is developed to work on the construction during its full lifetime.

The GENESI SHM system is designed to be installed during the construction phase of a new structure. After that it will remain in place to detect long term changes in the structure due to ageing, accidents or other changes. This provides experts longer data sets and more scenarios to compare.

The features GENESI is providing for this purpose are:

- System can easily be deployed: it does not need cabling or wiring, is independent from electronic infrastructure (powering, data transmission) and can easily be deployed on sites.
- System can easily be modified: nodes can be moved, added or removed if needed. Same with the base station. Without cabling and external powering this is very efficient and economic.
- A whole bunch of analog and digital interfaces are available on each node. This makes the system very wide for all types of sensing.
- Monitoring rates can be changed, advanced sampling mechanisms help reducing data when capturing long data sets.
- System is designed for long lifetime without maintenance (self powering).
- All data can be transmitted to the Internet, pushed into a data base and be accessible on webpages with time-line graphs.

In addition, GENESI SHM can also be applied in constructions that are already accomplished. Here during renovations or when critical conditions can be seen the system can be installed.

The system is conceived for structural health monitoring but due to the fact GENESI technologies enable long lasting, energy neutral autonomous operation, and due to the flexibility of the deployed system, GENESI system can be applied to a variety of domains, enhancing current sensing systems, such as landslides monitoring, environmental monitoring, monitoring of the preservation status of cultural heritage. The GENESI system is inexpensive, cable-less (thus resulting in lower costs, lower maintenance, and lack of esthetics degradation of monitored sites), it is flexible and modular, making it an ideal solution for construction companies, structures owners and operators (i.e, facility managers), and for authorities both in charge of preservation of public buildings and infrastructures, and in charge of the integrity of natural and historical heritage.