Structural Monitoring of Concrete Structures

Branko Glišiæ, Daniele Inaudi and Samuel Vurpillot
SMARTEC SA, Switzerland

ABSTRACT

Structural monitoring consists of regular recording of parameters related to the structural behaviour. The life of a concrete structure can be divided in several stages: it begins with construction works, pouring and cure of concrete and is followed with testing, service and possible refurbishment or straightening. The benefits of the information obtained by monitoring during each period of the structure life are apparent in several domains. First, it helps to improve and enlarge the knowledge concerning structural behaviour and makes an accurate calibration of numerical models possible. Second, permanent monitoring can give early indications of structural malfunctioning. In this way, safety measures can be considered in time, and intervention on the structure can be performed immediately and with minimal economical losses. The importance and the benefits of monitoring during the each stage of the concrete structure's life as well as the requirements for monitoring systems are presented in this paper and illustrated by real application examples.

1. INTRODUCTION

Civil structures are omnipresent in every society, regardless of culture, religion, geographical location and economical development. It is difficult to imagine a society without buildings, roads, rails, bridges, tunnels, dams and power plants. Structures affect human, social, ecological, economical, cultural and aesthetic aspects of societies and associated activities contribute considerably to the gross internal product. Therefore good design, quality construction as well as durable and safe exploitation of civil structures are goals of structural engineering.

The most safe and durable structures are usually structures that are well managed. Measurement and monitoring often have essential roles in management activities. The data resulting from the monitoring program is used to optimise the operation, maintenance, repair and replacing of the structure based on reliable and objective data. Detection of ongoing damage can be used to detect deviations from the design performance. Monitoring data can be integrated in structural management systems and increase the quality of decisions by providing reliable and unbiased information.

Many structures are in much better conditions than expected. In these cases, monitoring allows to increase the safety margins without any intervention on the structure. Taking advantage of better material properties, over-design and synergetic effects, it is possible to extend the lifetime or load-bearing capacity of structures. A small investment at the beginning of a project can lead to considerable savings by eliminating or reducing over-designed structural elements.

Malfunctioning of civil structures often has serious consequences. The most serious is an accident involving human victims. Even when there is no loss of life, populations suffer if infrastructure is partially or completely out of service. Collapse of certain structures, such as nuclear power plants, may provoke serious ecological pollution. The economic impact of structural deficiency is twofold: direct and indirect. The direct impact is reflected by costs of reconstruction while the indirect impact involves losses in the other branches of the economy. Fully collapse of historical monuments, such as old stone bridges and cathedrals, represent an irretrievable cultural loss for society.

Learning how a structure performs in real or laboratory conditions will help to design better structures for the future. This can lead to cheaper, safer and more durable structures with increased reliability and performance. Structural diversity due to factors such as geographical region, environmental influences, soil properties, loads etc. makes absolute behavioural knowledge impossible: there are no two identical structures. Structural monitoring represents a good way to enlarge knowledge of structural performance.

Concrete is the most used material in civil engineering. It is subjected to ageing and its mechanical properties change during the whole its life.

In this paper first a concept of structural monitoring of concrete structures is presented. It includes notion of structural monitoring, presentation of principal components of the monitoring systems and monitoring assessment. In the second part of paper, particularities of monitoring during each stage of concrete structure life, from the pouring to the end of service, are presented and illustrated by examples performed on-site using monitoring system called SOFO.

2. MONITORING SYSTEM AND MONITORING ASSESSMENT

2.1. Monitoring and Monitoring System Basic Components

Monitoring (or auscultation) of structures involves recording of time dependent parameters during certain periods. Monitored parameters can be physical, mechanical, chemical or other, and is usually present in each point of the structure.

Totality of means used for monitoring is called monitoring system. The main components of a monitoring system are sensors, carriers of information, reading unit, interfaces and data managing subsystems. The aim of sensor is to detect the magnitude of monitored parameter and to transform it to transportable information (e.g. optical of electrical information). The carrier leads the information from sensor to the reading unit, which decodes the information and retrieves the magnitude of the monitored parameter. The measurement is visualised and presented to the operator by user interface. Finally, the data managing subsystem is necessary to control operation and to manage the data obtained from monitoring. The components of a monitoring system can be separated or differently combined (e.g. sensor and carrier can make one device). Example of a monitoring system and it components, in case of the system called SOFO, is presented in Figure 1. The system is based on lowcoherence interferometry and deals with long-gage deformation sensors. More information concerning the system can be found in bibliography (Smartec 2002). In Figure 1 extension optical cables have a role of carriers and the software along with reading unit datalogger and PC hard disc have a role of interface and data managing subsystems.

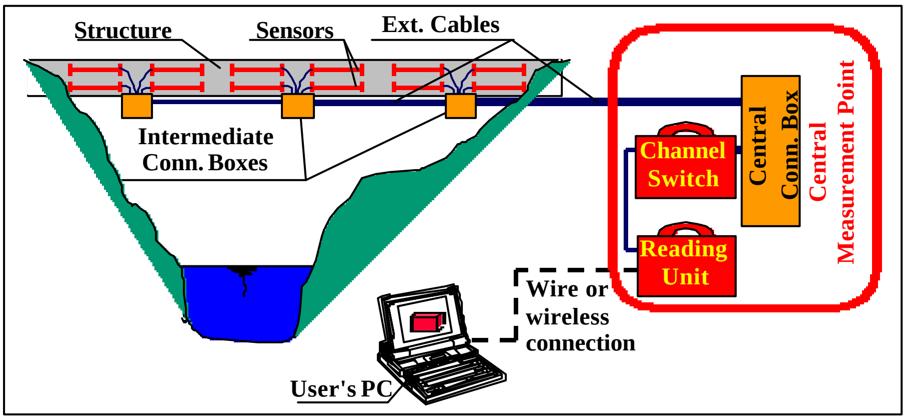

Figure 1. Example of monitoring system installed on structure (SOFO)

Generally, the sensors can be discrete or distributed. Discrete sensors can have short or long gage. Discrete sensor detects the observed parameter only at location where it is installed, while the distributed sensor detects the observed parameter in several locations of the structure. SOFO, Bragg-grating and Brillouin scattering based sensors are examples of discrete long-gage, discrete short-gage and distributed sensors.

2.2. Structural Monitoring – Basic Notions

Monitored parameters can be observed on material or structural level. Main difference between these two levels is in used monitoring strategy and monitoring system: material monitoring provides information related to material behaviour, but poor information concerning the structural behaviour; structural monitoring provides information related to structural behaviour. The difference between the material and structural monitoring is highlighted in Figure 2.

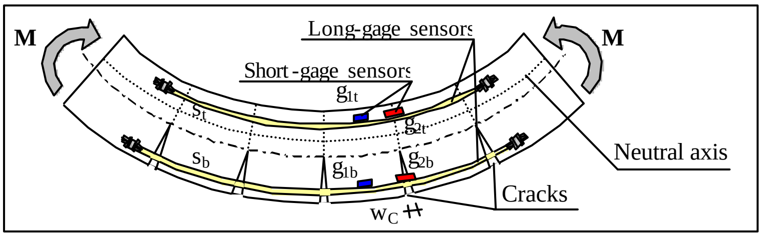

Figure 2. Difference between material and structural monitoring

In Figure 2, strain monitoring of a bended concrete beam using four discrete short-gage sensors (g_{1t}, g_{1b}, g_{2t} and g_{2b}) and two long-gage sensors (s_t and s_b) is presented. All sensors placed in the top of the beam (g_{1t}, g_{2t} and s_t) measure the same value, while the bottom sensors (g_{1b}, g_{2b} and s_b) measure different values, due to the crack openings. Short-gage sensors (g_{1b} and g_{2b}) are highly influenced by crack presence and they provide information related only to their locations in beam. The long-gage sensor (s_b) measure an average value of the strain combined with the crack openings, which is related to the structural behaviour. E.g. it is possible to determine structural behaviour of the beam by calculating its curvature as ratio between measurement difference and distance between sensors (Vurpillot 1999). There is no simple technique that allows determination of structural behaviour using results obtained from short-gage sensors. Hence, for the monitoring strategy presented in Figure 2, long-gage sensors allow monitoring at structural level, while the short-gage sensors allow monitoring on material level.

2.3. Monitoring assessment

There are different approaches to assess the structure and we can classify them in three basic categories: static monitoring, dynamic monitoring and system identification and modal analysis, and these categories can be combined. Each category is characterised by advantages and challenges and which one (or ones) will be used depends mainly on structural behaviour and goals of monitoring.

Each category can be performed during short and long periods, permanently (continuously) or periodically. The schedule and pace of monitoring depends on how fast the monitored parameter changes in time. For some applications, periodical monitoring gives satisfactory results, but information not registered between two inspections is lost forever. Only continuous monitoring during the whole lifespan of the structure can register its history, help to understand its real behaviour and fully exploit monitoring. The investment in the maintenance of the structure, using periodical inspections as a mean of control, can exceed the cost of a new structure.

3. MONITORING OF CONCRETE STRUCTURES

Concrete structure can be structurally monitored during different phases of its life, from the construction to the end of service. Each stage is presented in this paper and illustrated with on-site application performed with the SOFO system.

3.1. Monitoring during construction of a new structure

Construction is a very delicate phase in the life of concrete structures, since the material properties change through ageing. It is important to know whether or not the required values are achieved and maintained. Defects (e.g. premature cracking) that arise during construction may have serious consequences on structural performance. Monitoring data help engineers to understand the real behaviour of the structure and this leads to better estimates of real performance and more appropriate remedial actions.

Important information obtained through monitoring during construction includes the following: Estimation of hardening time of concrete in order to estimate when shrinkage stresses begin to be generated; Deformation measurements during early age of concrete in order to estimate self-stressing and risk of premature cracking; When structures are constructed in successive phases, measurement can help to improve the composition of concrete when necessary. In case of pre-fabricated structures, sensors may be useful for quality control; Optimisation between two successive phases of pouring due to evaluation of cure in previous phases; For prestressed structure, deformation monitoring of cables helps to adjust prestressing forces and determine the relaxation; Monitoring of foundation settlement helps to understand the origins of built-in stresses; Damage caused by unusual loads such as thunderstorm or earthquakes during construction may influence the ultimate performance of structures; Optimal regulation of structural position during erection; Knowledge improvement and recalibration of models.

The installation of a monitoring system during the construction phases allows monitoring to be carried out during the whole life of the structure. Since most structures have to be inspected several times during service, the best way to decrease the costs of monitoring and inspection is to install the monitoring system from the beginning, i.e. to embed the sensors into the concrete.

Cut-and-cover tunnel of Champ Baly, Switzerland (Glisic 2000), was monitored during the construction in order to determine structural behaviour of different components of the tunnel (foundations and vaults). The four meters long sensors were embedded into the foundation as well as in different position of the vaults, as shown in Figure 3 (sensors are represented with letter S and serial number).

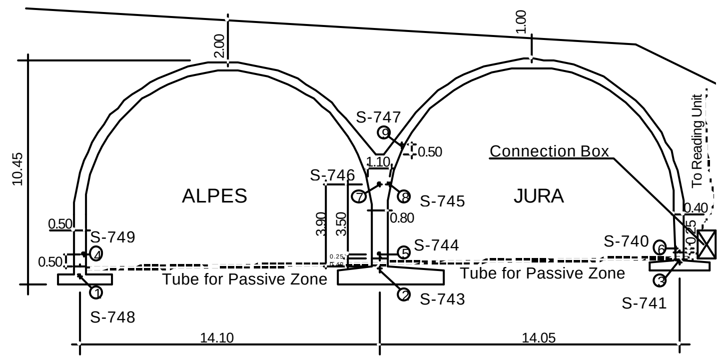

Figure 3. Position of sensors in monitored cross-section of cut-and-cover tunnel of Champ Baly

Foundations were poured approximately three months before the vaults. Evolution of its deformation (average strain multiplied with the length of the sensor) registered over first six months is presented in Figure 4. Different stages in foundation behaviour are clearly observed: thermal expansion during the very early age, shrinkage, contraction imposed by construction of vaults, and a period afterwards.

Early and very early age deformation of vaults registered during the first week after the pouring is presented in Figure 5. Distortion of the cross-section due to different thermal effects in different levels of the vaults was observed. Interaction between central foundation and the vault is estimated as good since the diagrams became parallel when the temperature in both elements became approximately identical (4 days after the pouring). Interaction between left foundation and vault was also very good, but compatibility of deformation was achieved only after the cracking (after 4 days). The cracking was detected first by sensor and than visually confirmed.

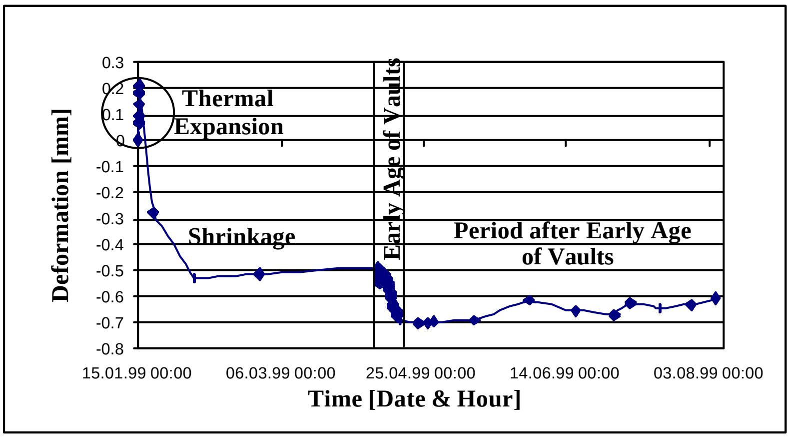

Figure 4. Deformation history of the foundation measured by sensor S-743

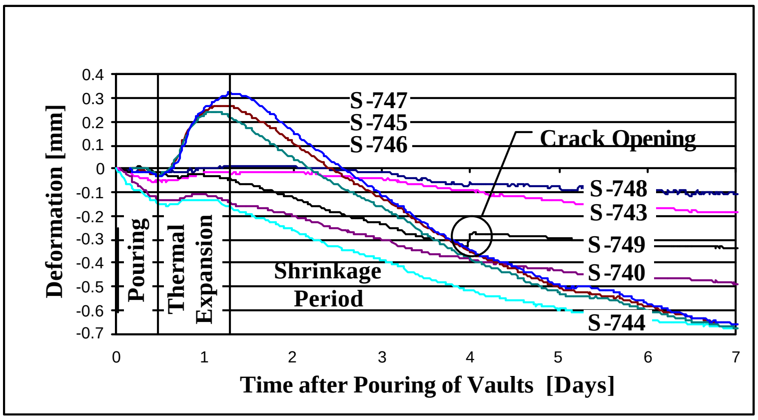

Figure 5. Deformation measurements during the early age of the vaults

3.2. **Monitoring after refurbishing, strengthening or enlargement**

Material degradation and/or damage are often the reasons for refurbishing existing structures. Also, new functional needs (e.g. enlarging) lead to requirements for strengthening. If strengthening elements are made of new concrete, a good interaction of new concrete with the existing structure has to be assured. Early age deformation of new concrete creates built-in stresses and bad cohesion causes delamination of the new concrete, thereby erasing the beneficial effects of the repair or strengthening efforts.

Since new concrete elements observed separately represent new structures, the reasons for monitoring them are the same as for new structures, presented in previous subsection. The determination of the success of refurbishment or strengthening is an additional justification. In example of Champ Baly cut-and-cover tunnel it is shown how the quality of interaction between an old structure (foundations) and a new structure (vaults) can be determined.

3.3 **Monitoring during testing**

Some structures have to be tested before service for safety reasons or to check their behaviour. At this stage, the required performance levels of structures have to be reached. Typical monitored parameters (such as deformation, strain, displacement, rotation of section and cracks opening) are measured. Tests are performed in order to understand the real behaviour of the structure and to compare it with theoretical estimates. Monitoring during this phase can be used to calibrate numerical models describing the behaviour of structures. The benefits from mentoring during testing are illustrated on example of piles monitored during the tests.

A new semi-conductor production facility in the Tainan Scientific Park, Taiwan, is to be founded on a soil consisting mainly of clay and sand with poor mechanical properties. To assess the foundation performance, it was decided to perform an axial compression, pullout and flexure test in full-scale on-site condition. Four meters SOFO sensors were used.

The pile was divided into eight zones (called cells). In the case of axial compression and pullout tests, a simple topology was used: the eight sensors were installed in a single chain, placed along one the main rebar, one sensor in each cell, as shown in Figure 6. To detect and compensate for a possible load eccentricity, the top cell was equipped with one more sensor installed on the opposite rebar with respect to the pile axis (see Figure 6).

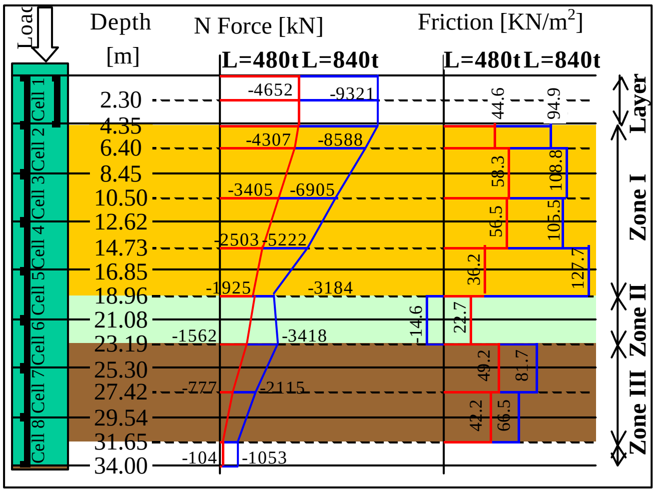

Figure 6. Sensor topology and results obtained by monitoring during the axial compression test

As a result of monitoring rich information concerning the structural behaviour of the piles is collected. Important parameters were determined such as distributions of strain, normal forces (see Figure 6), displacement in the pile, distribution of frictional forces between the pile and the soil (see Figure 6), determination of Young modulus, ultimate load capacity and failure mode of the piles as well as qualitative determination of mechanical properties of the soil (three zones are distinguished in Figure 6) (Glisic 2002).

In case of flexure test, a parallel topology was used: each cell contained two parallel sensors (as in cell 1 in Figure 6) installed on two opposite main rebars, constituting two chains of sensors. This topology allowed determination of average curvature in each cell (see subsection 2.2.), calculation of deformed shape and identification of failure point. Diagram of horizontal displacement for different steps of load as well as failure location on the pile are presented in Figure 7. In Figures 6 and 7 loads are presented in tons.

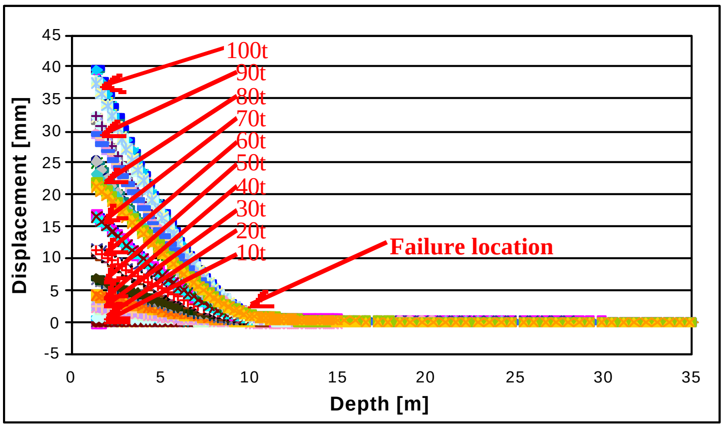

Figure 7. Deformed shapes of the pile and identification of failure location

3.4. Monitoring during the service

The service phase is the most important period in the life of a structure. During this phase, construction materials are subjected to degradation by ageing. Concrete cracks and creeps, and rebar steel oxidises. The degradation of materials is caused by mechanical (loads higher then theoretically assumed) and physico-chemical factors (corrosion of steel, penetration of salts and chlorides in concrete, freezing of concrete etc.). As a consequence of material degradation, the capacity, durability and safety of structure decrease.

Monitoring during service provides information on structural behaviour under predicted loads, and also registers the effects of unpredicted overloading. Data obtained by monitoring are useful for damage detection, evaluation of safety and determination of the residual capacity of structures. Early damage detection is particularly important because it leads to appropriate and timely interventions. If the damage is not detected, it continues to propagate and the structure no longer guarantees required performance levels. Late detection of damage results in either very elevated refurbishment costs or, in some cases, the structure has to be closed and dismantled. In seismic areas the importance of monitoring is most critical.

Subsequent auscultation of a structure that has not been monitored during its construction can serve as a basis for understanding of present and for prediction of future structural behaviour.

Monitoring during the service is illustrated on example of Versoix bridge, Switzerland (Inaudi 1999). The existing concrete bridge was enlarged with the third lane. Monthly quasi-static measurements are performed in order to monitor strain and displacement evolution of the bridge. Main concern was interaction between new and old concrete and long term performances. Total of more than 100 sensors is used to equip two spans. Five years strain evolution of a cross-section is presented in Figure 8. After the cross-section is bended horizontally due to unequal heat and different time of concrete pouring, all sensors measures approximately same deformation confirming that the cross-section is not exposed to unexpected bending due to damage or delamination.

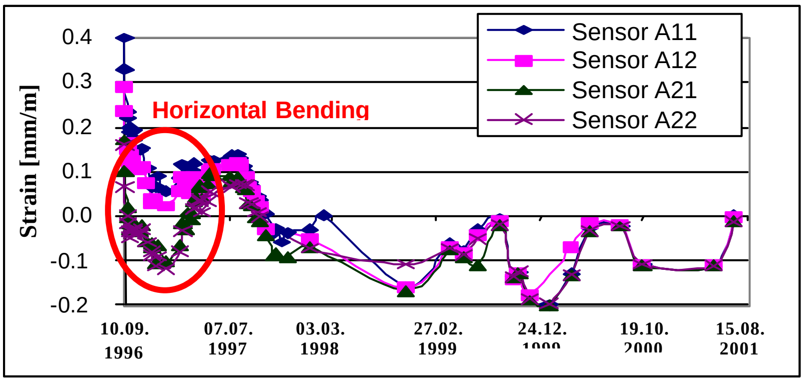

Figure 8. Versoix bridge five-years strain evolution

In Figure 9 diagrams of strain obtained by measurements (sensor A11) are compared with the models (Strain – calc. Shrinkage + temperature) and very good accordance is observed confirming good design and realisation of the bridge. The evolution of shrinkage is not finished but it is stabilised (see Figure 9). The seasonal temperature variation influenced behaviour of the bridge and can also be seen in Figure 9.

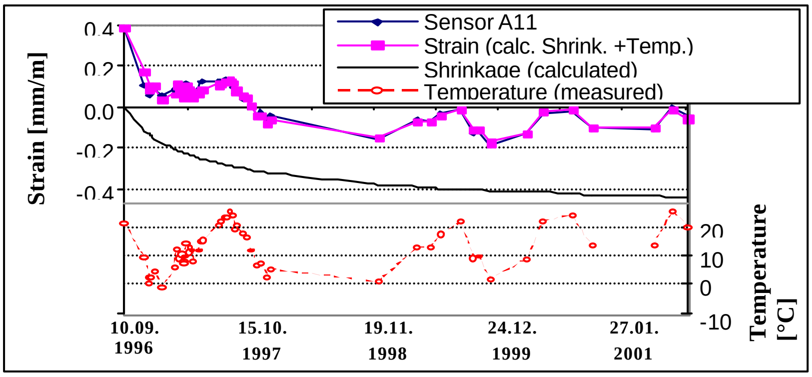

Figure 8. Uncoupling of shrinkage and temperature

3.5 Monitoring during dismantling

When the structure does no longer respond to the required performances and the costs of reparation or strengthening are excessively high, the ultimate life-span of the structure is attained and the structure should be dismantled. Monitoring helps to dismantle structures safely and successfully.

4 CONCLUSIONS

Structural monitoring is defined as such type of monitoring that allows conclusions concerning global, structural behaviour of the structure and not local, material behaviour. Since the concrete is non-homogeneous material, containing inclusions (aggregate) and discontinuities (cracks) it is recommended to use long-gage sensors for its structural monitoring. Since the concrete is subjected to dramatic dimensional and structural changes during hydration process, it is recommended to embed the sensors.

It is not enough to use appropriate equipment for monitoring, but it is also necessary to employ good monitoring strategy. What topology of sensor will be used for monitoring depends on type of the structure and of expected loads. Good monitoring strategy can provide excellent results with relatively limited budget.

Benefits of structural monitoring of concrete structures during different periods of the structure life are presented and illustrated by results obtained using the SOFO system. Knowledge provided by structural monitoring helped understanding the real behaviour of the structures.

ACKNOWLEDGEMENTS

Authors would like to thank to Mrs. Claire Nan from RouteAero, Taiwan, Mr. Pascal Kronenberg, IMAC-EPFL, Switzerlnad, and personel of IBAP-EPFL for precious help they offer during realisation of presented projects.

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