RECENT INSTRUMENTATION, SOFTWARE AND ANALYSIS PRACTICES IN STRUCTURAL HEALTH MONITORING

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ABSTRACT:

Technological developments in instruments caused an evolution both at the number and the scope of the structural health monitoring applications for civil engineering structures. This developments also paved the way for structural health monitoring to be the unique realistic technique for studying the dynamic building behaviour, today, moving the civil engineering laboratories to real-world. Taking precautions and preventing failures against severe earthquakes and other damaging effects started to become possible by monitoring the integrity of the structure in real-time. Many instrumentation combinations entered into the picture forcing the researchers, consultants, building owners and authorities to choose the best fitting methodology. Building codes are being modified today, including instrumentation and monitoring. This study covers different instrumentation approaches based on real-world application experiences including high-rise buildings, hospitals, and historical structures with dynamic monitoring using accelerometers under ambient vibration, and also static monitoring with tilt sensors, crack gauges, inclinometers. This study also opens a new window to a robust methodology that can be used for decision support, with the real-time and post-process, analysis and reporting. This approach is called as Health Monitoring Center Substructure and provides the tools for ending up with deliverable results from a vast amount of data coming from the sensors.

KEYWORDS: Real-Time Structural Health Monitoring, Operational Modal Analysis, Ultra-Low Noise Accelerometer, Force-Balance Accelerometer, Ambient Vibration, Dynamic Identification.

1. INTRODUCTION

Every civil engineering structure has an estimated lifetime. Engineering science intends to find and apply the most suitable and economical solution. However, due to an excessive loading (i.e. earthquake, flood, explosion, deep excavation) or repeated loading (fatigue) or ageing, the structure can be damaged or become unsafe. Evaluating the risks on the structure to perform repair and strengthening or evacuating and demolishing the structure at the correct time with enough information and data is quite essential. The process of mostly real-time monitoring as well as reporting the behaviour and probable damage condition of civil engineering structures under earthquake or other severe damaging effects with the help of the installed sensors is named as Structural Health Monitoring(will be abbreviated as SHM). This methodology leads to a decision support tool related to the safety of the building. Scope of this study consists of the instrumentation methods, devices, sensors, electronic systems, software and application practices used in structural health monitoring, especially for buildings and among a wide range of civil engineering structures. Çelebi (2002) emphasizes the importance and positive contribution of seismic monitoring and accelerometer-based structural health monitoring applications on buildings describes the methods and recommends everyday use of seismic instrumentation on federal buildings in the report prepared for USGS (US Geological Survey). It has been stressed that the information that will be collected as a result of these monitoring studies will form a unique database of knowledge for the practice of earthquake-resistant design. Real-time structural health monitoring is one of the most recent technologies which produce unique results. By the start of the 21st century, SHM became more reachable at lower costs due to technological developments and began to spread out rapidly. There are descriptions and directions about seismic instrumentation and application of accelerometers at high-rise buildings both at San Francisco Building Code (2014) and Los Angeles Tall Buildings Structural Design Council Consensus Document (2008). Guidelines and Implementing Rules on Earthquake Recording Instrumentation for Buildings (2015) defines the Structural Health Monitoring standards for high-rise buildings (above 50 meters) in the Philippines. Strong Motion Instrumentation of buildings in New Zealand is summarized by Deam and Cousins (2002). Section 13.8 of the Turkish National Earthquake Building Code published by the Disaster Management Authority of Turkey (AFAD) brings the obligation to health monitoring of high-rise buildings above 105 meters.

1.1 Types of structures to be monitored

SHM solutions can help to monitor nearly all types of civil engineering structures. However, the motivation to monitor, planning and philosophy of the instrumentation can change from structure to structure. This section classifies the structures, monitoring options and ideas according to needs.

1.1.1. High-rise buildings

High-rise buildings are one of the most vulnerable structures to the earthquakes. Recorded responses of 2 high-rise buildings during the Loma Prieta earthquake were analyzed by Şafak and Çelebi (1991). When high-rise structures are monitored using accelerometers, modal analysis and finite element model update can be carried out; modal frequencies can be monitored for a life-time. Any sudden or unexpected change in the modal frequencies after a severe earthquake will warn the decision-makers to take precautions. After an earthquake, the damaged buildings can be detected to a certain probability within hours. Soyoz et al. (2010) studied the structural reliability estimation with vibration-based identified parameters. Furthermore, the data gathered from these buildings will form the most realistic database to evaluate the effectiveness of the building codes for the next revisions.

1.1.2. Historical structures

Certain doubts can arise about the structural integrity of historical structures when cracks or other signs of pre-failure are observed on the structure. Strengthening and restoration work involving high levels of forced vibrations and demolishing, re-construction work temporarily multiplies the failure risk. Real-time monitoring during construction activities will minimize sudden failure risk. Crack, tilt, settlement and soil movement monitoring are the most common options. Besides, operational modal analysis of the structure before and after the strengthening would form a quantitative comparison base to evaluate the strengthening.

1.1.3. Bridges and tunnels

Among all civil engineering structures, bridges & tunnels are two of the leading types that should be monitored by sensors due to their critical fatigue and creep behaviour. Especially natural events such as earthquakes, floods, storms increase the importance of monitoring. Different types of instruments and sensors should be combined in health monitoring for railway/highway bridges, tunnels, tube crossings and subways. Although customization has significant importance in a specific SHM instrumentation project of a bridge or tunnel, accelerometers, strain/crack gauges, tilt, environmental sensors are the most preferred ones.

1.1.4. Hospitals with seismic isolators

Hospitals are a particular type of buildings that have to function 24/7 and 365 days. Uninterrupted functionality is even more critical after a major earthquake. Vibration levels are critical for sensitive medical equipment that can easily be affected by a high level of vibrations and surgery rooms. For all these reasons new hospitals being constructed in seismic zones are isolated by seismic dampeners installed under the foundation. However, the proper functioning of the seismic isolator afterwards is critical. Therefore the structure should be instrumented by accelerometers below and above the isolators, to monitor the performance of the isolators. Static and dynamic monitoring

Structural Health Monitoring can be carried out more statically (logging data, in less frequent terms like minute/hour or day based), more dynamic way (including vibration analysis by accelerometers) or a combination of both. In dynamic monitoring, accelerometers are the primary sensors. Tiltmeters, crack-gauges, inclinometers are the main actors for static monitoring.

1.2. Modal analysis under ambient vibration

Álvaro Cunha et al. (2006) investigated in detail, the evolution of dynamic identification and structural health monitoring studies from input-output techniques towards output-only, quite practical operational modal analysis intensively today. The theory of operational modal analysis is summarized in this section without going into the details of the mathematical model. Operational modal analysis is also called as ambient vibration testing as only the measurement of reactions is targeted under little daily vibrations. In this way, it is possible to stay in the operational system of the structure, and there is no need to force it externally. (Figure 1) On the other hand, ultra-low noise and high precision accelerometers are required for being able to measure and acquire these micro-g level vibrations, especially on buildings, in this technique.

At the analysis stage, besides simple peak picking, advanced techniques are proposed. Frequency Domain Decomposition-FDD (Brincker et al. 2001) in the frequency domain and Stochastic Subspace Identification (SSI) (Peeters et al., 1999) in the time domain are two of the most preferred techniques.

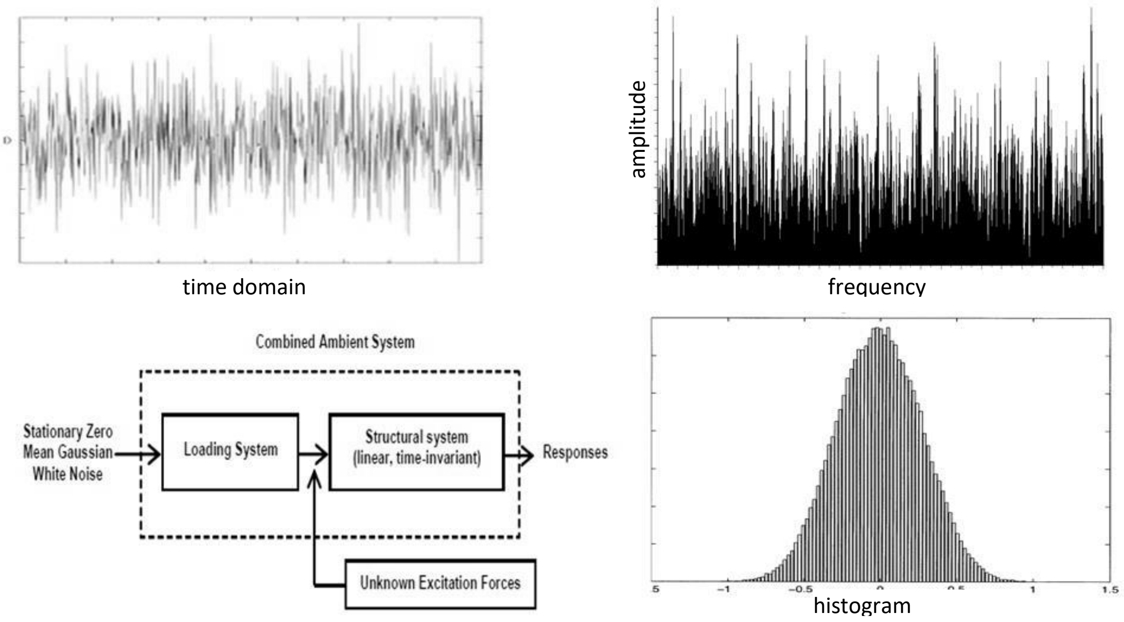

Figure 1. White Noise-Time/Frequency domain, histogram, Combined Ambient System

2. APPROPRIATE SELECTION OF THE EQUIPMENT

Since SHM is a new and innovative technique, deciding the best fitting equipment can be confusing. An essential number of monitoring projects fail because of the inappropriate instrument selection. Confusion is mostly caused because of the requirement to combine the different monitoring motivations/strategies and structure types with a bunch of different sensor technologies, resolution, sensitivity and precision requirements related to the measurement site, the distinguishable physical parameters to be reached at the end. Accelerometers (Enough vs more than enough or not enough) For dynamic monitoring and modal analysis under ambient vibration, the most critical component is the accelerometer. Taking sufficient selection parameters into consideration will dramatically affect the project budget. Under-qualified selection of the accelerometers will cause almost no interpretable data at the end. On the other hand, over-qualified selection of the accelerometers, will directly increase the project budget considerably, generally resulting in the insufficient number of sensors or unaffordable solution at the end.

2.1. Results of the accelerometer sufficiency comparison tests under ambient vibration

An important comparison test was conducted in TDG Scientific Laboratories in 2016. This building was a four-story concrete building, including the basement floor. The test took place on the 2nd floor directly on the concrete area next to a column as an ambient vibration test which aims to log data over-night, when the vibration was at the minimum level. TESTBOX2010-4 channel digitizer was used. This digitizer has four 24-bit, simultaneous sampling, input channels, 137dB dynamic range. Three sensors compared: (2nd channel left empty.) first channel: R-Sensors-MTSS1031A, 130 dB dynamic range, 130 ng/√Hz noise density at 10 Hz, manufactured with force-balance based, Molecular Electronic Transducer (MET) Technology.3rd channel: Silicon Designs SD1521, 100 dB MEMS technology. 5 µg/√Hz noise density. 4th channel: Colibrys-SiFlex SF1500A, 120 dB force-balance based, MEMS, 300 ng/√Hz. (obsolete now)

Test results showed that, while R-Sensors MTSS1031(green) and Colibrys SF1500A(red) successfully sense the modal frequencies under ambient vibration, the base noise level of the SD1521(blue) was far over the building acceleration response level, not enough to differentiate the modal frequencies. (Figure 2)

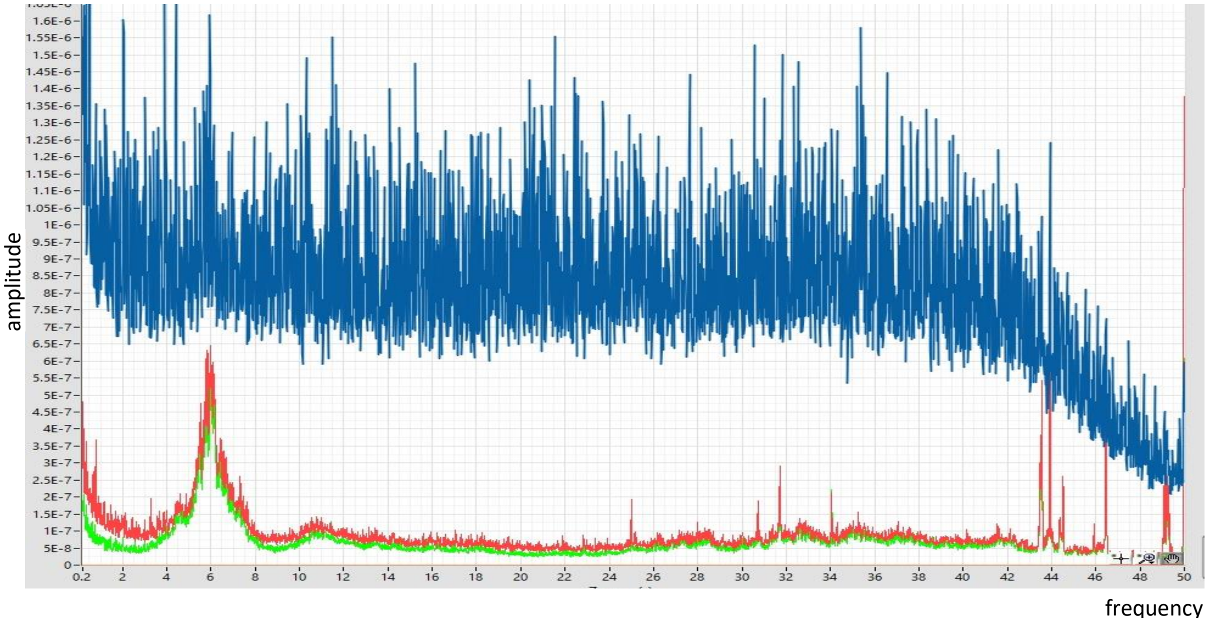

Figure 2. FFT- building frequency response under ambient vibration / 3 accelerometers compared

2.2. Precision (Dynamic Range – Noise Density)

Most confusions about the precision of the accelerometers arise from the conflicting figures on the data sheets prepared by the manufacturers. Some data sheets present dynamic ranges, while others give noise density figures. Even the dynamic range of the same sensor models may differ in different datasheet versions of the same sensor. Furthermore, the noise density for a specific sensor can be different for different frequency ranges. For example, a very high dynamic range (DR) can be observed for 0.1- 1 Hz and the DR is considerably lower for 1-10 Hz or 10-100 Hz. Manufacturers generally present the highest DR they observe. Although extremely high figures (more than 160 dB) exist in some parts of the datasheet, this does not represent overall sensing performance. The definite conclusion among all these conflicts is that an accelerometer over 120 dB overall DR successfully detects the building response under ambient vibration. DR above 120-130 dB, while dramatically increasing the sensor costs, is usually more than enough for buildings. For more flexible structures like bridges, there are excellent examples that even 100 dB sensors can lead to meaningful data. (Pakzad et al., 2008) However, for buildings, less than 120 dB accelerometers would be useless. There are many experimental types of research on ambient vibration testing conducted with the accelerometers of this dynamic range and noise level.) (Soyöz et al., 2013)

2.3. Measurement range and frequency response

In general, what is expected from an accelerometer used in SHM under ambient vibration, is the ability to differentiate the modal frequencies (mentioned in detail above) and at the same time to log the unclipped acceleration data during an earthquake. For this reason generally, a range of ±2 g is preferred. Modal frequencies for a structure starts from 0.2-5 Hz and can go up to 50 Hz for higher degree modes. When the building is a high rise one (above 100 meters), the 1st mode can generally is below 1 Hz. For these reasons, a frequency response of 0.1 Hz to 50 Hz (or 100 Hz) will be adequate for all cases.

2.4. Manufacturing technology

Tests and data sheets show that accelerometers with different technologies can satisfy the significant parameters for ambient vibration analysis. The conventional force-balance technique is the oldest manufacturing method. Even this technique has capacitive and inductive sub-solutions. Alternately, Molecular Electronic Transducer (MET) based force balance, piezo-electronic and MEMS-based force balance technologies exist. Summary of the main selection criteria for SHM under ambient vibration. As a result, manufacturing technology is not a determining parameter in sensor selection. Table 1 summarizes of the parameters that should be considered for accelerometer selection.

Table 1. Accelerometer Selection Criteria for SHM under Ambient Vibration

Parameter	Appropriate Values
Precision (based on Dynamic Range)	120 dB (min.)
Precision (based on Noise Density)	300 ng/√Hz (max.)
Measurement Range	±2 g
Frequency Response	0.1-50Hz (or 100 Hz)
Manufacturing Technology	Conventional Force-Balance or MET or Piezo

2.5. Digitizers

The digitizer is the component of the system that converts the analogue data to the digital value that can be logged, monitored and analyzed by computers. As the sensor, the digitizer is a vital part of the system.

2.5.1. The resolution, dynamic range, SNR

The golden rule for the digitizer precision is to select it according to the highest sensor precision, in the SHM system. For SHM under ambient vibration, only 24-Bit digitizers will support the accelerometers discussed in the previous section. The resolution itself is not the only parameter. Dynamic range should also be considered. Different 24-bit digitizers generally have different dynamic ranges. If the accelerometer is selected as 130 dB, the digitizer should be slightly above that. Usually, digitizers between 130-140 dB would meet the requirements.

2.5.2. Sampling frequency and simultaneous sampling (time synchronization)

As the maximum frequency response of the accelerometers will change between 50-100 Hz, digitizers with 100-200 Hz (100-200 samples per second per channel) should be used according to Nyquist theorem. Besides, for dynamic monitoring for operational modal analysis with accelerometers, time synchronization is the main issue. The synchronization can be classified as (i) the synchronization between the channels inside one multichannel digitizer and (ii) the synchronization between more than one digitizer. For the first one, a multi-channel digitizer must be chosen to be fully simultaneous sampling among its input channels. The second issue is generally solved with GPS based time synchronization. For this, all the separated digitizers should have a GPS antenna and be able to align their time base with respect to satellite time.

3. MONITORING PRACTICES

In the last five years, TDG was involved in many comprehensive monitoring projects. Among the high-rise buildings, some of them were

(i) Two Buildings with 30-31 Floors, Istanbul -Centralized Solution –8 channel digitizers, 1 triaxial and 5 units of uniaxial 130 dB force-balance accelerometers were installed on the buildings,

(ii) Sisli/Istanbul: 40 Floors, 161 meters, one of the highest buildings in Istanbul – Centralized Solution – 16 channel digitizer, 16 units of uniaxial 130 dB force-balance accelerometers were installed on the building.

(iii) Besiktas Istanbul: 4 Towers with 20 Floors, 161 meters– a similar centralized system was installed.

Most interesting results were obtained related to the first one. These buildings have been monitored for 2 years now. It was possible to observe the long term and seasonal changes on the natural frequencies of the buildings. (Figure 3)

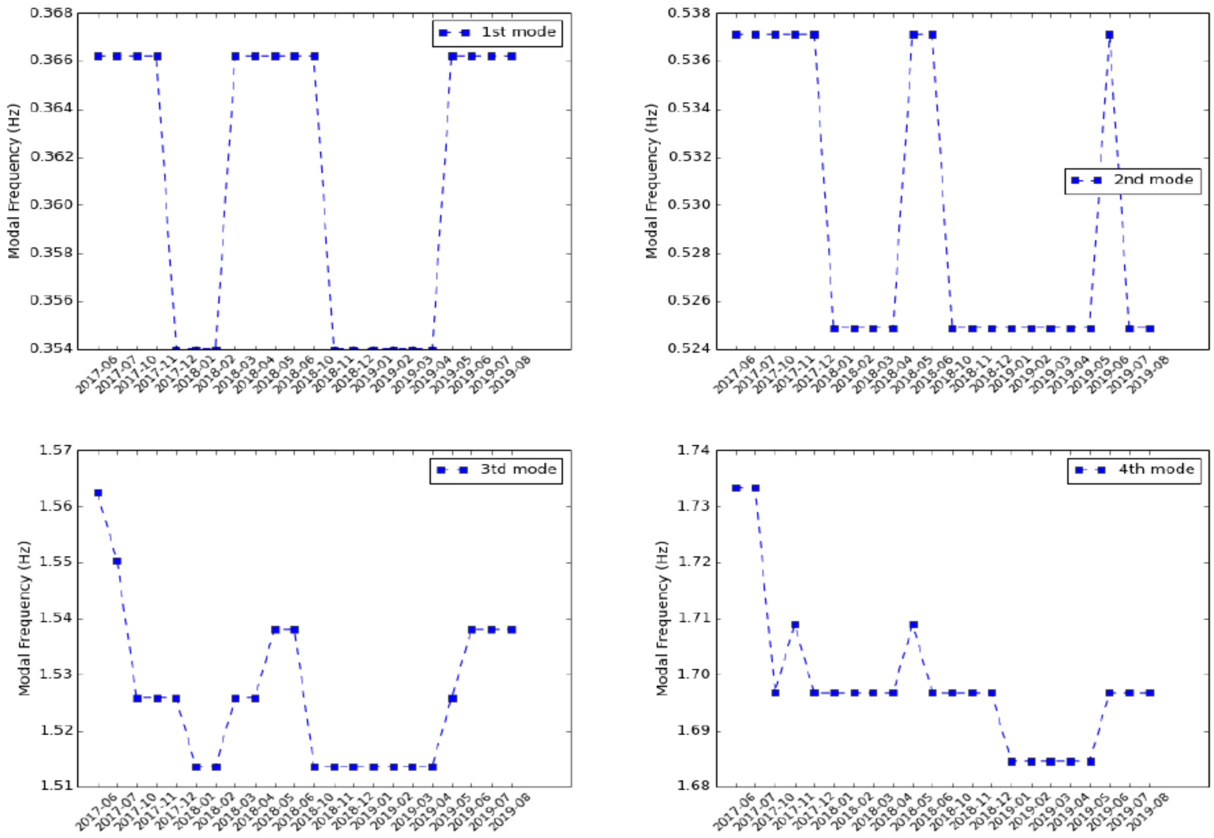

Figure 3. FFT- Long-term and seasonal building frequency responses under ambient vibration

The maximum seasonal changes at the natural frequencies were %3.2, %2.4, %3.2, %2.9 for first, second, third and fourth modes respectively. Especially for the first and second modes, seasonal changes mostly dominated the changes at the frequency response of the building. The changes at the frequencies were in both directions and returned to the original values indicating that they mostly depend on the environmental and seasonal effects rather than loss of rigidity related to structural integrity.

Regarding historical structures undergoing strengthening and restoration work, two most extensive monitoring projects were Galataport Project in Istanbul and Ulu Mosque in Sivas Divrigi. In both, a combination of static and dynamic monitoring was used. In Galataport 5 different buildings were instrumented. (106 tiltmeters, 21 accelerometers, 5 environmental, 13 units of multi-channel digitizers).

A different approach was used in Galataport for the first time as tiltmeters were used for settlement analysis. The main motivation was detecting the different settlement schemes on the buildings during the restoration process as an early warning of excessive movements on the structure related to the construction work. As at will be very hard to obtain absolute reference points for settlement analysis tiltmeters were installed across the axes of the buildings on the floor to get the relative changes at the horizontal and vertical angles. In this way, relative settlements were calculated from the measurements successfully for ensuring the safe construction process.

Another comprehensive project was in Ankara. Historical headquarters of Ziraat Bank, being one of the first structures of the Republic of Turkey, was instrumented during a strengthening process. Settlement analysis with tiltmeters method was re-used in this project. (30 settlement, 26 tiltmeters, 8 crack, 2 environmental, 6 inclinometers, 4 units of 16 Channel, 1 unit of 8 Channel Digitizers). Clock Tower and Oshki Church in Erzurum, Selimiye Mosque in Edirne, Eyup Sultan Mosque in Istanbul were some of the other monitored historical structures by TDG.

In Sivas Divrigi, Ulu Mosque project, tilt and crack monitoring were established, mainly. (8 tiltmeters, 25 crack meters, 11 accelerometers, 4 laser displacement sensors, 2 in-wall humidity sensors, 6 wall surface temperature sensors, 6 environmental, 5 units of 16 channel digitizers) Force-balance 130 dB accelerometers were installed in both projects.

Five recently built City Hospitals of Turkey with seismic were instrumented with accelerometers. The primary motivation behind was to monitor the performances of the seismic isolators. The general strategy was installing triaxial accelerometers below and above the isolators. Another accelerometer was installed on the top floor. In this way it is possible to record the seismic acceleration on the ground, then above the foundation of the building isolated by the dampeners, then the maximum acceleration of the building at the top.130 dB force balance based Molecular Electronic Transducer(MET) type accelerometers were used.

One interesting result obtained from one of these hospitals with base isolators was during an earthquake with magnitude 5,1, in 70 km distance far. The acceleration values were recorded during the earthquake both from the sensors below and above the seismic isolator levels successfully. These acceleration values were converted into displacement values after applying a high-pass filter and double integration. When the horizontal displacement values corresponding to the sensors below and above the isolators were compared, an exact match was observed in both time and frequency domain. This indicated that there was no horizontal relative displacement related to the base isolators, and the base isolators behaved almost as a rigid structure which was expected for an earthquake corresponding to this level of magnitude.

For all projects, the data was transferred to the Monitoring Center of TDG. Real-time analysis software was active to trigger alarms 7-24 to the project owners. A web-based frontend allowed the engineers to follow the data online. Monitoring systems were beneficial, ensuring safe construction work all the project long.

4. HEALTH MONITORING CENTER SUBSTRUCTURE

The real-time and post-process, analysis and reporting that can be used for decision support is as much critical as the instrumentation itself. TDG developed an approach for this which is called as Health Monitoring Center Substructure and provides the tools for ending up with deliverable results from a massive amount of data coming from the sensors. (Figure 3) Several software components are included in this flow, which is continuously being developed further.

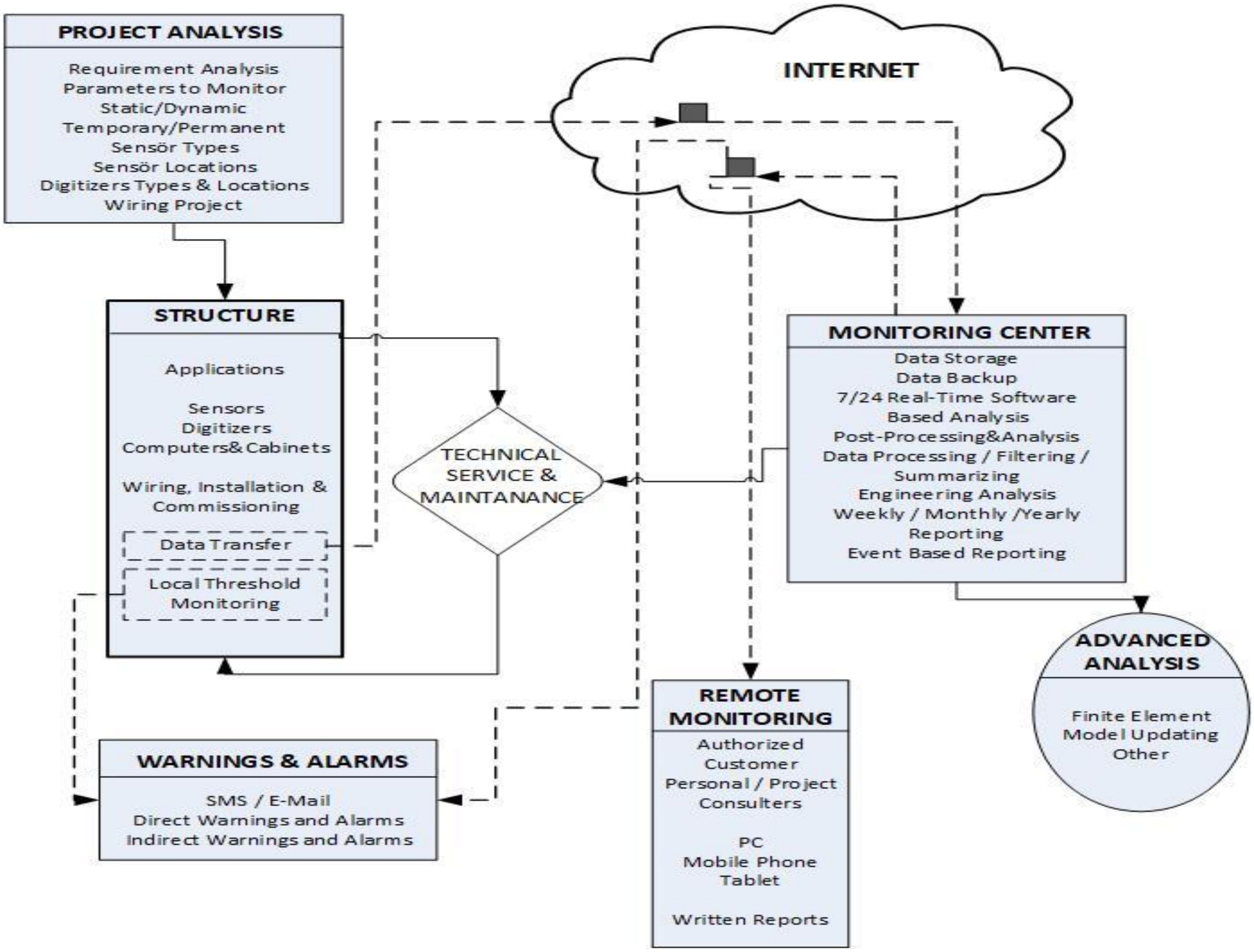

Figure 3. Health Monitoring Center Substructure

The most comprehensive part of the software functions is related to the monitoring centre for real-time analysis. Real-time analysis is essential for coping with a large amount of data. Analyzed and summarized resulting data and graphs are logged and presented to the decision-makers. Web-based data monitoring is developed for this purpose. Currently, natural frequency domain comparison analysis for buildings is carried out based on FDD (Frequency Domain Decomposition) technique. Both short-term and long-term changes of the first three translational and torsional modes are compared in real-time. Seasonal changes of the frequencies throughout the year are compared with past years, for long term analysis. Any degradation or long term rigidity loss due to ageing or fatigue analyzed. After an earthquake of M5.0 epicentre close to the structure, the structure is checked for a significant loss of integrity. Also, dynamic top displacements and seismic isolator displacements are calculated from acceleration values using high-pass filtering, double integral and offset correction techniques. For static monitoring components, threshold values are determined and updated periodically.

5. CONCLUSIONS

Structural health monitoring today is the unique technique for studying the dynamic behaviour of existing buildings, moving the civil engineering laboratories to real-world. Taking precautions and preventing failures against severe earthquakes and other effects started to become possible by monitoring the integrity of the structure in real-time. High-rise buildings, historical structures, hospitals, bridges and tunnels are the main types of structures commonly being monitored in recent years. Both dynamic and static monitoring are being applied to these structures. From many current instrumentation possibilities selection of the accelerometers and digitizers are of vital importance. Among current accelerometer technologies (i) conventional, electro-mechanical force-balance (FBA), and (ii) molecular electronics (MET) type FBA accelerometers are the best-fitting and commonly used technologies. However, any accelerometer having a dynamic range above 120 dB, noise density below 300 ng/√Hz, the measurement range of at least ±2 g, and frequency response at least in between 0.1-50Hz DC is adequate for operational modal analysis under ambient vibration. For the digitizers, a minimum of 24-bit resolution, 130 dB dynamic range with a sampling frequency of at least 200 Hz/channel is needed. One vital parameter for the digitizers is synchronization. Simultaneous sampling is required for operational modal analysis. When the digitizers have to be separated 1-10 microsecond timing resolution is required, and this is generally reached by GPS time synchronization. Whenever possible (semi)centralized installation architectures with low-noise permanent analogue cables should be preferred. Analysis and reporting the data for decision support is at least as critical as installing the best-fitting instrumentation. A monitoring centre approach with a real-time analysis software at the core has been developed to deal with a large amount of data coming from the instrumentation. This approach provides the tools for ending up with deliverable results from a massive amount of data coming from the sensors.

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