Blackbox concept can help promote widespread use of S2HM

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Abstract

A good example for a universally established worldwide status and performance monitoring system, which almost any person can relate to, is maybe the flight data recorder known as the “black box” in aircraft.

The broad concept of instrumental status and performance monitoring has been in use for about a century for keeping a watchful eye on many man-made structures and structural systems, and it has picked up an increasing momentum in the last few decades in comprehensiveness and intelligence.

Seismic instruments are being utilized with increasing success for Seismic Structural Health Monitoring (S2HM), regarding post-earthquake status and timely occupancy & service resumption of civil engineering structures, especially by virtue of the recent advances in the science and technology in their features and interpretation of their data. It is however a wonder why such use is not yet as established worldwide as the aircraft black box, although potential benefits of S2HM seem to be even higher considering the sheer number of civil structures located in high seismic risk areas, serving millions of people on a permanent basis.

Providing various examples of successful and large scale S2HM examples from Europe, this paper discusses utilization and promotion of such systems in the region currently, the motivations and initiatives towards a wider deployment of such systems, the difficulties or burdens facing such widespread use, along with suggestions to improve the establishment of S2HM systems as universally accepted and implemented attributes of civil engineering structures while proposing a concept similar to the aircraft black box.

Keywords: structural health monitoring, blackbox, post-earthquake status, occupancy resumption, business continuity

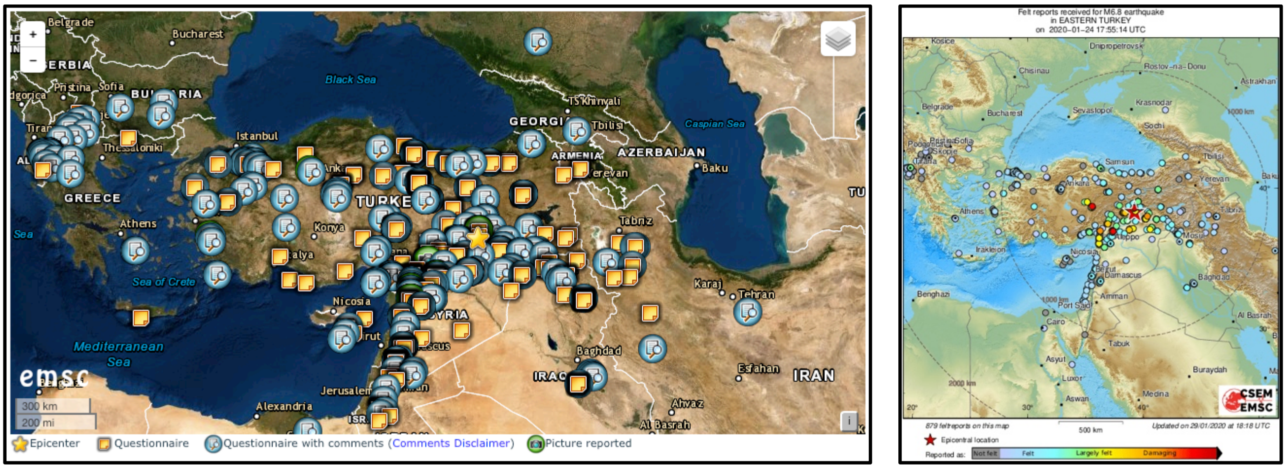
1. Introduction

The purpose of this paper is to help promote a widespread use and acceptance of standardized S2HM systems especially for areas of high seismic risk, where major losses may occur due to and after a significant seismic event, or a high level of insecurity may arise after a medium to small-but-felt event, leading to substantial collateral losses as a result of delayed re-use or re-occupancy.

It is suggested that widespread use of standardized S2HM systems will provide multiple benefits in the rapid assessment of the extent of the actual impact in terms of post-event management. It will be possible to perform fact-based filtering of suspicious structures that require detailed assessment and prioritization of such assessment amongst a large number of structures. In the meantime, it will be possible to declare many structures as safe or operational within a very short timeframe based on monitored parameters and established criteria.

2. Motivation

In the aftermath of a seismic event, a large demand for information develops. In fact, based on such demand, a number of world-renowned earthquake information and notification services have been established, such as the one developed by European-Mediterranean Seismological Centre (EMSC) [1], which basically operate on geographic profiling of digital witness manifestations or footprints such as on search engines, social media, etc. The recent 24 January 2020, Elazığ, Turkey, Mw6.8 earthquake well demonstrates how such demand helps EMSC to create intensity maps by using contributions in terms of felt-reports, as shown in Figure 1.



(a) (b)

Figure 1. (a) Contribution map and (b) Intensity map, based on felt reports of the 24 January 2020, Elazığ, Turkey earthquake [2]

The demand for information is not only based on simple curiosity but also on the need of understanding whether any risk or safety concern is associated with such an event. Particularly for any structure, the concerns are associated with the safety level of the structure regarding the continued usage or occupancy after the event.

The ultimate post-event safety level regarding any suspicious structure can be evaluated only by structural experts' inspection or analysis which may last for days or weeks per structure. However, once safety becomes questionable – especially after a significant event, the response time is of great essence in terms of reducing consequences of downtime of any structure. Therefore, the majority of emergency management plans include rapid assessment procedures for identifying clearly safe structures. Such rapid assessment procedures involve, as a minimum, a physical walk-through and visual (thus in part subjective) inspection of the structure by experienced personnel and may still take up to a few days per structure [3]. The planning of such an assessment campaign can be a very challenging task in the wake of a significant event and its execution can span a long period of time depending on the number of structures to be evaluated and on the number of available personnel, hence the assessment may no more be sufficiently "rapid". In addition, it is well possible that rapid – one time – assessments based on subjective evaluations may not be ultimately valid, for example regarding any aftershocks of a significant earthquake or other natural or man-made hazards. For example, after the 4 September 2010, Canterbury, New Zealand Mw7.1 earthquake and the following significant ground motions known as "Canterbury earthquake sequence", the access restrictions to parts of Christchurch's central business district were in place for up to two years later [4]. Based on a comprehensive survey conducted during the following year from May to September 2011, one of the most frequently (57%) cited reasons for temporary or permanent closure for the industry was reported to be "building waiting to be structurally assessed" [5].

On the other hand, if a widespread deployment of S2HM systems can be realized within a region, this will facilitate reaching to rapid assessment conclusions within a matter of minutes, and will be based on actual measured data and established and proven methods. Furthermore, such systems will continuously perform assessments before, during and after any event – basically all the time, perpetually.

A good example for a universally established worldwide status and performance monitoring system, which almost any person can relate to, is maybe the flight data recorder known as the "black box" in aircraft. Since its early prototypes, the deployment, use, capabilities and benefits of an aircraft black box have significantly expanded and improved. Moreover, these are well told and well understood, promoting the system to be a mandatory component of aircraft [6].

The broad concept of instrumental status and performance monitoring has been in use for about a century for keeping a watchful eye on many man-made structures and structural systems, and it has picked up an increasing momentum in the last few decades in comprehensiveness and intelligence.

S2HM aims to provide information on the status and performance of civil engineering structures under the influence of ground motions associated with seismic events, by utilizing state-of-the-art seismic measuring instruments. One of the most immediate and practical targets in using S2HM systems is to be able to acquire a timely result after a seismic event outlining whether the civil structure is still safe to occupy / utilize, based on actually-measured data.

Seismic instruments, which have been around at least as long as the aircraft black box, are being utilized with increasing success for S2HM, especially by virtue of the recent advances in the science and technology in their features and interpretation of their data. It is however a wonder why such use is not yet as established worldwide as the aircraft black box, although potential benefits of the S2HM seem to be even higher considering the sheer number of civil structures located in high seismic risk areas, serving millions of people on a permanent basis.

There is a vast number of publications regarding the benefits of S2HM systems and perhaps even more on the useful results obtained by in-depth analysis of data for numerous civil engineering structures around the world. Almost all of this research individually focuses on a particular structure and derives conclusions specifically for that structure. This may seem to be a reasonable outcome due to the fact that every civil engineering structure is different, however it does not waive the fact that they may be singular. In terms of design and performance criteria more or less all structures within a same category (i.e. categories like buildings, bridges, dams, etc.) share similar evaluation or monitoring parameters at an engineering level.

Establishing a well-defined set of parameters for monitoring the state and health of structures facilitates providing a quite generic monitoring solution that may be suitable to deploy on any structure within a same category and that furthermore may be quite versatile to adapt to all different categories too.

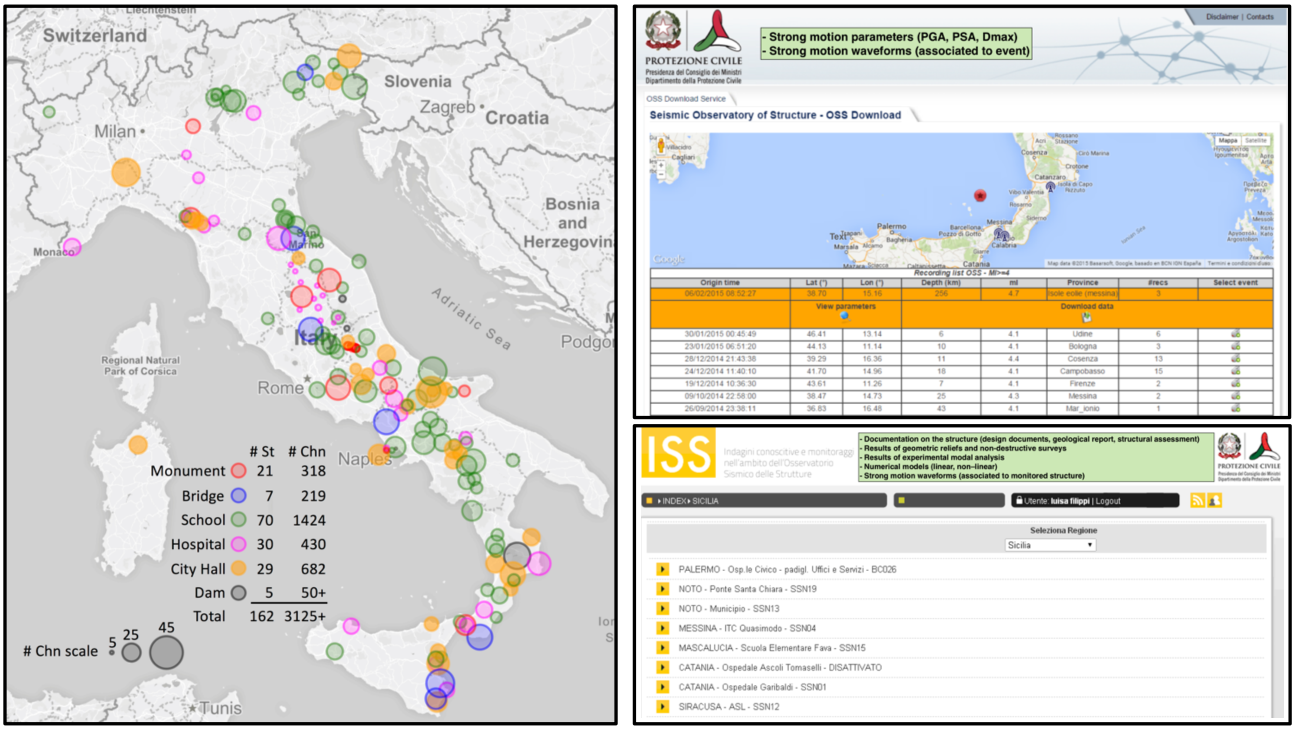
2. European Experience

In Europe numerous civil structures with monitoring systems exist, each having their particular uses and goals. In addition to the fact that such structures are a mere minority of the overall European civil structure stock located in high seismic risk areas, the majority of these systems are very specific to the structure they are installed on; most of the time they are related to research or to a case where very particular features of each individual structure are monitored or analyzed, not necessarily targeted for S2HM.

Except very few examples, there is not an established system requirement or definition towards S2HM, which after a seismic event can provide results that are immediately useable or understandable by the owners, maintainers or decision makers for civil structures.

Government institutions tasked with assuring and sustaining public safety are motivated, mostly due to laws and regulations, to utilize S2HM systems, although very few are organized enough to address the challenge.

One of the most advanced and systematically maintained systems in Europe out of such few examples is the integrated system, Seismic Observatory of Structures (OSS), that is being operated by the Department of Civil Protection (DPC) of Italy [7], which covers a very large number of civil structures instrumented with S2HM systems providing a consolidated and homogenized output and result to the department as well as the public in case of a seismic event.



(a) (b)

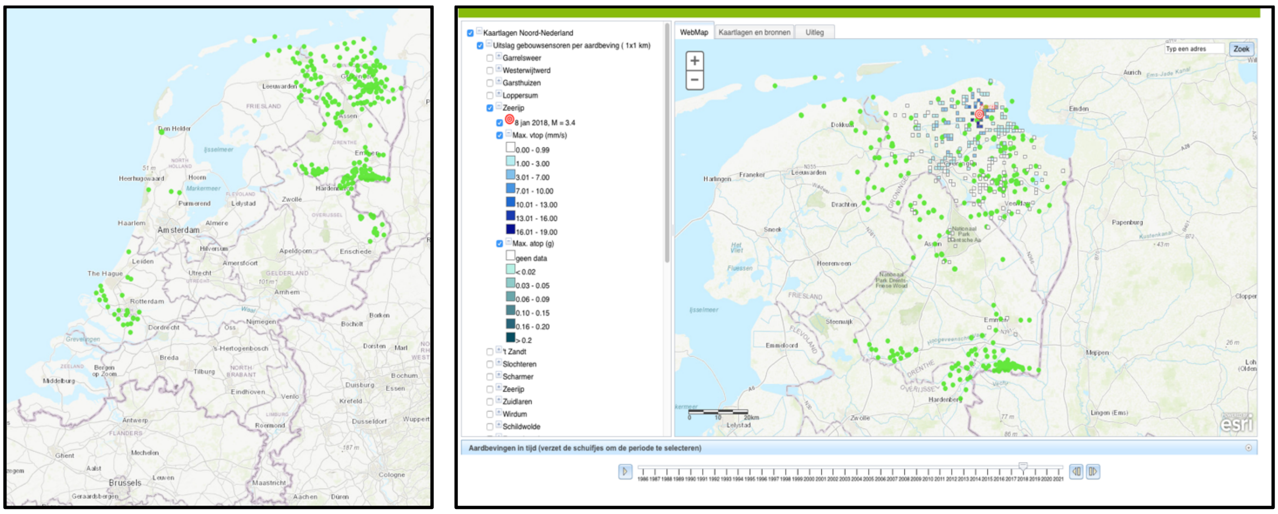
Figure 2. (a) OSS distribution map, where # St: number of structures, # Chn: number of sensor channels. Although three dams are plotted, five are listed based on interaction with DPC. Plotted locations are from officially published data [9], (b) OSS public online reporting interfaces [10] and [11] (requires registration)

As of 2018, 162 structures have been equipped with S2HM systems throughout seismically high-risk areas in Italy as shown in Figure 2.(a), with totally more than 3000 accelerometer channels, sending the recorded ground and structural motion data to the OSS central server in Rome. Within about 20 minutes after a seismic event of magnitude greater than or equal to 4, a report is generated which provides the maximum measured values and various calculated parameters, that represent both the incoming earthquake and the structural response so that the damage distribution can be assessed. The report is distributed via e-mail to DPC and regional administrations, and is also published automatically, together with the recordings, on the public OSS website. In addition to this permanent network, within the first few hours following a significant earthquake, at least four simplified monitoring systems are deployed around the epicentral area and are integrated into the OSS as a temporary network on buildings which are used as co-ordination centers for emergency management [8].

This brings in the question whether the use of such systems in Europe could be widespread enough if they were officially specified such as in building codes via laws or regulations. This presumption is also supported by the fact that there are certain initiatives on the regulatory level, for example in Turkey [12], [13] and Romania [14], to include requirements for S2HM systems into building codes.

However, looking at other European countries, even at ones encompassing high seismic risk zones, currently there does not seem to be any widespread trend to establish and regulate utilization of S2HM systems.

Another impetus for deploying standardized and managed S2HM systems is to address elevated public awareness and concern about seismic risks especially after a disturbing or damaging seismic activity. The Groningen region in the Netherlands can be shown as an example where local residents had elevated concerns about earthquakes induced by reservoir depletion as a result of gas extraction in the region, which introduced a potential safety risk and property damage probability, increasing over the years. Responsible parties including Dutch Petroleum Company (NAM) had to define and execute an extensive action plan to mitigate the impact of production-induced seismicity and to install S2HM systems more than 300 buildings to monitor ground motions [15], [16]. Deployments in town halls, other public buildings and NAM locations throughout the Netherlands are as shown on Figure 3.(a). For privacy reasons, locations of households are not displayed. Evaluations of earthquake damage is conducted in cooperation with the Netherlands Organization for Applied Scientific Research (TNO) by collecting and analyzing the factual and objective data on the relationship between the intensity of the vibrations and the degree of damage that they may cause to the buildings.



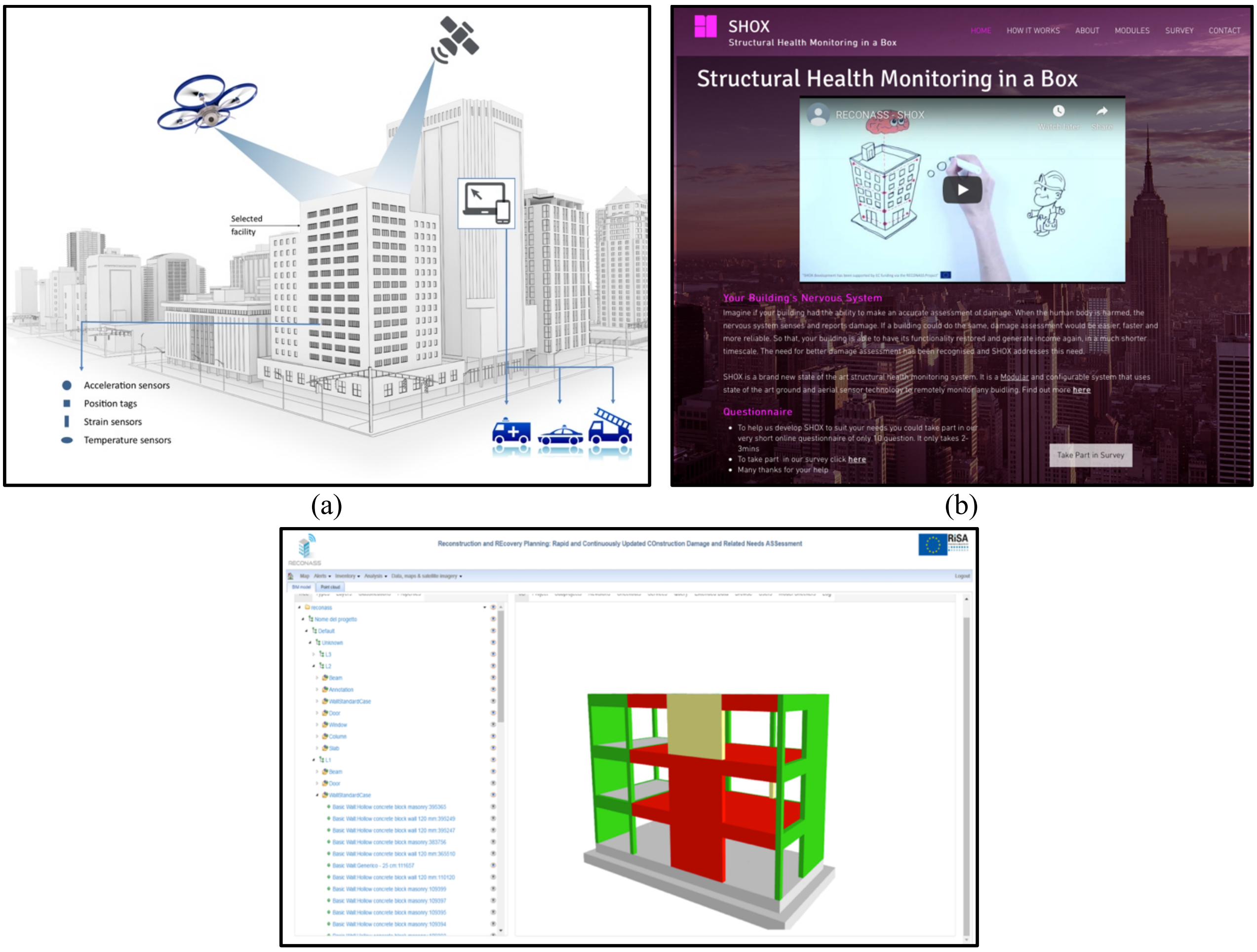
(a) (b)

Figure 3. (a) Station distribution map and (b) Interactive map reporting a M3.4 event from 08. January 2018 with observed maximum velocity and acceleration per square kilometer [17]

3. Other Concerns

Responsibility and accountability seem to contribute to both sides of the motivation / resistance medallion regarding deploying S2HM systems. While the above examples demonstrate how these can contribute to the incentive to deploy a large number of S2HM systems, on the other hand the consequences of overtaking the materialization and products of such systems may put one into reluctance.

One of the main difficulties in deploying S2HM is the requirement of expertise for the definition of the system architecture (how many measuring points are required, what to measure, and so on) for a particular structure. On top of that, interpretation of the data and results obtained from a S2HM system may as well be a burden for end users of the system. The level of uncertainty on the obtained results may at times present itself as another concern while taking a decision to deploy such systems. Furthermore, dealing with the "big data" that may be generated by the system, and the associated data reduction, archival, database implementation per an individual structure or for a very large group of structures, seem to be additional issues to be concerned about while planning for a S2HM system. There are numerous projects under the umbrella of the European Union framework regarding structural monitoring for civil structures, where especially expertise, experience and technology have thrived. Only a few examples were focused towards S2HM, such as RECONASS [18].



(a) (b)

(c)

Figure 4. (a) RECONASS monitoring concept, (b) SHOX, 'Structural Health Monitoring in a Box' solution offered as a result of the project [19], (c) PCCDN Tool developed within the project.

The RECONASS project produced a monitoring system for critical buildings that will provide a near-real time reliable and continuously updated assessment of the structural condition of the monitored building after a disaster. The system uses inputs from in-building sensors; accelerometers, local positioning tags, strain and temperature sensors and the assessment picture is complemented by oblique aerial photography of the damaged building and surrounding area. The observations and outcome of such detailed monitoring is reported by a Post Crisis Needs Assessment Tool in regards to Construction Damage and related Needs (PCCDN tool) which was demonstrated by a destructive (explosion) field test that the proposed system as a whole assesses rapidly the structural condition of the monitored building after a disastrous event. A commercial outcome from the project was the SHOX system as demonstrated on Figure 4.(b). SHOX acts like an aircraft 'black box' or nervous system for a building or structure. It provides a monitoring system for the building or structure in a near real time, reliable manner. It uses deployed sensors to continuously update an assessment of the operational loadings and structural condition of the building, during normal operation and should a disaster occur. In the event of a disaster, it has enough detail to be useful for early and full recovery planning [19].

As an example for standardized solutions; to benefit from the continuous assessment features of the S2HM systems, a five-story industrial building, in Switzerland, was equipped with a streamlined S2HM system consisting of nine acceleration channels and a straightforward software interface, GeoSMART, as shown in Figure 5, [20].

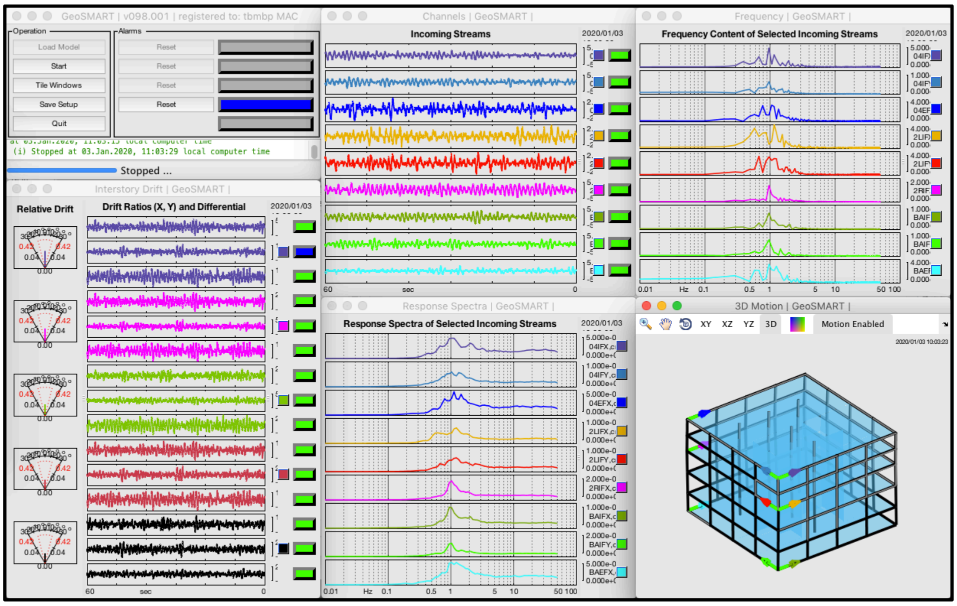


Figure 5. GeoSMART providing continuous structural monitoring and analysis in the real-time; in this example revealing that one interstory drift ratio exceeded a first limit (blue rectangular LED) while all else were within allowed limits (green rectangular LEDs)

The system continuously measures, monitors and evaluates the near real-time response of the building and provides notifications in case any predetermined criteria has been exceeded such as in displacements, interstory drift ratios and rotations or frequency spectrum. Notifications are available locally as visual indicators and physical relay contacts for desired operations, as well as email messages to registered users. In addition, all raw and calculated data are continuously stored and is made available locally and at a remote server for post review and analysis in case of an exceedance or for review purposes.

Another puzzling factor in deciding the deployment of S2HM systems—especially for owners of structures—may be within the circle of privacy, ownership of information and potential risk of reduction in value (due to probable seepage of negative information about the structure's status and health, even if it was not critical in practical terms). Nevertheless, the potential benefits of a potential increase in the value of ownership will remain on the motivating side, where such value can be achieved by being prepared for the aftermath of a seismic event or being able to reap certain benefits from insurance policies on account of being well organized towards any losses due to seismic activity. In this context, insurance companies can improve their customer reach as well as accuracy of their claim assessments by creating incentives to building owners by offering lower premiums if their building is instrumented with standardized S2HM systems. In addition, governments may offer tax incentives if building owners would deploy such systems and the systems would share the collected information with emergency management departments. The result would yield multiple benefits of increased number of factual information helping a better organized disaster management and thereby reduced overall cost and a fair return on investment for all sides.

4. Outlook

A standardized S2HM system / solution should have high reliability, low maintenance, low cost in procurement, installation and operation, while being applicable to a high variety of structures. Ultimately the system has to be capable enough to detect a detrimental influence of a felt seismic activity on the structure, locate where or what parameters such influence has affected, and quantify the extent of the influence, thereby providing a result leading to a competent decision for what action shall be taken. In addition, such a system should be capable to store and safe-keep all the acquired data and any analysis results locally as well as to transmit to authorized recipients, so that verification and exploitation of all the factual information is possible at site and/or remotely. A fundamental advantage of having such standardized systems will be to largely improve and facilitate the process of critical decision making based on unambiguous, reliable and objective data, rather than subjective observations.

Moving forward, with all the accumulated improvements in technology and know-how in the instrumental monitoring field, it seems plausible to devise a standardized structural safety assessment system, a "Structural Black Box", that consists of a package providing a basic S2HM solution assorted depending on various structure categories it may be deployed on, from its architecture to its output. Sustained and continuously improved by a close cooperation, consultation and contribution of world-class seismic, structural and earthquake engineering experts as well as industry leaders, the system(s) shall provide, through a guided and intuitive interface, all the tools to advise and facilitate the system design and deployment, shall perform all the necessary calibration, data acquisition, storage and processing, as well as in case of a seismic event shall output reports, notifications and useful data, as much automated and streamlined as possible with minimal maintenance. The ultimate target is to establish an internationally standardized S2HM system that can feasibly and reliably declare that structural safety is a) intact or b) questionable and facilitate rapid safety assessments.

Commercial availability of such streamlined systems will not only remove the majority of the significant burdens in front of achieving a widespread use of S2HM, but will promote them by demonstrating their capabilities and advantages to achieve success similar to that of the example of the airplane black box.

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