Urban-Scale Earthquake Risk Management Utilizing Structural Health Monitoring Technology

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Abstract. With the adoption of the Sendai Framework for Disaster Risk Reduction at the United Nations Disaster Risk Reduction Conference in 2015, an important step was taken toward creating more resilient cities. For cities under high seismic risk, the most important gaps in the implementation of the risk management processes are the uncertainties and lack of recorded data, before, during, and after the earthquake. Real-time data is needed to determine the status of the existing building stock, to create seismic risk and shake maps, and to evaluate the situation rapidly during the disaster coordination and after the earthquake for achieving a rapid comeback to the normal flow of life. Structural Health Monitoring (SHM) is the technological decision support system that helps to monitor, analyze and report the structural integrity and the damage condition of civil engineering structures with the help of sensors against earthquakes and other destructive causes. The most innovative part of the SHM arises from the dynamic identification of a structure under ambient vibration in real-time, using ultra-sensitive accelerometers. A rapid change in the characteristic response of the building is usually accepted to be an indicator of damage, revealing the loss of structural integrity and stiffness. It is possible to compare the dynamic response of the building just before and after an earthquake to form the most rapid data-driven approach to support decision-makers, building owners, engineers, and people in charge of disaster management. Even though the SHM solution is adopted for high-rise buildings and other critical structures mostly in recent building codes, generally the greater number of low to mid-rise older buildings lies in the higher risk group. It is feasible to monitor these buildings even with one to three triaxial ultra-sensitive accelerometers. This gives the great opportunity to monitor a greater number of buildings cost-effectively. With the effective utilization of SHM technologies, it is possible to acquire the essential real-time to manage the disaster in a data-driven manner. In this study, a three-component technology-based, holistic method is proposed, to increase urban resilience and effectiveness in earthquake risk management.

Keywords: urban resilience, earthquake risk management, resilient cities, seismic rick, structural health monitoring, accelerometer, operational modal analysis

1 Disaster Risk Reduction – Resilient Cities

1.1 UN Sendai Disaster Risk Reduction Framework (2015-2030)

With the adoption of the Sendai Framework for Disaster Risk Reduction at the United Nations Disaster Risk Reduction Conference in 2015 [1], an important step was taken towards creating more resilient cities. The concept of urban resilience includes combating the destructive social, economic and psychological effects of disasters, assuring the fastest response time, and efficient post-disaster reconstruction and adaptation processes in order to ensure rapid comeback to the normal flow of life. The Sendai Framework outlines seven clear targets and four priorities for action to prevent new and reduce existing disaster risks: (i) Understanding disaster risk; (ii) Strengthening disaster risk governance to manage disaster risk; (iii) Investing in disaster reduction for resilience and; (iv) Enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation and reconstruction.

1.2 Seismic Risk & Resilience

The recent earthquakes in 2023, in Kahramanmaraş, Türkiye, Pazarcık(Mw 7,8) & Elbistan(Mw 7,5), once again showed the difficulties in struggling with the painful results of the disaster. More than 50.000 people in Türkiye, were reported to be dead, more than 500.000 buildings collapsed or were damaged, and about 14 million people are estimated to be seriously affected by the earthquake, in eleven cities. Many people were economically affected, lost their homes, workplaces or jobs, many industrial facilities quitted production, all also ending up with negative psychological effects. For the authorities and voluntary help organizations, difficulties aroused in managing the first 48 hours of the crisis and identifying the damage level of the buildings.

For cities under high seismic risk, the most important gaps in the implementation of risk reduction, crisis management and recovery processes are the uncertainties and lack of data before, during and after the earthquake. Real-time data is needed to determine the status of the existing building stock, to create more accurate seismic risk and real-time shake maps, to evaluate the situation rapidly for well-targeted disaster coordination and to fasten the recovery processes after the earthquake.

1.3 Increasing the Capabilities for Seismic Risk Management

Past experience has shown that urban transformation, strengthening or reconstructing the huge number of building stock under high risk is not a quite feasible process in terms of time and finance. Additionally, Kahramanmaraş earthquakes have shown even the younger buildings, assumed to be constructed in-line with the recent earthquake building codes may carry the collapse risk. Although the final target should be increasing the weight of risk management instead of crisis management, the current situation implies the importance of increasing the abilities for the following steps:

1)Pre-earthquake risk management & early diagnosis

2)Well-targeted management of the earthquake moment and the first 48 hours after the earthquake

3)Post-earthquake management (Recovery-rapid comeback to the normal flow of live)

All three steps can be divided into other sub steps:

For the first step, pre-earthquake stage, obviously strengthening, re-construction, and urban transformation is important. In practice this is not an easy process, considering time and financial resources. The risk zones and buildings should be prioritized with rapid, but more accurate scanning and investigation methods. Another important need is more accurate and localized analysis of the dynamic characteristics of the soil. Micro-zoning is important at that point. This will lead to more accurate seismic risk maps & design response spectrums. Additionally, even if a building is strengthened or constructed according to latest earthquake building code, past experience showed that this does not ensure the building will not collapse in case of a major earthquake. Checking and monitoring the condition of the newly constructed or strengthened buildings is also quite important. Otherwise, there will be a risk to lose the effectiveness of urban transformation against all the valuable efforts and resources spent.

For the second step, management of the valuable first 48 hours after an earthquake, certainly coordination of resources like rescue teams and equipment is of major importance. However, another important parameter is prioritizing the rescue efforts. For a well-targeted disaster management, more data from the earthquake zone should be gathered in real time. Rapid evaluation of the condition status of the critical pathways, gathering locations, critical buildings, disaster management centers, hospitals, as well as real-time shake intensity maps are considered to be the valuable inputs for crisis management.

Third step, rapid comeback to the normal flow of life is quite important for recovery. This step is vital for decreasing further life or health loss due to post-disaster effects, like fires or diseases arising for the elongated time of living in temporary shelters. Decreasing the interruption time of industrial facilities and workplaces is important to recover the economic losses. This step is also important for reducing psychological effects. For this, risk and damage status of the suspicious buildings should be evaluated in the shortest time possible.

1.4 Technological Approach to Increase Seismic Resilience

Considering all the steps described above, it is possible to develop a quite effective earthquake risk management methodology utilizing the recent technological developments, besides urban transformation, better construction and strengthening efforts. In this study, a holistic approach is proposed utilizing the real-time structural health monitoring technology, depending on dynamic analysis & identification, mainly. First the functionality and current possibilities regarding structural health monitoring technology are examined in the next 2 sections.

2 Structural Health Monitoring

2.1 Definition and Scope

Structural Health Monitoring (will be abbreviated as SHM) is the technological decision support system that helps to monitor, analyze and report the structural integrity and the damage condition of civil engineering structures by the help of sensors against earthquakes and other destructive causes. By the start of 21st century, the technological developments caused an evolution both at number and scope of Structural Health Monitoring applications. This development also paved the way for structural health monitoring to be one of the most realistic techniques for studying the dynamic behavior of the structures, moving the civil engineering laboratories to real-world, and monitoring the health of a building in real-time.

Although the sensors & instrumentation may change from structure to structure, nearly all types of civil engineering structures like high-rise buildings, hospitals, residential & office buildings, hotels, bridges, viaducts, tunnels, airports, industrial & power plants can be monitored by SHM solutions.

2.2 Operational Modal Analysis, Dynamic Identification, Real-Time Monitoring

Most innovative part of the SHM arises from the dynamic identification of a structure in real-time, using ultra-sensitive accelerometers under ambient vibration (daily micro-scale vibration excitation, generally unsensed by human beings). The structure responds to these minor vibrations by oscillating according to its natural frequencies. It is possible to identify the dynamic characteristics of the building like natural frequencies, mode shapes and damping ratios using operational modal analysis technique. A rapid change in the characteristic response of the building is generally accepted to be an indicator of damage, revealing the loss in structural integrity and rigidity. In this way, it becomes possible to compare the dynamic response of the building just before & after an earthquake in matter of hours, in order to form the most rapid data-driven basis to support decision-makers, building owners, engineers and people in charge of the disaster management.

Çelebi [2] emphasizes the importance and positive contribution of seismic monitoring and accelerometer based structural health monitoring applications on buildings, describes the methods and recommends common 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.

2.3 Theory & Practice for SHM under Ambient Vibration

Álvaro Cunha et al [3] 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. Operational modal analysis is also called as ambient vibration testing as only the measurement of reactions are targeted under little daily vibrations. In this way it is possible to stay in the operational systematic of the structure and there is no need to externally force it. (See Fig. 1) On the other hand ultra-low noise and high precision accelerometers are required for being able to measure and acquire this micro-g level vibrations especially on buildings, in this technique.

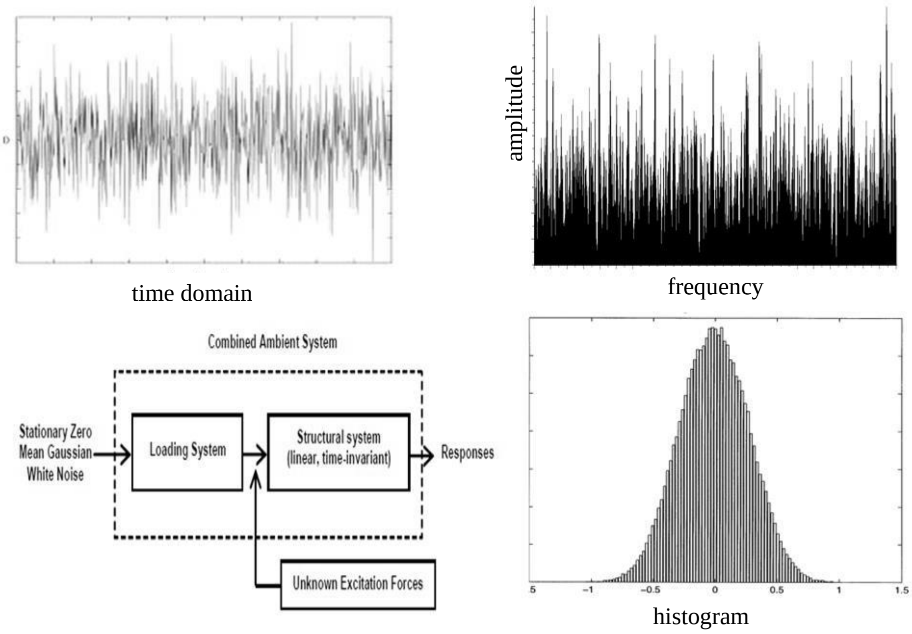

Fig. 1. White-noise, time/frequency domain, histogram, combined ambient system

At the analysis stage, besides simple peak picking, advanced techniques are proposed. Frequency Domain Decomposition-FDD [4] in frequency domain and Stochastic Subspace Identification (SSI) [5] in time domain are two of the most preferred techniques.

For relatively rigid structures like buildings, less than 120-160 dB (dynamic range) accelerometers would be useless for ambient monitoring. There are a number of experimental researches [6], [7], [8] on ambient vibration testing conducted with the accelerometers of this dynamic range and noise level. For more flexible structures like bridges, there are well examples [9], [10] that even 100 dB sensors lead to meaningful data.

2.4 Effective Utilization of Natural Frequency Analysis Depending on the Previous Studies Conducted by TDG under Ambient Vibration

TDG delivered many SHM projects in last 15 years. Acquired instrumentation experience has been shared in previous studies [9], [11]. Additionally, three other important studies conducted by TDG are as follows:

Natural Frequency Shift of a Damaged Building in İstanbul. TDG has conducted a special experimental program in order to observe the natural frequency shift of a building induced by damage in Kartal, Istanbul, in 2013. 2 identical buildings were selected in a demolishing area. The first one was undamaged and selected as the reference building. The second was controllably weakened by hammering of selected columns and infill walls, before demolishing of the building by implosion. (See Fig. 2)

Fig. 2. Left: Undamaged – selected as the reference Right: Controllably Damaged – selected to observe the shift in the natural frequency

The natural frequencies of both building have been measured under ambient vibration using TDG-eQUAKE strong motion recorder which included a triaxial 140 dB dynamic-range accelerometer. (See Fig. 3)

Fig. 3. Ultra-sensitive eQUAKE acceleration recorder glued to the rigid floor area at 6th floor and exactly to the same location in both buildings

One-hour long acceleration data were recorded at both buildings under ambient vibration. For natural frequency analysis, the acceleration time domain was transformed to frequency domain using Power Spectral Density (PSD). Significant natural frequency shift (33%) was observed in both 1st and 2nd modes especially in the East-West direction, in which the controlled damage was targeted by the demolishing company. (See Fig. 4) In N-S direction the natural frequency shift was observed as 6%.

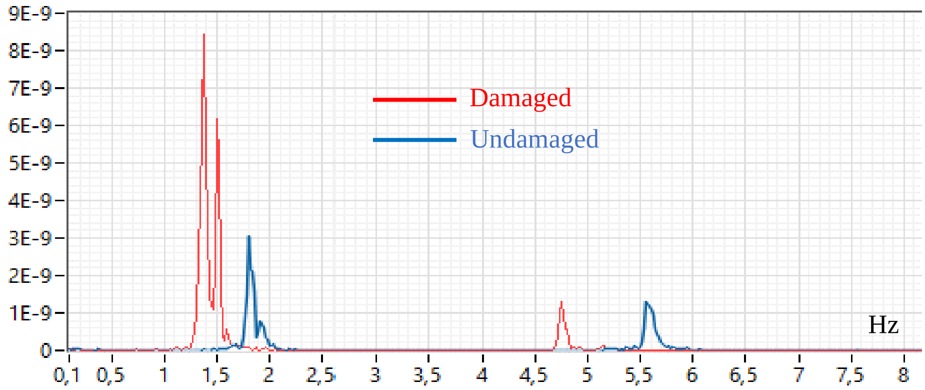

Fig. 4. 33% natural frequency shift in both 1st and 2nd modes due to induced damage (PSD of the Recorded Acceleration)

Before-After Comparison, Just After An Earthquake in İstanbul. Just after the İstanbul Earthquake 26 September 2019 – M5.8, TDG analyzed and reported the natural frequencies of a high-rise building in İstanbul in one hour's time, by comparing 1 hour long-data just one day before the earthquake and just after the earthquake, recorded at the same hour of the day (ambient vibration). The comparison revealed that there was no significant frequency shift observed in neither mode. (See Fig. 5)

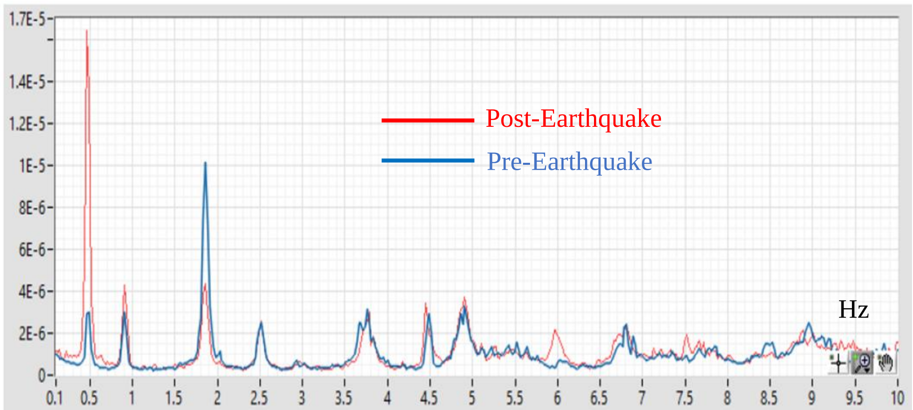

Fig. 5. Before and after comparison. Natural frequencies of the high-rise building (Fast Fourier Transform of the Recorded Acceleration under ambient vibration)

Long-Term Monitoring for Fatigue and Aging Analysis. It is possible to observe degradation in the stiffness of a structure in time due to fatigue, aging, wind loads or past earthquakes the structure has been exposed to. Although in bridges the fatigue effect is more obvious due to cycling traffic and wind loads, the degradation is also possible for aged buildings. TDG has been monitoring a high-rise building in Istanbul for about 5 years and 6 months. The recorded total monthly acceleration data has been transformed into frequency domain using FFT. In this way a single average monthly natural frequency value has been obtained for each mode, and for each and every month, a total of 66 months. (See Fig. 6) It is possible to make comments on the condition of the building using this valuable data. The limited up and down shifts of the natural frequencies obviously implies the probable effect of seasonal temperature changes. For the first mode no degradation in the stiffness was observed, and the average monthly natural frequency of the building always returned back to the original value. For the second mode there is a little downside shift trend. For the 3rd and 4th modes this trend is again limited but slightly higher when compared to 1st and 2nd mode. In order to decide to the needs for the necessary precautions like repairing or strengthening, this data can be analyzed further by the design engineers in charge. It is possible to conduct a finite element model update according to the measured data. Afterwards, the possible current risk level can be analyzed according to updated computer model in line with the measured data.

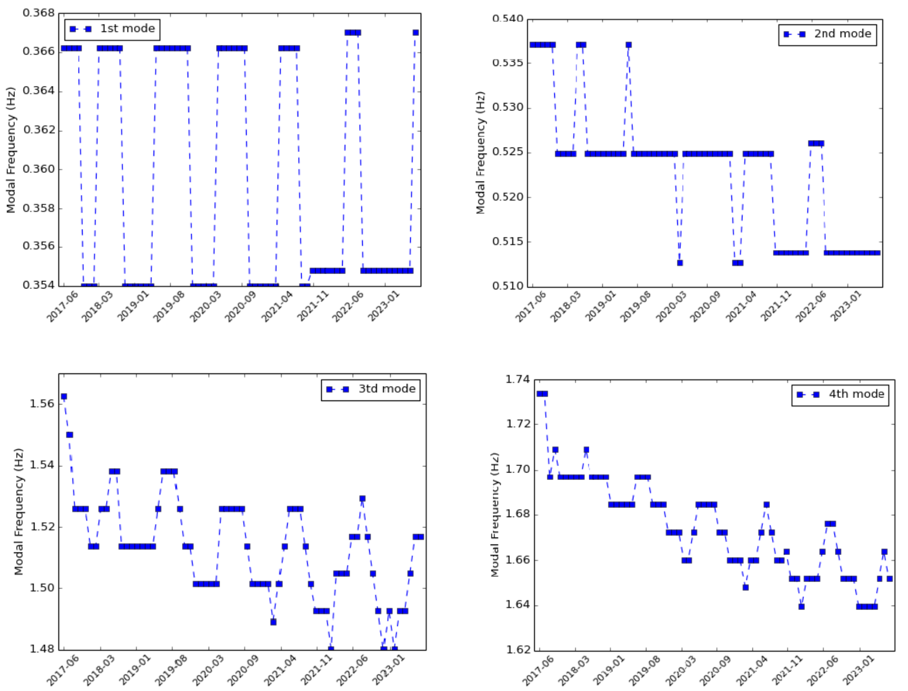

Fig. 6. Monthly average natural frequencies of a high-rise building for first 4 modes, and for 66 months under ambient vibration

Among many analytical and experimental studies in this area, the above 3 studies by TDG, prove once again that, the natural frequency monitoring (real-time dynamic identification) is one of the most effective, rapid and useful tools for the damage and risk assessment of civil engineering structures against earthquakes and other destructive causes.

2.5 SHM in Building Codes and Regulations

There are descriptions and directions about seismic instrumentation and application of accelerometers at high-rise buildings both at San Francisco Building Code [12] and Los Angeles Tall Buildings Structural Design Council Consensus Document [13]. Guidelines and Implementing Rules on Earthquake Recording Instrumentation for Buildings [14] defines the Structural Health Monitoring standards for high-rise buildings (above 50 meters) in Philippines. Strong Motion Instrumentation of buildings in New Zealand is summarized by Deam and Cousins [15]. Section 13.8 of Turkish National Earthquake Building Code (2019) published by Disaster Management Authority of Turkey (AFAD) brings the obligation to health monitoring of high-rise buildings above 105 meters and the detailed design guidelines for instrumentation of high-rise buildings were published in 2020 [16]. This final instrumentation structural health monitoring guideline in Turkey, requires a minimum number of 16, 24 and 36 accelerometers respectively for buildings 105 to 155, 156-205 and above 205 meters high.

3 Compact & Optimum Solution for More Extensive Utilization of SHM

3.1 Building Stock under High-Risk

Even though SHM solution is currently being adopted for high-rise buildings mostly in recent building codes, generally the greater number of low to mid-rise older buildings lies in higher risk group. These buildings have lower number of significant mode shapes and the first 3 modes (x,y bending & torsion) generally determines the dynamic behavior. It is possible to monitor these mid-rise buildings even by a few (1-3 units of) tri-axial ultra-sensitive accelerometer(s), installed to the top and the foundation of the building. This gives the great opportunity to monitor greater number of buildings under high risk, in the most cost-effective way. In this method, it is important to keep or even increase the sensitivity level of the accelerometer (>150-160 dB dynamic range), as lower buildings are even more rigid than the high-rise ones, and thus the excited acceleration levels under ambient vibration are even lower when compared to high-rise buildings.

3.2 Case Studies for Compact Structural Health Monitoring

TDG installed compact health monitoring systems to low-mid size buildings in last 5 years. The effective and practical results of two of these studies are shared in this section.

Monitoring of a 5-Story Office Building with A Single Triaxial Accelerometer. The following 5-story office building in Ankara has been monitored for last 5 years with a single triaxial ultra-sensitive (>160 dB dynamic range) accelerometer under ambient vibration. (See Fig. 7) The accelerometer was located eccentrically to detect the torsional frequency as well as the bending modes in x and y direction.

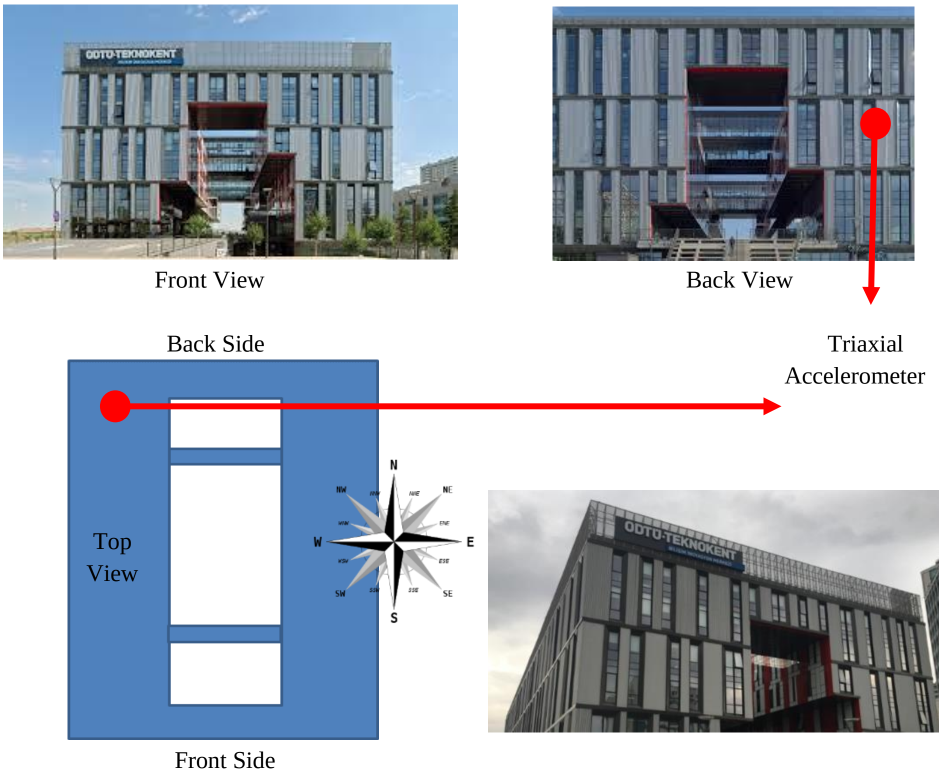

Fig. 7. The five-story building monitored with a single triaxial accelerometer and the sensor location

Power spectral density (PSD) graph of the measured acceleration under ambient vibration in presented below. (See Fig. 8) As it can be followed from the PSD graph, it is possible to detect and differentiate between the first 3 modes with even with a single ultra-low noise accelerometer. The bending modes about E-W and N-S directions can be differentiated easily and measured as 1.42 and 1.66 Hz respectively. The third mode which is detected by both lateral perpendicular accelerometer components and coincide at the same frequency is concluded to be the torsional mode and measured as 3.77 Hz.

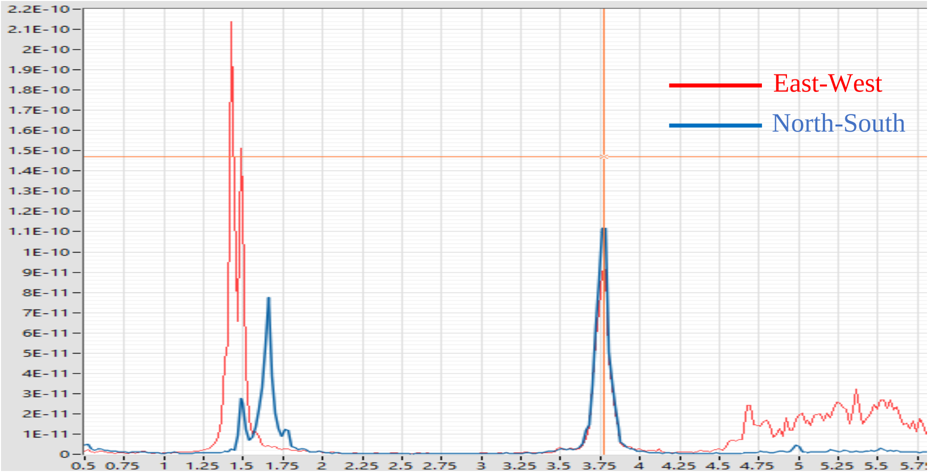

Fig. 8. PSD graph, natural frequencies corresponding to first 3 modes of the building

Monitoring of a 3-Story School Building with Three Triaxial Accelerometers. The following 3-story school building in İstanbul has been monitored for last 3 years with three triaxial ultra-sensitive (>160 dB dynamic range) accelerometers under ambient vibration. (See Fig. 9) The aim to install an accelerometer (1) at the ground level, was to measure the accelerations, earthquake intensity and the ground level displacements in case of an earthquake. Second accelerometer at the same vertical axes(central) at the top level (2) aimed to record the top-level accelerations and displacements in case of an earthquake, and calculating the inter-story drift ratios in combination with the ground level sensor (1). Obviously, the aim of the third accelerometer (3), which was mounted eccentrically, was to detect the torsional mode for the building.

Fig. 9. The three-story school building and the triaxial accelerometer locations

Power spectral density (PSD) graph of the measured acceleration (accelerometer 2) under ambient vibration in presented below. (See Fig. 10) As it can be followed from the PSD graph, it is possible to detect the first 4 modes (2 bending modes in each axis- E-W/N-S) with even with an ultra-low noise accelerometer.

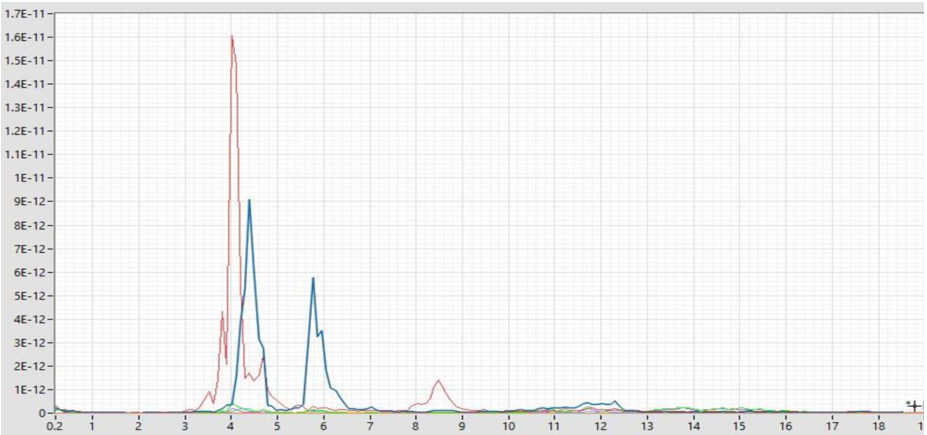

Fig. 10. PSD graph, natural frequencies corresponding to first 4 bending modes of the building

The 2 studies mentioned above shows that, for low to mid-size buildings, it is possible to carry out a basic level of real-time natural frequency monitoring under ambient vibration even with 1-3 ultra-sensitive accelerometers.

4 Proposed Method for Urban Scale Earthquake Risk Management Utilizing SHM Technology

4.1 General Description of the Method

Real-time data and rapid analysis tools are needed for determining and monitoring the status and the risk condition of the existing and new building stock, developing a data-driven urban transformation plan, updating seismic risk maps, and evaluating the situation rapidly during the disaster coordination and providing rapid recovery after the earthquake. With the effective utilization of structural health and vibration monitoring technology, it is possible to acquire the essential data in real-time, to manage the disaster risk and the crisis in a measurement/data-driven manner. For this, a three-component technology-based, holistic method is proposed, to increase urban resilience and effectiveness in earthquake risk management, and minimize the negative results. (See Fig. 11). The effectiveness of this method comes from the utilization of an intersected set of instrumentation leading to an internet of things (IoT) ecosystem. Sensors and instruments in each component contribute to all three components. This method is proposed as a decision support system for the authorities in charge and the building owners.

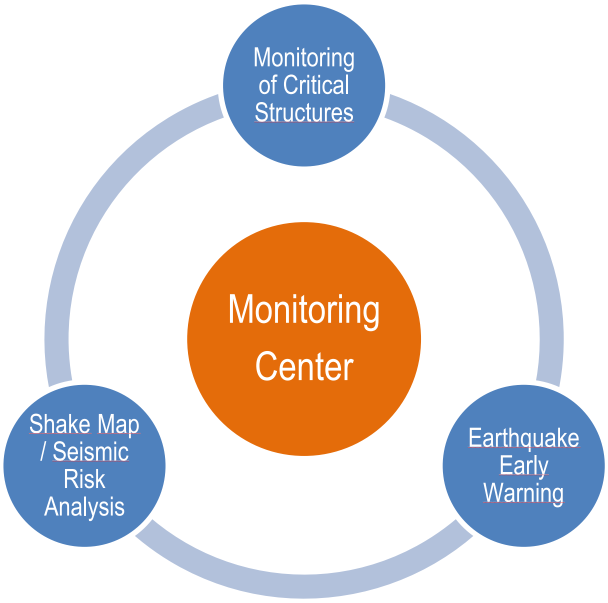

Fig. 11. General scheme of the proposed method

4.2 Monitoring of Critical Structures (Component 1)

By installing sensors, mainly accelerometers to critical structures and infrastructures, like public buildings, hospitals, pass ways (bridges, viaducts, tunnels), emergency coordination centers, data centers, the integrity of these structures can be monitored 24/7 in real-time. In time of an earthquake, these critical structures should be rapidly ensured for safety and continue to uninterrupted service.

A decision support system can facilitate damage analyses and coordination processes after a major earthquake. Furthermore, it is possible to involve increased number of monitored buildings by the help of compact structural health monitoring methodology described in Section-3. By installing 1-3 ultra-sensitive accelerometers to low-mid rise buildings such as apartments, work places, schools, dormitories, shopping centers, industrial facilities, it is possible to keep much more people safer, furthermore to get higher efficiency for the other components mentioned. This contributes to early diagnosis of building degradation, rigidity loss or unexpected behavior in the pre-earthquake risk management phase. In the crisis management phase, well-targeted disaster management would be possible by detection of the most effected regions, intensity levels and even quick determination of risky and suspicious buildings. This would also be quite effective for post-earthquake recovery phase, by utilizing rapid before and after comparison tool and further analyses providing rapid comeback to the normal flow of life. (See Fig. 12)

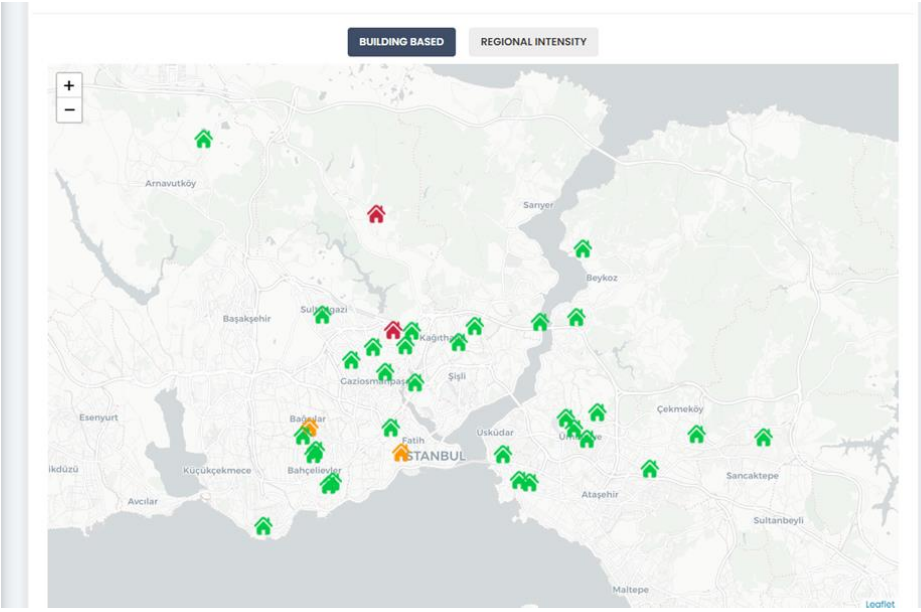

Fig. 12. Expected outputs of common monitoring of structures

4.3 Shake Maps, Micro Zoning, Seismic Risk Analysis (Component 2)

The second component is the creation of city-wide real-time shaking intensity maps. In this way, micro-scale seismic risk maps can be created. High-resolution real-time shake maps also contributes to the micro-zoning measurements, more accurate design response spectrums and hence supports urban transformation planning. The accelerometers installed to the foundations of the buildings mentioned in Component-1 would also contribute to this part. (See Fig. 13)

Fig. 13. Expected outputs of shake/intensity maps in case of an earthquake

4.4 Earthquake Warning System (Component 3)

The third component is the Earthquake (Early) Warning System, which has many successful examples worldwide (Japan, China, Mexico, United States of America). It is possible to get a more reliable warning system with higher number of sensitive accelerometer nodes spread over the region as mentioned in Component-1. Functionality can be increased by placement of ground motion recorders in specific areas and around the city (closer to fault-lines).

4.5 Monitoring Center (Coordination)

For coordination of these three components, a Structural Health and Earthquake Monitoring Center should be established in the city/region. This center will ensure the effective coordination, management and transferring the results of the first three components to the public.

5 Summary and Conclusion

Effective use of recent technologies will contribute to establishment of a data/measurement driven real-time approach for seismic risk management. In this study, the struggles against risk & crisis management in case of a major earthquake are discussed in detail, in the context of UN Disaster Risk Reduction Sendai Framework and concept of seismic resilience. The rapid and practical uses of SHM technology are examined based on both past experimental studies in the literature and TDG monitoring experience. Furthermore, the results and observations based TDG experimental studies are presented to utilize this technology more extensively for low to mid-size buildings. Finally, a simple but effective methodology is proposed depending on structural health and vibration monitoring. The outputs and conclusion of this study can be summarized as follows:

SHM (Structural Health Monitoring) based on accelerometers is adopted as a technological way to monitor the dynamic behavior & condition of structures in real-time in recent codes and regulations.

Natural frequency monitoring, operational modal analysis, and complementary analyses based on dynamic identification under ambient vibration provides an effective and rapid decision support tool for the risk and damage assessment of the buildings.

Furthermore, it is possible to utilize this tool to monitor a higher number of low to mid-size buildings which lie in the high-risk group in a cost-effective way.

Strategic use of SHM can help to accelerate the resilient city concept, in terms of managing the pre-disaster risk effectively, contributing to the management of the first hours and days in case of a major earthquake. Additionally, this technology facilitates the recovery time, in terms of rapid comeback to the normal flow life, reduced economic losses and hence decreased psychological effects, by providing rapid decision support data to damage and risk assessment of the buildings.

Technological and data-driven urban scale disaster risk management is possible with a three-component methodology using shared instrumentation network: (i) SHM of critical buildings and infrastructure (administrative buildings, schools, hospitals, bridges, low to mid-rise buildings), (ii) real time shake/intensity maps, accurate seismic risk analysis and micro-zoning, (iii) earthquake early warning

City based monitoring centers are essential for coordination and a fully functional solution.

This methodology has the potential to provide the valuable and unique data for future urban planning & transformation, regulations, and academic research.

References

1. UNDRR Homepage, https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030, last accessed 2023/08/28.
2. Çelebi M (2002) Seismic Instrumentation of Buildings (with Emphasis on Federal Buildings). Special GSA/USGS Project –USGS Project No-0-7460-68170 GSA Project no: ZCA72434
3. Cunha A, Caetano E, Magalhães F, Moutinho C (2006) From Input-Output to Output-Only Modal Identification of Civil Engineering Structures, SAMCO Final Report 2006 F11 Selected Papers
4. Brincker R, Zhang L, Andersen P (2001) Modal identification of output-only systems using frequency domain decomposition, Smart Materials and Structures, 10 (3): 441
5. Peeters B, Roeck G (2000) Reference-Based Stochastic Subspace Identification for Output-Only Modal Analysis, Mechanical Systems and Signal Processing (1999) 13(6), 855-887
6. Soyöz S, Taciroğlu E, Orakcal K, Nigbor R, Skolnik D, Luş H, Şafak E (2013). Ambient and Forced Vibration Testing of a Reinforced Concrete Building before and after Its Seismic Retrofitting, Journal of Structural Engineering 139(10):1741-1752
7. Şafak E, Çelebi M (1991) Analyses of recorded responses of two high-rise buildings during the Loma Prieta earthquake of October 17, 1989, Bulletin of Seismological Society of America, Special Issue on the 1989 Loma Prieta, California, earthquake and its effects, October 1991, 2087-2110.
8. Soyöz S, Feng MQ, Shinozuka M (2010) Structural Reliability Estimation with Vibration-based Identified Parameters, Journal of Engineering Mechanics, ASCE, 136 (1), 100-106.
9. Dincer S, Aydın E, Gencer H (2019) Recent Instrumentation, Software and Analysis Practices in Structural Health Monitoring In: Proceedings in 5ICEES Fifth International Earthquake Engineering and Seismology pp.74-83, Ankara
10. Pakzad SN, Fenves GL, Sukun K, Culler DE 2008 Design and Implementation of Scalable Wireless Sensor Network for Structural Monitoring, Journal of Infrastructure Systems, Vol 14 Issue 1
11. Aydın E, Dinçer S, Turfan M (2022) Detection of Strand Natural Frequencies and Vibration Levels Using MEMS Accelerometers Before and After the Installation of Tuned Mass Dampers for a Stayed Cable Bridge In: İstanbul Bridge Conference Paper ID37, İstanbul
12. San Francisco Building Code (2014) AB058. Building Seismic Instrumentation- Procedures for Seismic Instrumentation of New Buildings
13. Los Angeles Tall Buildings Structural Design Council (2008) An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region

14. Guidelines and Implementing Rules on Earthquake Recording Instrumentation for Buildings (2015) Philippines DPWH Homepage, http://www.dpwh.gov.ph/dpwh/references/guidelines_manuals/earthquake_recording, last accessed 2023/08/28.
15. Deam, BL, Cousins, WJ (2002) Strong-motion instrumentation of buildings in New Zealand" NSZEE Homepage, https://www.nzsee.org.nz/db/2002/Paper23.PDF, last accessed 2023/08/28.
16. AFAD Homepage, https://www.afad.gov.tr/kurumlar/afad.gov.tr/Mevzuat/Yonergeler/Bakan_Onayli_YSIS_Yonergesi_1_.pdf , last accessed 2023/08/28.