POLITECNICO DI TORINO
Repository ISTITUZIONALE

Present and future resilience research driven by science and technology

Original
Present and future resilience research driven by science and technology / Domaneschi, Marco; Cimellaro, Gian Paolo; Xie, Lili; Bruneau, Michel; Wu, Zhishen; Didier, Max; Noori, Mohammad; Mufti, Aftab; Lu, Xilin; Lu, Xinzheng; Ou, Jinpin; Sheikh, Shamim; Zhou, Ying; Yoda, Teruhiko; Taciroglu, Ertugrul; Häring, Ivo; Sextos, Anastasios. - In: INTERNATIONAL JOURNAL OF SUSTAINABLE MATERIALS AND STRUCTURAL SYSTEMS. - ISSN 2043-8621. - ELETTRONICO. - 5:1/2(2021), pp. 50-89. [10.1504/IJSMSS.2021.115783]

Availability:
This version is available at: 11583/2857039 since: 2021-08-17T01:10:39Z

Publisher:
Inderscience

Published
DOI:10.1504/IJSMSS.2021.115783

Terms of use:
openAccess

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

08 November 2022

Present and future resilience research driven by science and technology

Marco Domaneschi[1], Gian-Paolo Cimellaro[1], Lili Xie[2], Michel Bruneau[3], Zhishen Wu[4], Max Didier[5], Mohammad Noori[6], Aftab Mufti[7], Xilin Lu[8], Xinzheng Lu[9], Jinpin Ou[10], Shamim Sheikh[11], Ying Zhou[12], Teruhiko Yoda[13], Ertugrul Taciroglu[14], Ivo Häring[15], Anastasios Sextos[16]

[1] *Department of Structural, Geotechnical and Building Engineering (DISEG), Politecnico di Torino, Turin, Italy*

[2] *Institute of Engineering Mechanics (IEM), China Earthquake Administration (CEA), China*

[3] *Department of Civil, Structural, and Environmental Engineering, University at Buffalo, New York, USA*

[4] *Department of Urban and Civil Engineering Faculty of Engineering, Ibaraki University, Ibaraki Prefecture, Japan*

[5] *Department of Civil, Geomatic and Environmental Engineering (D-BAUG), ETH Zurich, Switzerland*

[6] *California Polytechnic State University, San Luis Obispo, California, USA*

[7] *University of Manitoba, Winnipeg, Manitoba, Canada*

[8] *Department of Disaster Mitigation for Structures, Tongji University, Shanghai, China*

[9] *Department of Civil Engineering, Tsinghua University, Beijing, China*

[10] *Department of Civil and Mechanics, Harbin Institute of Technology, Harbin, China*

[11] *Department of Civil and Mineral Engineering, University of Toronto, Toronto, Canada*

[12] *Department of Disaster Mitigation for Structures,, Tongji University, Shanghai, China*

[13] *Department of Civil and Environmental Engineering, Waseda University, Shinjuku, Tokyo, Japan*

[14] *Department of Civil and Environmental Engineering, UCLA, Los Angeles, California, USA*

[15] *Department of Safety Technologies and Protective Structures, Fraunhofer EMI, Freiburg, Germany*

[16] *Faculty of Engineering, University of Bristol, Bristol, United Kingdom*

ABSTRACT. Community resilience against major disasters is a multidisciplinary research field that garners an ever-increasing interest worldwide. This paper provides summaries of the discussions held on the subject matter and the research outcomes presented during the Second Resilience Workshop in Nanjing and Shanghai. It, thus, offers a community view of present work and future research directions identified by the workshop participants who hail from Asia—including China, Japan, and Korea—, Europe, and the Americas.

KEYWORDS: Community resilience; Critical Infrastructure; Regional Assessment

1. Introduction

The Second Resilience Workshop (henceforth, simply, workshop) hosted by the Southeast University and the Tongji University convened to bring together both senior and junior researchers in order to address fundamental issues in disaster resilience. The workshop's proceedings provide a conventional compilation of the presentations given and discussion sessions held (Lu and Wu 2018). In the present paper, the authors have aimed to aggregate and organize the workshop's contents and to develop a community perspective on future research directions.

The starting point in the Workshop was the evaluation of the state-of-knowledge on resilient infrastructure in light of the lessons learned from recent major disasters. Attendees represented researchers from Japan, China, Hong Kong, Korea, Europe, and the Americas.

The keynote talks addressed critical themes in current and emerging threads of research in resilience, such as studies on community- and regional-scale resilience, dependencies among infrastructure systems, and human behavior during catastrophes. Discussions also included evaluating the benefits that may come from structural control and health monitoring, laboratory and field testing for model/method validation, and quantitative reconnaissance during, and in the aftermath of, extreme events.

Keynote and invited speakers from each region presented their visions on where the resilience levels of built environment need to be, and on how interdisciplinary research can delineate these levels and illuminate the path toward their attainment. Subsequently, small-group discussions took place on the (*i*) design and improvement of new and existing structures and infrastructure systems, (*ii*) implementation of novel engineering practices to rapidly enhance resilience of communities, and (*iii*) emerging disciplines such as Artificial Intelligence (AI) and other fields that bring can forth drastically improved assessment and modeling capabilities at regional scales. Different approaches that are presently being explored around the world and their potential synergetic effects were examined, which led to ideas on coordination of these efforts for accelerating the discoveries/developments. The Workshop participants then resolved to create several Working Groups who were tasked to brainstorm in order to develop action plans that identify the present knowledge/capability gaps, and delineate specific applications together with their potential impacts.

The present manuscript is organized into two parts: the first part is devoted to an overview of the state-of-the-art of resilience research that emerged from the keynote and invited speakers in the sessions of the workshop. The second part presents on the Working Group outcomes.

1.1 Grand challenges in achieving resilient socio-cyber-technical self-learning infrastructure systems

Resilience—a term comprising Latin roots *re-* and *salire*-"back," (MWD, 2020)—was initially used in a technical sense to denote the capacity (strength) of a material to withstand dynamic (impulsive) loads without fracturing by Thomas Young in early 19-th century (see, pg. 143, Young, 1847). The use of the term has since expanded into disciplines, which include psychology, ecological systems science, community and social sciences. In particular, civil engineers have begun using the term resilience to denote the ability of critical infrastructure systems to return to pre-disaster conditions and attempted to define it as a quantitative measure for different natural hazards (see, for example, Bruneau et al., 2003).

Resilience is often context-sensitive and can take on different meanings at individual, societal, jurisdictional, levels. It also aggregates a range of capabilities in preparing for, responding to, protecting from, detecting, preventing, and recovering and learning from disruptive events. Correspondingly, resilience cycle phases include (a) preparation, (b) building up protective capabilities (e.g. of structures), (c) detection, (d) prevention, (e) absorption, (f) response, (g) recovery, (h) adaption, and (i) learning. While, in an overall sense, resilience is understood as a measure of system functionality, it is not yet known how to systematically determine which resilience cycle phases are relevant for given infrastructure and hazard scenarios.

While concepts of resilience are increasingly adopted, customized, and operationalized under various disciplines, researchers and relevant agencies are continuously confronted with ever-increasingly complex, and highly interconnected and interdependent systems. Questions often thus arise whether the paradigm is taken up at sufficient complexity and granularity to make any practical impact.

While technological capabilities that can devise more resilient systems, and analytical capabilities that offer better quantification/understanding of resilience are improving at a rapid pace, potential threats and hazard exposures also appear to be increasing. The natural question therefore is whether these improvements can abate potential catastrophic disruptions to critical infrastructure systems due to natural hazards.

1.2 Working groups for devising roadmaps of future research on resilience

The participants inter alia had backgrounds in the fields of earthquake engineering, civil engineering of infrastructure (e.g., bridges), catastrophe management, network modelling, electrical engineering, quantitative risk analysis, technical and functional safety, and computer science. A wide range of methodologies was covered from conceptual frameworks, engineering analytical approaches, component and large-scale structure resilience and their simulation, modelling and simulation to network modelling sciences, Machine Learning (ML) and AI expert systems.

Taking this background into account, and for stimulating the formulation of detailed future resilience research roadmaps based on identified challenges, technological drives and societal needs, three working groups (WGs) were created to try to answer some critical questions about the resilience of infrastructure and communities, taking up also feedbacks of participants (States 2018; Boumphrey and Bruno 2015; Thoma et al. 2016; Häring et al. 2016).

(1) **WG #1 - Frameworks, fundamentals and education for future infrastructure risk control and resilience**: How to enhance understanding of the fundamental processes underlying natural hazards, extreme events on various spatial and temporal scales, as well as the variability inherent in such hazards and events? What curricular changes are necessary to better prepare the future generation of Civil Engineers for Critical Infrastructure Security (CIS) and Resilience Research (States 2018)?

(2) **WG #2 - How to improve Critical Infrastructure Systems with Emerging Technologies: Future critical infrastructure systems predictive simulation and emerging technologies**: How to improve our capability to model and forecast (including uncertainty quantifications of) such hazards and events by better understanding of infrastructure socio cyber-physical systems? How to advance modeling and smart technologies that promise an opportunity for groundbreaking discoveries to improve resilience? For instance, how to transform infrastructure, from physical structures to sensing, self-aware and responsive systems? How to assure that increasingly interconnected CIS meet demands and withstand environmental hazards?

(3) **WG #3 - Big data analytics, ML and AI for future human support in disruption events and critical infrastructure system resilience**: How to enhance societal preparedness and societal resilience against the impacts of natural and man-made hazards? How to make sound research investments to better develop technology that supports critical infrastructure and human-technology interactions? How to leverage in this context big data, AI platforms and data analytics at various scales? How to promote a multidisciplinary collaboration between the Engineering, Computer and Information Science, and Social, Behavioral and Economic Sciences, also to address socio-political and technical issues?

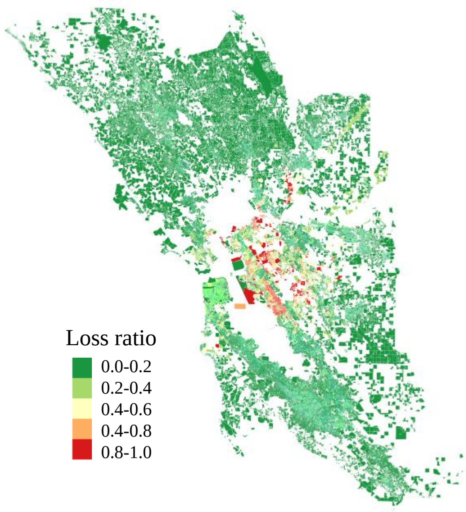
2. State-of-the-art in existing research on resilience of civil infrastructure systems

In this section, references are made to the main contributions that were presented during the Second Resilience Workshop. These were classified into five main groups: (i) methods and progresses for assessing community resilience, (ii) aspects specifically related to infrastructures with special attention to bridge structures, benefits to resilience that can be derived from (iii) control, (iv) monitoring solutions, and (v) the contribution of large-scale laboratory tests to the assessment and improvement of building resilience.

2.1 Earthquake resilience of communities

Seismic damage simulation of buildings on a regional scale is of great significance to enhancing community resilience. The topic has received worldwide attention and many methods have been proposed in recent decades (Council 1985; Hori and Ichimura 2008; Lu and Guan 2017; MRl 2003). Among them, the cityscape nonlinear time-history analysis is one of the representative methods (Lu and Guan 2017). A series of key challenges in earthquake scenario simulation can be addressed using this method, including modeling the features of different buildings and ground motions (Lu et al. 2014; Xiong et al. 2016; Xiong et al. 2017), high-fidelity visualization (Xiong et al. 2015), secondary disaster simulation and resilience assessment of urban buildings (Xu et al. 2016; Zeng et al. 2016).

The cityscape nonlinear time-history analysis has been adopted by the NHERI SimCenter supported by the National Science Foundation (NSF) of the United States to simulate community resilience, through which an open-sourced general-purpose framework for seismic damage simulation and resilience assessment of urban buildings (referred to as SimCenter Workflow) was proposed (Lu et al. 2020). A seismic damage simulation and loss prediction for 1.8 million buildings in the San Francisco Bay Area were performed using the SimCenter Workflow. The simulation included the entire process from the earthquake fault rupture to the building loss. Specifically, the ground motions based on a 7.0-magnitude simulated Hayward fault earthquake were used as the input ground motions. Different buildings had different ground motion inputs according to the simulated earthquake scenario. The seismic response of each building was then predicted using the nonlinear time-history analysis. The distribution of the median building loss ratios and repair/rebuilding times were computed with the SimCenter Workflow for all buildings as shown in Figures 1 and 2, respectively. The seismic responses of buildings in downtown San Francisco were visualized realistically to promote earthquake disaster mitigation for non-professional people, as shown in Figure 3. This implementation provided a useful reference for simulating earthquake resilience of the large-scale community.



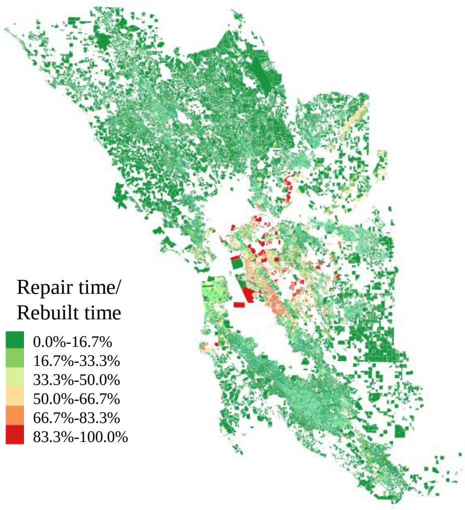
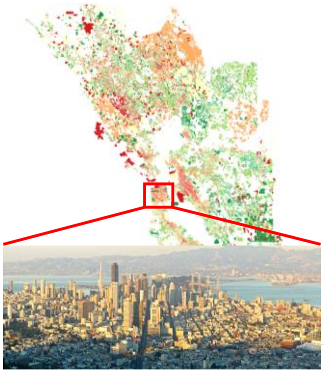


Figure 1 Distribution of median building loss ratios in the Bay Area

Figure 2 Distribution of the median building repair/rebuild time in the Bay Area



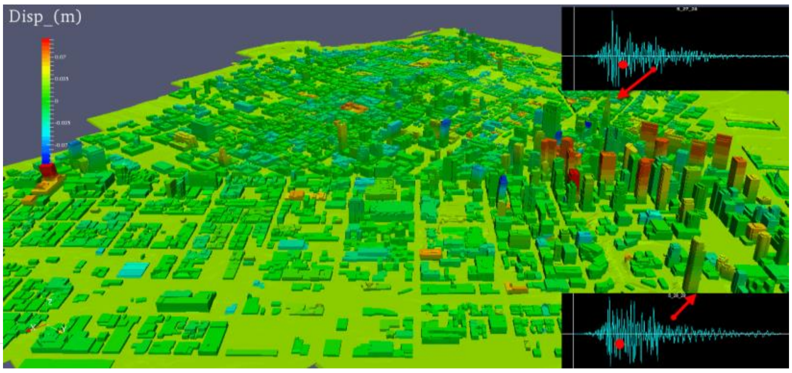
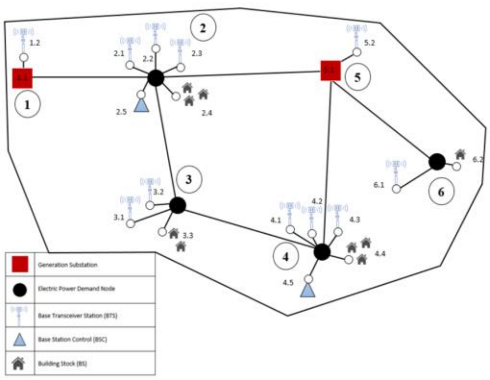


Figure 3 Visualization of the seismic response of buildings in downtown San Francisco (t=13.2 s)

Focusing on the issue of modelling the infrastructures' interdependency that may have a critical role in cascading and amplification effects, the Re-CoDeS (Resilience – Compositional Demand/Supply) framework allows to explicitly consider the evolution of demand and supply for infrastructures service over time. The goal of the Re-CoDeS framework is to apply the compositional demand/supply approach to an interdependent system of systems composed by several civil infrastructures and a community. Furthermore, it enables the resilience quantification. Using this extension, the dependency of one system on another one can be determined considering the resource or service demand, the resource or service supply, and the coupling of these two metrics. Such a holistic understanding of the evolution of the demand and supply in an interdependent setting would allow de-aggregation of community resilience objectives in order to focus and redirect resources to those systems and components that will produce the greatest overall benefit.

Figure 4 depicts the virtual setting to test the Re-CoDeS framework composed by the electric power supply system, the cellular communication system, and the building stock, which is divided into different agglomerations. Figure 5 reports the results of the case study, showing the resilience of the electric power supply system during the first 100 days after the disaster (occurring at t=0) (Didier et al. 2018).



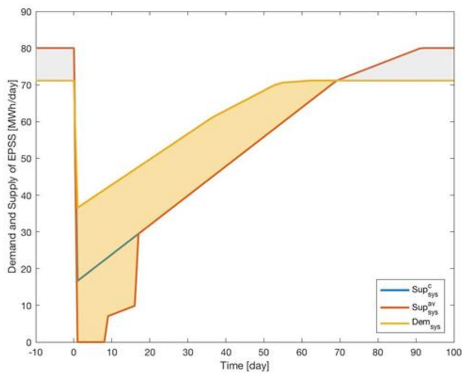


Figure 4 Virtual case study proposed to test the extension of the Re-CoDeS framework for interdependent CISs

Figure 5 Resilience of the electric power supply system during the first 100 days after a disaster (left)

Moving to community resilience and real-world case studies, after the Canterbury earthquakes, the central business district of Christchurch was demolished to a significant extent. It is presently being rebuilt as a city with a variety of structural forms, but predominantly with steel structures. Interviews with a significant number of stakeholders and engineers were conducted (Bruneau and MacRae 2017) to quantify the extent of the shift in construction practice taking place there, with the objective of identifying the drivers that have influenced the decisions on selecting structural materials and systems of new buildings that are being (will be) erected in the region.

The number of casualties caused by an earthquake is usually linked to the collapse of structures—a scenario wherein fatalities are either immediate, or imminent as people become trapped under debris. While human losses are positively correlated to structural damage, injuries have also been found to occur even when no damage was present. Such injuries are due to individuals being struck by objects or falling off staircases while trying to escape from the buildings. Therefore, the shaking itself is deemed to be a significant cause for injuries and death during earthquakes. Preliminary work in this area aimed at understanding the ability of normal people to maintain their positions during ground shaking. This subject has not been extensively studied, but some pioneer work has been carried out by Takahashi et al. (2004; 2011).

Test on humans due to vibration has been performed in other areas of knowledge (Griffin 1998; 2012). The main idea is to evaluate the ability to perform control evacuation or controlled pre-determined tasks. The literature review indicates that these conditions are influenced by stability of the individual in standing positions, the motion of individual in a sitting position, the level and frequency of the vibration at the points of entry to the individual, state of health, gender, age, and, most importantly, previous experience or practice. Due to the large number of variables and their variabilities among human subjects, testing is difficult to capture the overall tendencies. Additionally, the monitoring ability to detect the capacity of individuals is difficult due to their spatial motion. Tests were then performed on different individuals and human characteristics. Each person is equipped with sensors to analyze the person's stability and capability to maintain the initial position, heart rate and breathing in order to measure the main vital parameters and anxiety of the person during the shaking. A six degrees of freedom shaking table and a unidirectional shaking table are used to generate artificial earthquakes (Aguilar et al. 2017). In addition, a virtual reality setting is used in order to recreate a more realistic environment. During the experiment, special attention is given to the factor of "surprise" which is necessary to ensure a natural reaction of the individuals. Figure 6 reports the setup of the tests performed at the Politecnico di Torino (Resilience Lab). The individual is equipped with safety devices and placed on the shaking table wearing the virtual reality device. Kinect sensor is used to monitor the body movements during and after the simulated ground motions. Vital parameters are also monitored.

Figure 6 Tests performed at Politecnico di Torino (Turin, Italy)

Individual response is highly dependent on expectations, experience and mental preparation. In Chile due to its high rate of seismicity, with a magnitude 5 earthquakes, or higher, occurring in average 70 times per year, people are more trained to react to strong ground motions. Individuals were tested for several different motions and they learned quickly how to reposition themselves on more stable position. When the individual experiences loss of equilibrium, the first reaction observed is to lift and open the arms and to lower the body's center of gravity for ensuring equilibrium. It has been observed that the surprise component affects essentially the outcomes. Long ground and floor motions produce higher anxiety but not necessarily uncontrollable stability. The use of special tools as virtual reality and multi-degree of freedom platforms allows to reproduce more consistent conditions.

2.2 Resilience of critical infrastructures & bridges

Undoubtedly, infrastructure is the backbone of the world's economies. This include transportation networks, such as bridges, tunnels, subways, railways, ship yard cranes; water delivery, utilities, dams, various pipeline networks, power transmission, communication network, government centers, and large business centers. Resilience is fundamentally a theoretical concept. Yet ongoing and warranted reflection regarding this concept in the context of disaster and emergency management and mitigation, crisis management, and the protection of critical infrastructures, for instance, has thrust this concept into the policy making arena, where considerations concerning its practical application are becoming important. While difficult, given the complexity of resilience, and its definitional ambiguity, the ability to assess such a concept helps to bridge the gap between theory and application, between academic and policy circles.

The design and construction of civil infrastructures is a significant cost to a country but the proper use of the scientific methods to monitor and maintain these structures is indispensable. Therefore, civil engineers strive to design and construct structures meeting the highest standards of engineering in order to enhance durability and functionality of such infrastructures. However, civil engineers have been slow in adopting *Civionics* Engineering and Structural Health Monitoring (SHM) to maintain the infrastructures. Through the development of the new discipline of Civionics that integrates Civil Engineering and Electronics, innovative resilient structures can be developed (Mufti et al. 2007; 2010; Rivera et al. 2007).

There have been a number of bridge collapse accidents in recent years, causing large casualties and property losses. Concepts such as redundancy and robustness play a significant role, respectively to have alternative resources in the event of out-of-service of certain structural elements and to sustain certain performance or stress levels without showing degradation or loss of functionality. A new redundancy index was introduced to investigate the after-fracture redundancy of an aged truss bridge in Japan (Lin et al. 2016).

Traditional research focuses on the method of numerical analysis. For example, Domaneschi et al. (2018) studied the disproportionate collapse of an existing cable-stayed bridge at the numerical level by employing a validated model from literature and the Applied Element Method. The earthquake input is used for the numerical simulations and the role of redundancy in the bridge structural scheme is proved as the strategic measure for avoiding the disproportionate collapse and improving robustness. With this aim, new redundancy indexes that account the system reserve resources have been also introduced.

Numerical models are often devised and validated via tests on reduced-scale structures in the laboratory. However, boundary and loading conditions in such tests may not fully reflect the ground truth. As such, there is a continual need to extract data/metadata from real-life events for model validation. Forensic investigations (see, for example, Peng et al., 2019 - Figure 7; Domaneschi et al 2020; Morgese et al. 2020) and post-event reconnaissance campaigns (Stewart et al., 2019) provide this crucial data for component or system-level model validation, which, in turn, improves the accuracy of scenario-based regional-scale disaster simulations. With advances in computational capabilities, the use of detailed high-fidelity models to represent large/regional inventories of buildings, bridges, etc. has become possible. On the other hand, while recent technologies (e.g., drones, LIDAR scanners, etc.) enable rapid collection of voluminous data, it is still difficult to convert raw data (e.g., images, basic measurements) into *metadata* that needed for model development and validation, and for loss assessment.

Figure 7 Image-based measurements of the collapsed Florida University pedestrian bridge for forensic analyses (reproduced from Peng et al., 2019).

Moving to regional scale, intercity networks constitute a highly important civil infrastructure in developed countries as they contribute to the prosperity and development of the connected communities. This was evident after recent strong earthquakes that caused extensive structural damage to key transportation components. Quantifying therefore, the resilience of road networks (defined as their ability to withstand, adapt to, and rapidly recover after a disruptive event), it can be a challenging issue of paramount importance towards holistic disaster risk mitigation and management.

This feature can be can be approached by establishing a comprehensive, multi-criterion framework for mitigating the overall loss experienced by the community after an earthquake event. They are decoupled into the direct structural damage-related loss and the indirect loss associated with the travel delays of the network users, as well as the wider socio-economic consequences in the affected area. This probabilistic risk management framework (Figure 8) is implemented into a software to facilitate informed decisions of the stakeholders (Kilanitis and Sextos 2018), both before and after a major earthquake event, thus prioritizing the pre-disruption strengthening schemes and accelerating the inspection and recovery measures, respectively.

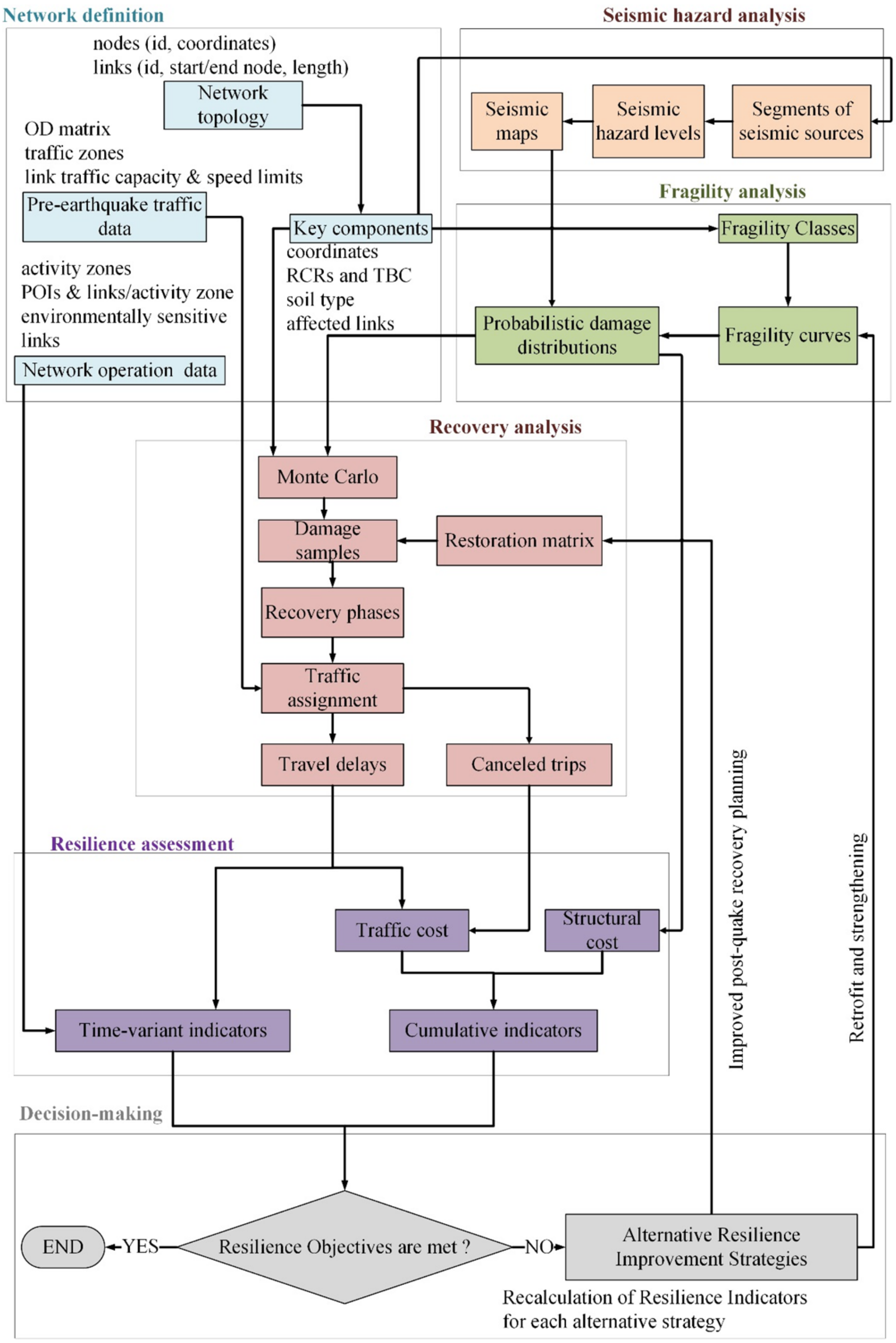


Figure 8 General workflow of the proposed framework (Kilanitis and Sextos 2018)

2.3 Structural control and base isolation solutions toward seismic resilience

Isolation has traditionally been considered as a passive technique in the classification of structural vibration control, while it has also active, semi-active and hybrid forms. Application to tall buildings is limited, because large displacements may introduce large overturning moment (Wu and Ou 2015).

Seismic performance of isolation layer determines the safety of isolated structures due to certain failure mode of isolation structures. Indeed, the deformability of isolation bearings has many restrictions such as limited foundation gap and horizontal stiffness.

In (Domaneschi and Martinelli 2015) the concept of seismic resilience of a controlled cable-stayed bridge has been explored through investigations and finite-element simulations. The case study is represented by a refined finite element model of an existent cable-stayed bridge, the object of an international benchmark. The semiactive signature of the structural control elements is exploited online to compensate for losses of performance due to failure of some of the control elements. The proposed control solution's results show the ability to nullify the time interval between the damage occurrence and restoration (even if not complete) of system performance. This innovative aspect is related to how the devices' semiactive feature is exploited to enhance resilience. Therefore, the concept of immediate resilience is first introduced. A new measure of resilience is also proposed with reference to the performed simulations. The positive outcomes coming from redundant and automatic seismic protection systems, such as the one here implemented, offer a contribution not only in undamaged working conditions but also when local failures occur, providing on-the-fly compensation to performance losses.

2.4 SHM and damage detection toward operational and hazard resilience

Monitoring systems may be useful to obtain information on the degradation conditions, to be able to adopt in advance the necessary actions and, thus, reduce risks of disproportionate collapses. In particular, a set of system identification techniques have been recently proposed using structural response variables only: they are usually mentioned as output-only techniques. These approaches originated by the need of operating without disrupting the normal activities (e.g., traffic flow) or by the difficulty of consistently measuring the input loading (e.g., wind pressure, traffic load, etc.). Such innovative identification technique can successfully perform when the response of the structural system is independent of the input, or in other words, when the transfer function of the system is independent of the external loading. It is usually related to stationary (or weakly stationary) white signals.

In (Domaneschi et al. 2017) damage detection in composite concrete-steel structures that are typical for highway overpasses and bridges is investigated by using only structural response variables (output-only technique). The method developed is based on the dynamic curvature analysis of real strain data from an in-service structure for real time applications. A FE approach is also developed in parallel for interpreting the structural behavior and then assessing the effectiveness of the method. The data are acquired from long-gauge fiber optic strain sensors under traffic loading of the structure. The probabilistic analysis of the peak values of dynamic curvature PSDs is used to study the real data and compared to FE results. The real data show unusual behavior at one location where the average and standard deviation of the peak values of curvature PSDs are significantly higher than expected. These outcomes are in accordance with a previous study that identified unusual behavior at the same location.

In (Domaneschi et al. 2016) an output-only arrangement of the Interpolation Damage Detection Method was checked for a suspension bridge based on responses to the wind-induced vibrations of a calibrated finite element model. Effect of noise was evaluated for different damage intensities and positions with respect to a number of damage scenarios. Damage is modeled by a reduction, at several different positions, of the local stiffness in bridge deck members. Both noise-free and noise-polluted scenarios were considered in the numerical simulations. The output-only arrangement has been demonstrated effective at the numerical level for the Level II damage identification (damage localization) on a wind excited long-span bridge.

2.5 Building resilience and large-scale laboratory tests

Seismic resilience of infrastructures or structures is the capability to withstand the effects of earthquakes and to recover efficiently the original functionality. Moreover, the time required to restore/recover that functionality, i.e. rapidity to restore the original functionality, is a critical parameter of resilient structures.

There is a call for the development of structural systems which realize supreme seismic performance without or with very slight increase of cost compared with those required in ordinary structures. Hence, the key concept in this part is to introduce rational structure systems for modern structures and retrofitting techniques, which suffer controlled damage from simulated seismic forces meanwhile substantial increase in cost is not required, to enhance but succeed the advantages of conventional structures.

Since the advantages of advanced composite materials—i.e., Fiber Reinforced Polymers (FRPs)—include: lightweight, high strength-to-weight or stiffness-to-weight ratios, corrosion resistance, and, in particular, the elastic performance; strengthening of existing structures and reinforcement of modern structures with FRP have drawn increased attention.

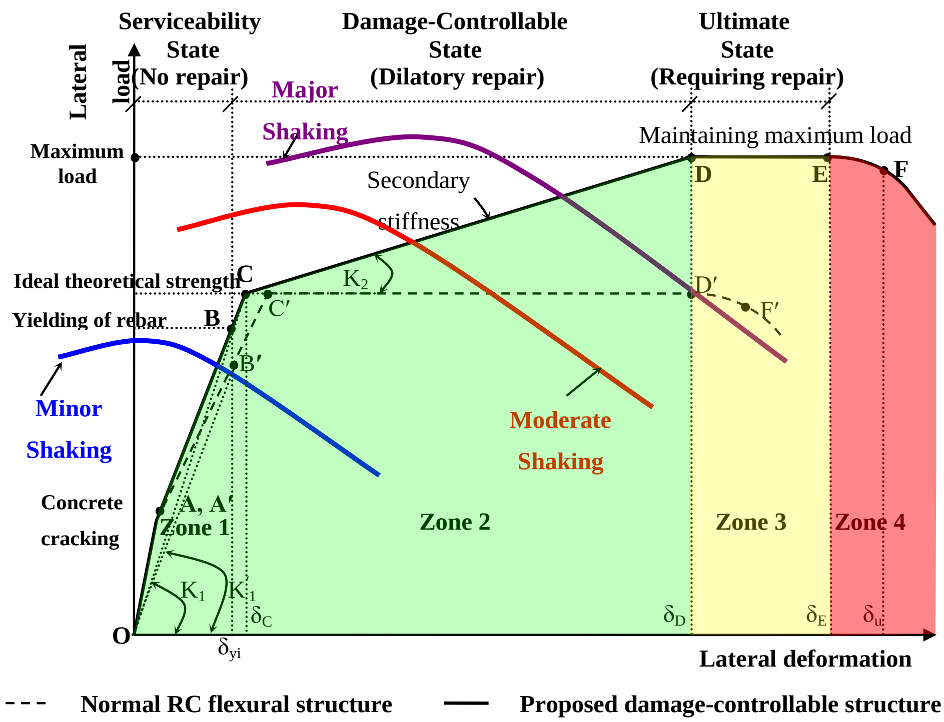


Figure 9 Idealized load-deformation behavior of the proposed FRP-steel damage controlled structures (Wu et al. 2009)

According to Figure 9, the proposed structure can be kept in place for a relatively long time without collapse during a large earthquake, though severe damage may occur, and the original function of the structures may be recovered through the replacement of some elements.

A comprehensive evaluation for the recoverability of existing bridge columns retrofitted with external FRP confinement was done by Mohamed (2010). Furthermore, as shown in Figure 10, application of bond-based Near-Surface Mounted (NSM) retrofitting technique using FRP bars was proposed and experimentally evaluated by (Fahmy and Wu 2012; Fahmy and Wu 2016).

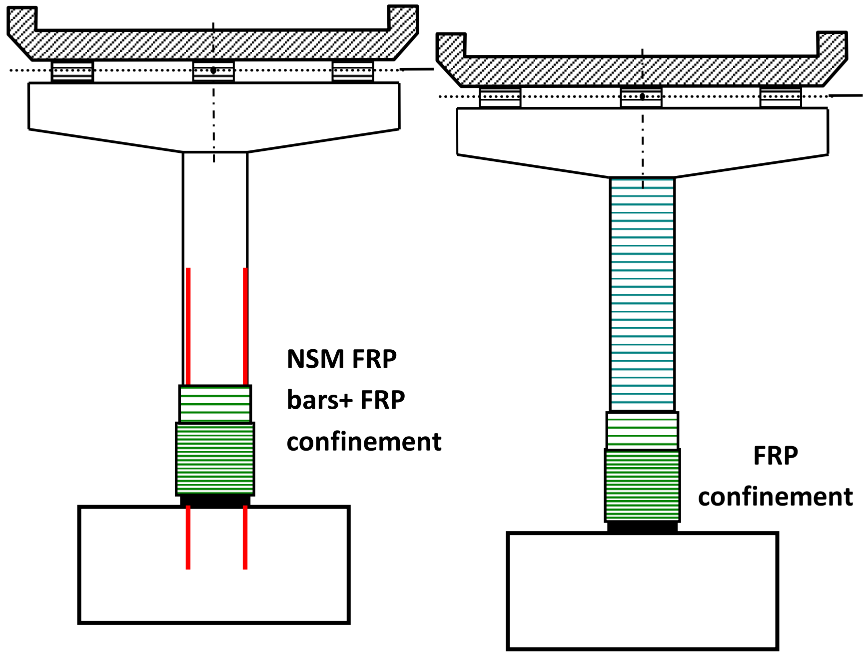


Figure 10 Proposed retrofitting techniques for existing structures using FRP

For modern structures, innovative hybrid reinforcement, Steel Fiber Composite Bars (SFCBs), was proposed as alternative reinforcement for columns in place of the traditional steel reinforcement. Experimental and numerical studies were carried out to evaluate the performance of bridge columns reinforced with the SFCBs (Fahmy et al. 2010). The innovative bar is composed of inner steel core and outer longitudinal fibers, so it combines the mechanical characteristics of both the elastic fiber and the ductile steel.

Furthermore, recently, a novel reinforcement details using both FRP bars and Steel Reinforcement was proposed for modern RC bridges and buildings (FSRC) (Ibrahim et al. 2016; Ibrahim et al. 2015; Ibrahim et al. 2018). Texture of the FRP bars was applied as a design parameter to control the performance of the FSRC elements.

To support the development of low-damage concrete structures, a system level shake-table test of a low-damage concrete wall building implementing state-of-art design concepts will be conducted on the multi-functional shake-table array at Jiading campus, Tongji University as part of an international collaborative project. The test building is a two-story building with plan dimensions of 5.4m×8.95m, and the total height of the building from foundation surface is 8m with each story 4m high. The overview of test building is shown in Figure 11, and more information about the test building can be found in (Zhou et al. 2018). The building structural system consists of self-centering concrete walls that provides the primary lateral-load resistance in both directions and concrete frames using slotted beam details are designed to resist predominantly gravity loads. The sizes of the key building components are listed in Table 1. The test building also incorporates dampers and implemented flexible or isolating wall-to-floor connections to reduce the interaction between wall and floor systems. Before the test, numerical analysis of the test building behavior based on the finite element model in OpenSees software was performed. The frames in the test building were modelled and analyzed. In the frame model, the self-centering concrete walls with dampers at the wall base were modeled using a fiber hinge model and the slotted beam joints were modeled with lumped plasticity elements. Simulation results agreed with the test building design and showed that the test building achieved the low-damage design philosophy with good energy dissipation. The simulation model will be used to further predict the results of the test building subjected to earthquake ground motions. And, the response of the simulation models will be further validated with the large-scale shake-table test results.

Figure 11. Test building overview

Table 1 Summary of member sizes

Member	Size (mm)
Columns in all levels	400 × 400
Beams in all levels	300 × 400
Walls at long span direction	150 × 2500
Walls at short span direction	150 × 2000

Damaged and deficient structures can prove to be among the biggest obstructions in an otherwise resilient community. An innovative rehabilitation technique was developed for the upgrade of such structures. The main component that helped build resilience in these structures were FRP. The associated lab investigation for one of the structures estimated that the observed damage caused about a 20% reduction in the capacity of the columns and much larger reductions in the ductility and energy dissipating capacity. The experimental results also showed that the strength and ductility of these structures could be more than recovered by repairing them using the developed techniques, which employed special grouts and FRP.

In particular, several bridge columns and beams damaged by steel corrosion along a major highway in Toronto made the bridge seriously deficient (Figures 12a, 12b) (Homam et al. 2001; Kharal and Sheikh 2018; Sheikh and Homam 2004; Sheikh and Yau 2002). An industrial structure was also studied which was found to be shear critical and deficient for seismic resistance (Figure 12c) (Duong et al. 2007). Based on an extensive research program in which half scale models of the prototypes were tested in the lab, innovative techniques were developed to rehabilitate the structures in a cost-effective manner with minimal closure time of the structures. The non-traditional materials used in the upgrade/repair included glass and carbon-fiber reinforced polymers. The bridge structure was closely monitored for over ten years after rehabilitation especially for corrosion. Although the corroded steel and the contaminated concrete were not removed from the structure, field measurements showed that the corrosion activity and risk of corrosion reduced with time in the repaired columns. The upgraded industrial structure has withstood severe earthquakes without any serious damage.

Figure 12 Highway bridge damaged by steel corrosion (a), Rehabilitated columns after twenty years of service (b), deficient industrial structure (c)

Based on the laboratory studies and field monitoring, it is concluded that innovative solutions involving FRP and specialized grouts can help upgrade structures for sustainability under severe load and environmental conditions. The upgraded structures have performed flawlessly for over twenty years, indicating high durability. It can be concluded that resilience and durability can be introduced into deficient or damaged structures through innovative techniques employing new materials such as fibre-reinforced polymers (FRPs).

3. <u>Future resilience research directions</u>

3.1 WG #1: Fundamental Concepts

Group #1 was composed of Lili Xie, Gian-Paolo Cimellaro, Michel Bruneau, Zhishen Wu as Co-Chairs, Max Didier as Reporter, Mohammad Noori and Ivo Häring as Contributors.

The identification of future fundamental resilience research *needs* and related *academic educational challenges* are the main topics identified within the WG #1 activity.

The needs were agreed to consist of the development of flexible and generally accepted frameworks, i.e. assessment process models, resilience improvement, development, implementation and optimization models. Such models should also take the cultural, societal context and expectations of operators, users, and citizens into account, in particular how to translate them in acceptance and evaluation criteria. Much more work is believed to be necessary to understand and simulate local loadings (e.g. on building level in case of earthquakes and flooding), especially of combined multiple threats, such as physical impact and flood loading or cyber combined with physical-natural and physical-terroristic. Measuring and metrics for resilience is believed to remain an ongoing future task, in particular on system level. Specific challenges identified comprise Mega Cities, legacy infrastructure, fast simulation of large-scale urban built environments as well as increasingly interlinked infrastructure systems, and the use of (unspecific and dedicated) data, data analytics up to self-learning approaches (ML, AI).

The education focus for long term scientific and applied capacity improvement is believed to build on strong (multiple) subject domain experts, who should take also advanced courses in system science modelling approaches as well as data-driven sciences. In all cases students are proposed to be taught also within broad real-world application projects to learn how to involve users and decision makers and respective participatory science approaches for enhancing future resilience research.

3.1.1 Frameworks, fundamentals and education for future infrastructure risk control and resilience

WG #1 identified several objectives regarding fundamental frameworks, research needs and methodological gaps for future resilient infrastructures. As acceptable overall risk control and resilience strongly depends on the societal context and consensus, it needs (i) to be better clarified which overall frameworks, process, and models, are necessary; (ii) to be better understood of threats; (iii) to be better modelled and simulated taking account of inter and intra dependencies; (iv) to provide of risk control and resilience quantities accepted by end users and academia; (v) to improve of risk and resilience evaluation criteria and consensus; (vi) to provide of fundamentals for better risk control and resilience, including fast but predictive models; (vii) to define of curricula guidelines for future resilience research taking account of the high variability of subject domains and the need for specific knowledge to allow for progress; (viii) to address the need for continuous academic education.

3.1.2 Key challenges for resilience research and education

The following specific challenges were identified: (i) Contextual boundaries of resilience research and how it links up with other fields (such as actuarial science) need to be addressed in a systematic way. (ii) Resilience quantification needs to be extended beyond civil engineering (or purely technical aspects) in order to take the social and economic impacts and dimensions (community holistic approach) into account. (iii) How different countries, regions, cultures, communities and determine the boundary conditions of resilience assessments need to be examined. (iv) the circumstantial and contextual scales and granularities at which resilience should be delineated—e.g., for individual, community, higher political, or social levels. (iv) the scaling and normalization of resilience metrics should be identified and broadly adopted. (v) research on hazard resilience of mega cities and lifeline (e.g., water, power, and transportation) systems should be prioritized.

So far, research on critical infrastructure in a civil context has not yet been canonized by any means. It is observed that true progress in this domain often depends on a broad knowledge in several disciplines. Typically, advancing the domain requires drawing on fundamental knowledge in related disciplines—e.g., civil engineering, mechanical engineering, computer science, physics, or other STEM (Science, Technology, Engineering, Mathematics) subjects. As such, it also appears imperative to devise educational opportunities for cross-training future researchers and scientists.

3.1.3 Major research gaps

Presently available resilience assessment frameworks—e.g., HAZUS (FEMA, 2006) are deemed inadequately populated with granular asset inventories, which, in turn, limit both their scopes and accuracies (see, e.g., Shultz, 2017). Given the present capabilities in data science, computing, and sensing, it appears that these deficiencies can be overcome within a few years through coordinated efforts (Cetiner et al., 2019; Yu et al., 2019). Moreover, existing frameworks are either too domain-specific to be generalizable or are too generic to yield actionable results. This occurs, in particular, if such frameworks and processes are de facto adapted to very specific applications, e.g. earthquake engineering. Examples include the MCEER framework of the Multidisciplinary Center for Earthquake Engineering Research of the University at Buffalo and, to a lesser extent, the PEOPLES framework (Renschler et al. 2010). Furthermore, existing frameworks do not systematically aim at the maximum separation possible between resilience assessment and improvement process steps—see, for example, the discussion in (Häring et al. 2017). Furthermore, most existing schemes/frameworks tend to miss interdependencies.

The advantages of deductive and inverse methods in resilience have not yet been considered. Also, a systematic dimensional analysis over resilience metrics have not yet been attempted. Current damage models at various scales, from structures to buildings and infrastructures, are still mainly focusing on initial damage effects, rather than on recovery, and even less so on post-event improvement options.

It is expected that advanced modelling tools and assessment frameworks will enable better pre-event planning, and rapid functional recovery.

3.1.4 Improved frameworks to address the challenges

Frameworks of improved risk control and resilience for critical infrastructures will need to account for several key issues. The following are deemed critical for immediate examination: (i) existing standards and their coverage and knowledge gaps, (ii) aggregation of societal and individual perspectives/metrics for hazard-loss and resilience more explicitly, (iii) more explicit articulation and consideration of risk acceptance criteria and societal priorities, (iv) participative and informed decision-making by individuals, stakeholders, and the government agencies.

Furthermore, frameworks should take advantage of the available access to digitalized spatial and semantic infrastructure data, be modular and sufficiently specific to predict effects on the level of individual buildings, take account of social media data and computational resources. Segregation and diversification of communication channels also need to be considered, as well the level of education and experience required to conduct the necessary assessments and decisions.

3.1.5 Roadmaps and strategies for future implementation

It is expected that mainly existing frameworks and approaches will be further extended, interlinked and enriched with new technological approaches and methods. Furthermore, standardization is expected to increase on different levels, especially standards as CityGML (CityGML 2019) on semantic digital city, infrastructure and building level and building information models (BIM) (Nawari 2018) on single building level are candidate formats not only for exchange of digital data, but also for assessment procedures using such data. Additional examples are extended GIS formats as well as, for example, OpenStreetMap or similar proprietary formats.

3.2 WG #2: How to improve Critical Infrastructure Systems with Emerging Technologies: Future critical infrastructure systems predictive simulation and emerging technologies

Group #2 was composed by Professors. Aftab Mufti, Xilin Lu, Jinpin Ou, Shamim Sheikh, Ying Zhou as Co-Chairs, Marco Domaneschi as Reporter, Mohammad Noori and Ivo Häring as Contributors.

This critical infrastructure resilience research roadmap focuses on better infrastructure modelling and simulation and leverage of future innovative technologies. It covers and extends classical definition of Critical Infrastructure System (CIS) and emphasizes known interdependencies of such infrastructures, which leads to the question of better understanding interfaces and interdependencies. Simulation resources are proposed to be much extended using advanced computing approaches as well as more flexible and scalable modelling approaches that will also cover uncertainty modelling. An ever-increasing fraction of empirical data-driven approaches is also expected. The gathering of data is assumed to be more and more automated using avionics approaches and specific as well as open source data. Up to large-scale mega city real-time monitoring and simulation is expected to be realized including with respective decision and planning support actions. Standardization activities are recommended to be supported also by academia to ensure consistency and take-up of worldwide already existing approaches.

3.2.1 Background and introduction

The current increment of extreme events and disasters all over the world due to climate change but also to increasing complexity and interdependency of modern communities highlights the fact that a policy for growth that will safeguard our medium- and long-term prosperity must far more emphasize on innovation than has previously been the case. This innovation has also to improve existing systems to keep them able to face new risks and multiple-hazards, but also lead to fundamentally new solutions and breakthroughs.

While the road to the enhancement of short term seems rather straightforward, one main challenge is to understand how to model and predict the more medium and long-term effects of self-learning or even AI systems on overall risk control and resilience of critical infrastructure systems. A further challenge is how to improve such smart technologies such that they actually support the handling of major undesired and unpredictable events, as opposed to technology that focuses on optimizing systems close to standard operation.

3.2.2 Critical infrastructure definitions and main objectives list

“Resilience is the ability of a system to withstand a major shock within acceptable degradation that is recoverable in reasonable time, cost and risk”. This is the definition adopted by Group 2 and it applies well when critical infrastructures are considered. Earthquakes, tsunami, floods, explosions, impacts, hurricanes and their combinations have been recognized as major disasters that can affect critical infrastructures.

Accordingly, with slight extensions of the definition of the USA PATRIOT Act (107–56 2001) and focusing on the classes of Critical Civil Infrastructures, they can be summarized in the following five main assemblies: (i) TI - Transportation Infrastructure, (ii) EI - Energy Infrastructure, (iii) WW - Water Waste Water System, (iv) ES - Emergency Services, (v) IT - Information Technologies, (vi) BR - Building Structures and Residences.

Based on this bottom-up constructive definition of resilience and main infrastructure elements that need to be considered, WG #2 identified the key challenges for future resilience research. In particular, the following subsections cover the main future resilience research topics believed to be of dominating impact on successful future research activities. In each case, selected major research gaps, frameworks and research contexts to address the challenges and new concepts, methods and technologies to be further developed in the future are given.

3.2.3 'Better understanding of the intra- and inter-dependencies of critical infrastructure systems '

Understanding the impact of disasters to civil infrastructure network allows to guide strategic pre-disaster hazard mitigation and post-disaster recovery planning of a community. However, civil infrastructures depend on each other to exchange products, information or services. When disasters happen, these dependencies would aggravate the initial damage and lead to cascading failures. Thus, understanding the dependencies among infrastructure facilities is also essential in modeling the damage and recovery of a community under disruptive events.

Interdependencies can be described through a matrix approach that also may be useful for numerical implementation with the use of logic functions. Table 2 identifies the interdependencies between the six critical civil infrastructures of section 3 that should be much further resolved in simulation approaches. For instance, WW does not influence TI ("No") but ES influences TI ("Yes").

Table 2 Interdependency-Based Modelling for Critical infrastructural systems

Infrastructure	**TI**	**EI**	**WW**	**ES**	**IT**	**BR**
TI - Transportation Infrastructure	*Yes*	*No*	*No*	*No*	*Maybe*	*Yes*
EI- Energy Infrastructure	*Yes*	*Yes*	*No*	*Maybe*	*Maybe*	*Yes*
WW - Water Waste Water System	*No*	*Yes*	*Yes*	*Yes*	*Maybe*	*Yes*
ES - Emergency Services	*Yes*	*No*	*No*	*Yes*	*Yes*	*Maybe*
IT - Information Technologies	*Maybe*	*Maybe*	*May be*	*Yes*	*Yes*	*Yes*
BR - Building Structures and Residences	*Maybe*	*No*	*No*	*Maybe*	*Maybe*	*Yes*

When the model of a critical infrastructure is developed, it must comprise the systems itself but also the interaction with other infrastructural systems. This last requirement is probably the main issue to be solved. Indeed, infrastructures are becoming more and more interoperable and interdependent within complex urban environments. Connected with this issue are the input requirements of modelling and simulation approaches that are affected by several parameters for describing the hazard itself and such as uncertainties, risks, actions and their space distribution that may be difficult to define. This is more evident when stochastic inputs are considered. However, also deterministic loadings are characterized by several parameters and (systematic) uncertainties.

3.2.4 'Data-informed and driven infrastructure modelling and simulation'

Models may comprise numerical (e.g. FE – finite element or Applied Element – AE models) but also analytical ones. Besides, physical and field models can be also developed. Connected with is the model validation that is usually a complex process to develop and conduct. This is more evident when community and multi-layer hybrid systems are considered. Indeed, it is usually difficult to have available validation data for complex systems or emergency evacuation due to extreme events. However, when input and output data are available, models can be also extrapolated.

Connected with the emergency evacuation issues, e.g. by employing Agent Based Models (ABM), is the Human Behavior (HB) modelling. Certainly, the role of emotions and altruism for example can be crucial during evacuation due to external shocks and may drive the decision-making procedures.

An issue related to both the human behavior and modelling of critical infrastructures is the structural collapse. It may affect the neighboring structures or interconnected critical infrastructures. Furthermore, local collapses or partial failures may affect the entire system collapse (progressive collapse) or its functions.

Lessons from the past and historical disasters of critical infrastructure systems may allow to establish post-disaster performance standards and objectives.

Besides, the opportunity of developing large scale numerical simulations and real time hybrid simulations (sensing and numerical) is also a critical interest. Indeed, they allow to assess and measure how existing communities can respond to disaster and to plan possible countermeasures to improve the community response. Figure 13 orders some elements regarding sensing, simulation and infrastructure improvements discussed above and in the following text sections.

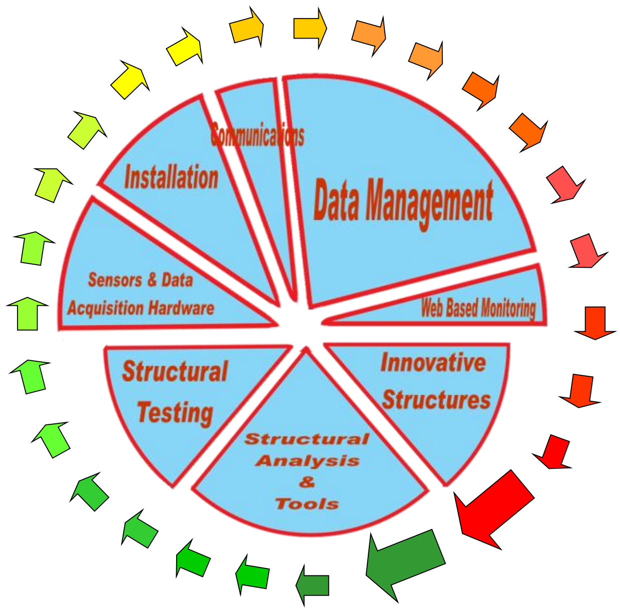


Figure 13 Sensing, simulation and evaluation of resilience of critical infrastructures

3.2.5 'Future health monitoring and early warning'

Connected to the critical infrastructures and resilience is the development of sensing technologies that may support the decision makers and the disaster management. Satellite technologies are gaining more and more interest for their ability to monitor large scale conditions and for the possibility to predict extreme weather events. This is also driven by free access high-quality data.

Early warning systems (EWSs) against natural hazards have focused the attention of scientists and designers in the last decades as an effective tool for improving resilience of communities and systems. EWSs can provide a few to a few tens of seconds warning prior to damaging ground shaking and are currently operational in Mexico, Taiwan and Japan. Their use is connected to the recent progress in the sensing systems technology, remote sensing and wireless systems.

The adoption of smart devices in emergency environments is becoming more and more important. Several scenarios, such as post-earthquake and fire emergency activities, are very attractive for possible applications, even if they present several scientific challenges that must be addressed in order to satisfy rescuers' requirements.

Critical infrastructures and urban structures need constant maintenance and inspection of the structural health condition and safety of the users. However, to access the structure is getting harder and harder due to the dimensions and compliances. In order to deal with this problem, many researchers have developed robots for system health monitoring (SHM) inspections.

3.2.6 'Resilience-based improvements for critical infrastructural systems already in service'

Reasonably expected and largely expected events to occur during the service life of a structural or infrastructural system may be useful to plan retrofitting, renovating and repairing actions. To this aim and to withstand to external hazard while protecting both new and existing structures and infrastructures, passive control, active, semi-active and adaptive control systems can be useful. Furthermore, control systems can be used to improve the system resilience through the automatic compensation of possible out-of-service of structural components (immediate resilience).

Focusing on structural and infrastructural renovation, duplication of critical components or functions of a system with the intention of increasing reliability of the system can be essential to provide additional reserve (redundancy). It means that the failure of a component does not result in the collapse of the entire system and alternative loading paths can be provided. This concept may play a significant role for existing structures but also for the design of new ones, and could be comprised in new standards and guidelines.

3.2.7 'Resilience-based design for infrastructure and systems, community resilience and demonstration flagship projects (living labs)'

Innovative approaches to decision-making methods for the design of new infrastructures in times of climate change, multi-hazards conditions and increasing interdependencies are expected. The result directly downstream of this innovation process is the creation of new guidelines that are directly available and can lead to a general development in the direction of the creation of resilient communities.

Besides, the community preparedness is also a crucial aspect towards resilient communities and can be deployed on many levels, from the higher-education level (e.g. engineers) to the training of technicians and citizens. If the first one is mostly developed at the academic level, citizens may be prepared to withstand and cope with disasters through civil protection and emergency agencies.

Demonstration projects can be also considered at this stage. A good example is the development of the Indian Ocean Tsunami Warning and Mitigation System (UNESCO) was initiated at the World Conference for Disaster Reduction in 2005, in which from that point many organizations have been engaged in the task of developing tsunami early warning systems and community-based disaster risk management in coastal regions.

3.2.8 'Emerging Technologies for innovation of resilient infrastructure and systems in design and planning'

Emerging technologies are expected to help in improving the community resilience and infrastructures supporting urban disaster risk management and strengthen community resilience. Climate change and urbanization are increasing the risk and impact of disasters and rapid urban development has been driving up urban risk. Mega-disasters are happening more frequently. This coupled with the growing urban populations makes it critical to better support community resilience, so that people living in urban areas can be supported by more effective organizations but also help themselves, as frequent shocks and stresses become a common part of everyday life.

To attain such objectives, emphasis must be made on the requirement of active engagement of scientific research and engineering applications, e.g. in the area of smart materials and nanotechnologies for future cities. E.g. the addition of nano-composite materials into cement has shown notable potential in improving its performance and compressive strength.

Traditional disciplines as SHM and control are required to make a new effort to understand and cope the new and evolving conditions. In addition, it is also necessary to push in the direction of new, multidisciplinary solutions, such as Civionics (Mufti et al. 2007) which, like Avionics and Mechatronics, still needs to be fully understood and developed, see Figure 14.

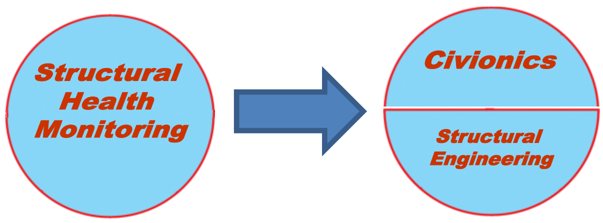


Figure 14 Expected development from classical system health monitoring to advanced approaches

Implementation of existing sensors and developing of new sensors for civil engineering needs toward a real time monitoring of civil structures and infrastructures is one of the primary actions that are expected. Developing equipment that is waterproof, robust and reliable, able to survive in harsh construction processes is also a foremost requirement towards new and effective solutions. Also, the provision of cheap localization of non-rescue persons and objects indoors remains challenging. Such a capability would open up many possibilities.

As a result of an increasing monitored world, an exponential increase in the data collected should be expected. Therefore, data mining, management, processing and interpretation will require major research and development efforts at university and industrial level. Connected with this is the development of web platform bases and cloud monitoring solutions. Connected to big data and data mining in an increasingly complex world is the ML, deep learning and the use of bio inspired algorithms. Indeed, the aforementioned technologies have changed the old paradigm "input-algorithm-output" toward a new scientific creativity.

Technologies like augmented reality in construction are emerging to digitalize the construction industry, making it significantly more effective. Furthermore, the digital twin — a concept of having a real-time digital representation of a physical object – is also an emerging technology towards resilient communities and infrastructures.

3.2.9 Roadmaps and strategies proposed for future implementation

Different goals had been aligned along an ambitious timeline, with appropriate measures along all phases (short term, medium term, long term) (Lu and Wu 2018). Among the others the following ones are herein reported: (i) advancement of single key approaches and technologies, including the better understanding of tipping-point damage modelling, but also technologies for safety of individuals. (ii) Taking advantage of ever better sensors in multiple smart phones, smart watches and further mobile devices. (iii) AI- and ML driven active protection systems with no material or physical redundancy, i.e. with nothing but intelligent system immediate response resilience back-up.

It is expected that future implementations of technological and scientific advances toward resilience improvements will be driven besides research results also by the development of new guidelines and standards. Indeed, although it is vital to continue scientific research and the development of new technologies, and therefore to advance in the various fields that can support new infrastructures and resilient communities, it is essential to create a strong link from research to scientific application. This link, obviously adapted to real-life conditions and local social, economic and political issues, is represented by guidelines and standards. In other words, the key rules that are established by governments themselves in order to unify and improve the conditions of countries. Here supporting scientists and the countries should take up existing approaches and collaborate to further pool expertise.

3.3 WG #3: Big data analytics, ML and AI for future human support in disruption events and critical infrastructure system resilience

Group #3 was composed by Professors Teruhiko Yoda, Ertugrul Taciroglu, Ivo Häring as Co-Chairs, Anastasios Sextos as Reporter, Mohammad Noori as Contributor.

Recent research results as well as lessons learnt after man-made and natural disasters reveal that critical infrastructure relies on interactions between humans and technical solutions that are implemented during crisis. Such experiences and the continuously increasing amount of available data, analytics and intelligence stimulates the question how future resilience research can exploit technological advancements to improve the capacity of both humans and critical infrastructure during disruption events. The present workshop report summarizes the options available to (a) involve users, operators and decision makers in joint research, (b) take advantage of digital semantic urban and rural data, to use ML to determine input parameters for modelling and simulation of infrastructure, (c) design a modular hub for storage of information and risk and resilience assessment with respect to a broad set of potential threats, as well as (d) use of similar modules within systematic procedural approaches, e.g. spatial scenario definitions, person exposure, abstract threat visualization, visualization of damage. It is envisioned that the scientific community can build around a hub platform with the aim to enhance the resilience of critical infrastructure networks in terms of downtimes and disruption costs, including large scale, “what-if”, vulnerability scenarios.

3.3.1 Motivation, background and introduction

Even though the above abstract notion of resilience objectives is generally agreed, the challenge to reach such goals is still debatable among different schools of thought originating from different disciplines, such as engineering, economics and social sciences). As a result, resilience of critical infrastructure remains a versatile task, in particular when approached with mainly engineering, technical and natural science research instruments.

Taking advantage of the existing and future options offered by big data analytics, ML and AI for human support in case of disruption events within CIS, the main technological and engineering challenges can be critically discussed addressing the following questions on how to: (i) enhance societal preparedness and societal resilience against the impacts of natural and man-made hazards, (ii) make sound research investments to better develop technology that supports critical infrastructure and human-technology interactions, (iii) promote a multidisciplinary collaboration toward an holistic resilience approach.

From a systemic perspective, resilience of individual assets to single threats are rather well understood. This holds in particular, when noting that most infrastructure subsystems when sufficiently isolated can be well assessed almost to any degree of resolution and with respect to all aspects when resorting to traditional disciplinary sciences, e.g. classical earthquake engineering, by doing more and better "of the same or similar" approaches. However, there is still a lack of a holistic framework to assess the resilience at an infrastructure system level considering all interactions among individual component, network and inter-systems level.

At the same time, it was acknowledged that new scientific approaches on subsystem and component level are critical for overall system resilience. However, it was argued that only in the context of the overall system assessment it can be decided whether such resilience improvements are of real benefit. This is an argument to avoid allocating resources to non-relevant system capabilities and designs for modelling and simulation and even more in real world rather than into real bottlenecks for better resilience.

As modern communities become more interdependent than ever, the potential impacts of hazardous events have a broader potential footprint on infrastructure systems. The frequency, modality and level of extremity of known and new hazards (e.g., climate, cyber-related, "AI-related") as well as our exposure to them is expected and often (already) observed to be massively increasing. At the same time serviceability, functionality, safety and security (technical) capabilities of infrastructure systems are massively increasing as well. In particular, technological capabilities and the ability to generate, harvest, predict and process data and relevant system information are rapidly enhancing. Quite general, the question arises whether the potential weaknesses of modern infrastructure systems can be cured with technological means itself. This will be one of the guiding questions and will be shown to be answered rather optimistically in the present report.

Key challenges identified that could be addressed with promising results in future resilience research include but are not limited to: (i) the lack of common language and approaches, (ii) the lack of will to collaborate across the boundaries of different disciplines (e.g. to overcome school of thought thinking), (iii) fragmentation and/or inaccessibility of data with unknown levels of reliability (bad quality data), (iv) high computational cost and modelling challenges, (v) uncertainties at various levels, (vi) liability concerns of stakeholders, (vi) resilience research is hard to validate, (vii) quantification, strategy and response to natural and man-made hazards are cultural, financial, local and experience-dependent, (viii) resilience is not yet generally believed and/or known to be a business case for success.

3.3.2 Major gaps in state-of-the-art

In the years after 9-11 several threads of research could be identified regarding critical infrastructure contextualization, assessment and improvement. Regarding the level of detail of investigations, at least in the European Union (EU) research calls opened by the European Commission (EC), a business-ready technology is sought with strong relevance to the civil security user community as well as for massive company involvement towards good economic prospects. This can be motivated by the insight that resilience assessment and improvement is most efficiently conducted at the level of economic decision makers by addressing improvements possible without changing the legal and societal framework.

Furthermore, there are not yet country-wide, multi-country or even worldwide generally accepted approaches and even less standards to understand, model and simulate interconnected critical infrastructure systems as well as single such infrastructures. If domain-specific standardization approaches have been successful, they have been supported by research insights and, often, only available on the community level. There is a lack of further such efforts covering resilience from a more generic technical perspective and much more so for specific infrastructure domains.

Regarding research needs, methodological frameworks are missing capable to improve the efficiency of resilience approaches, the time scales of adaption to true needs of society, economy and the environment. For instance, it is challenging to identify motivating factors that lead to increased engagement of actual decision makers, which are typically driven by economic revenue, branding options or patented innovation.

Besides these more generic red threads, more specific research gaps can be identified that result in the research questions and key challenges identified in sections 2 and 3. Cluster of gaps of current research include: (i) how to better cope with lack of data, bad data and big data. (ii) How to address the lack of man-power that can be assigned to more frequent resilience issues with the help of more automated approaches as accessible with ML and AI approaches, in particular for sensing, inspection, pre-decision making, (iii) how to design hybrid and partly autonomous systems for coping with rare events, which by definition generate few training data, (iv) how to quantify resilience gain in terms of economic profit.

3.3.3 Framework to address the challenges

Frameworks include: (i) the risk management and analysis approaches that focus on “risks on expected resilience behavior”(see, for example, §3 of Häring et al. (2016)), (ii) agile short term and long-term processes driven by disruption events to perform successful mitigations, (iii) semi-quantitative expert and citizen opinion assessment and evaluation frameworks (see e.g. sections 3 and 7 of Häring et al. (2016)), (iv) MCEER’s standard and more recent PEOPLES framework, see respectively Renschler et al. (2010) and Kilanitis and Sextos (2018), and (v) performance-function based resilience assessment and improvement processes. The objective is a sufficiently resolved and trusted system resilience quantification to show that all developed and implemented improvement measures lead to overall acceptable system resilience. (see e.g. Häring et al. (2017)).

An example is the structured approach of the “Foresight review of resilience engineering: Designing for the expected and unexpected” stipulated by Lloyd’s register foundation, which provides background, definitions and challenges while focusing on engineering solutions (Boumphrey and Bruno 2015).

The following non-exclusive actions are proposed to address the challenges to stronger support future resilience research: (i) explore synergies between inter-disciplinary groups and define common procedures and protocols, (ii) take advantage of data analytics and ML techniques to overcome communication barriers and costs, (iii) aim at “all-resilience” approaches, (iv) extend or combine existing simulation urban risk control and resilience frameworks as developed in the EU projects D-BOX, ENCOUNTER, VITRUV and EDEN (Fischer et al. 2018; Häring et al. 2018; Vogelbacher et al. 2016), (v) develop data harvesting tools for building inventories (data pipelines), (vi) customize ML techniques for resilience applications, (vii) train public data sets for model calibration and verification, (viii) develop APIs (Application Programming Interfaces) and interface technologies between assets, sensors, geo-spatial data (GIS), smart systems representations (digital twins), digital building, infrastructure and urban areas models such as BIM, City-GML, Internet of Infrastructure (IoI), and early warning systems. Furthermore, (ix) enhance rapid real-time post-event capabilities, (x) promote seamless transition between system health monitoring and functionality assessment, (xi) define core professional competencies for engineering practitioners and students in the domain of resilience concepts.

3.3.4 Roadmaps and strategies proposed for future implementation

Figure 15 presents a tentative roadmap for future resilience research focusing on the development of a world-wide hub for representation, modelling, simulation of single critical infrastructure elements as well as networks and coupled networks. It is envisioned that such a development is conducted in several steps. It is believed that scientific exchange of a potential user community of such a critical infrastructure modelling and simulation hub is crucial for success, one such opportunity could be a third international workshop on critical infrastructure resilience.

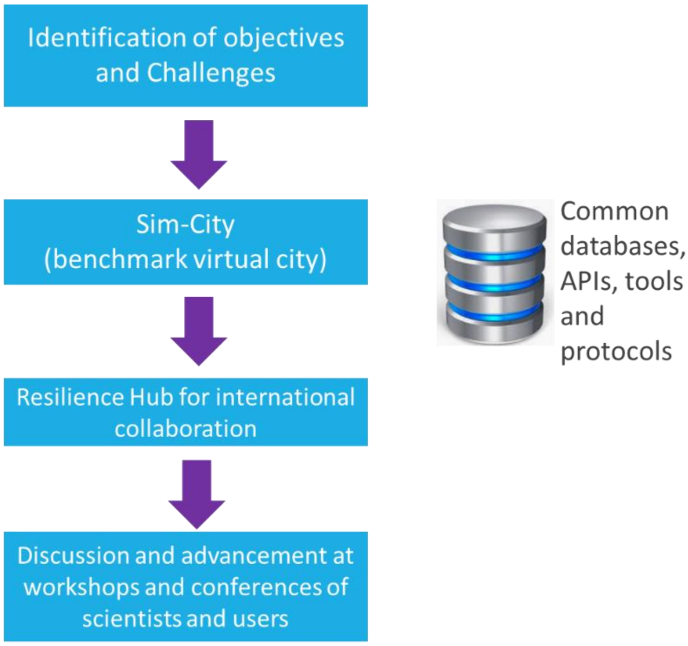


Figure 15 Tentative roadmap to an international exchange platform for large scale area and critical infrastructure simulation and assessment, also showing how it can be iteratively improved

4. Concluding Remarks

The 2nd International Workshop on Resilience was held during October 31-November 1, 2018 in Nanjing, and on November 2, 2018 in Shanghai; and was co-organized by the Southeast University, and the Tongji University. The workshop brought together participants from civil, mechanical, systems, and earthquake engineering fields. Participants brainstormed to identify pathways into more effective approaches for assessing and achieving hazard resilience of critical infrastructure systems. The workshop also aimed to summarize state-of-the-art and to identify the challenges that lie ahead. To facilitate the identification of critical issues to be addressed, three Working Groups were formed. It was envisioned that the pursuing the suggested research roadmaps proposed by the Working Groups and further refining them into community standards can result in safer and more resilient urban communities. It was equally deemed important to pursue the development of new integrated interdisciplinary programs for education of the next generation of civil and risk management engineers.

WG #1 was challenged to identify important threads of technology-driven resilience research for improving critical infrastructure systems. It was concluded that comprehensive and granular frameworks and processes that take advantage of current capabilities in data science and computation need to be further developed. To obtain stable assessments, frameworks that adequately take up the true needs of all actors—without anticipating solutions from a purely technical point of view—are required.

This vision therefore anticipates (i) regional simulations of a range of natural and man-made catastrophes, carried out at high resolution at local scales (e.g. for an individual building or bridge); (ii) inter-disciplinary fundamental research guided by true user needs; (iii) the development of fast computation capabilities for multi-scenario analyses, using advanced computational solutions that also can be employed in the aftermath of catastrophes for coordinated emergency response and functional recovery. It was also deemed crucial to (iv) develop curricula for resilience engineering to be rooted in dedicated domain-specific anchor subjects, as well as generic capabilities such as complex systems modelling.

WG #2 envisioned many of the proposed future innovations to be ready for operational use within at least mid-term time scales or even shorter, especially in the area of automated airborne inspection and rescue support. Further research activities are recommended to cover such areas as leveraging cloud/parallel computing technologies for large-scale infrastructure modeling and simulations, while taking advantage of dedicated sensor networks and open source data. Real-time capabilities need to be developed to better support operators, first-responders and infrastructure managers.

Modelling and simulation issues with the emerging technologies related to monitoring and early warning systems have also been discussed, which were considered as the two faces of the same coin—namely, the virtual simulation environments that examine large inventories of the digital twins or real-life assets, and the sensor networks and surveillance systems that collect the data in real-time from the real world. Integrated into a single system, virtual worlds can be used to simulate catastrophe timelines while updating the models (e.g., in a Bayesian sense) using during-event sensor measurements and observations. The existing and emerging technologies were also discussed to devise a future vision for smart and resilience infrastructure systems. Finally, the need for development of resilience standards and guidelines was also identified as strategic future effort.

WG #3 concluded that a convergence in advanced processes, methods, and technological advances is imminent and will yield resilience assessment capabilities that scale up to handle highly-complex and coupled systems and events. Automated development of asset inventories (digital twins) and application of machine learning methods are the primary capabilities that will result in the said convergence. The workgroup concluded that the workshop participants exemplified the current capabilities scattered around the world, and highlighted the need to develop sustainable and coordinated research efforts to accelerate discoveries and capabilities.

5. References

107–56, U. P. L. P. L. (2001). "UNITING AND STRENGTHENING AMERICA BY PROVIDING APPROPRIATE TOOLS REQUIRED TO INTERCEPT AND OBSTRUCT TERRORISM (USA PATRIOT ACT) ACT OF 2001."

Aguilar, R., Apostoliti, C., Boroshek, R., Cardoni, A., Cares, D., Cimellaro, G., Domaneschi, M., and Galdo, D. (2017). "Monitoring human emotions during earthquakes." *SHMII 2017 - 8th International Conference on Structural Health Monitoring of Intelligent Infrastructure*Brisbane (Aus)1122-1131.

Boumphrey, R., and Bruno, M. (2015). "Foresight review of resilience engineering: Designing for the expected and unexpected." *Lloyd's Register Foundation Report Series: No. 2015.2*.

Bruneau, M., and MacRae, G. (2017). "Reconstructing Christchurch: a seismic shift in building structural systems." *The Quake Centre, University of Canterbury, Christchurch*.

Bruneau, M., Chang S., Eguchi, R. , Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., and von Winterfelt D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra* 19(4): 733–752.

Cetiner, B., Koc, E., Soibelman, L., Taciroglu, E., Lee, E.J., and Nutakki, A. (2019). "A Granular Simulation of Bridge Closures Due to a Southern California Scenario Earthquake and Its Effects on the Disruption and Recovery of Freight Traffic to and from Ports of Los Angeles and Long Beach." *Proc. Int. Conf. on Sustainable Infrastructure 2019*, Los Angeles, CA pp. 575-585.

CityGML, <https://www.citygml.org/ >. (2019-01-15).

Council, A. T. (1985). *Earthquake damage evaluation data for California*, Applied technology council.

Didier, M., Broccardo, M., Esposito, S., and Stojadinovic, B. (2018). "SEISMIC RESILIENCE OF INTERDEPENDENT CIVIL INFRASTRUCTURE SYSTEMS."

Domaneschi, M., Cimellaro, G. P., and Scutiero, G. "Disproportionate collapse of a cable-stayed bridge." *Proc., Proceedings of the Institution of Civil Engineers-Bridge Engineering*, Thomas Telford Ltd, 1-14.

Domaneschi, M., Limongelli, M. P., and Martinelli, L. (2016). "WIND-DRIVEN DAMAGE LOCALIZATION ON A SUSPENSION BRIDGE." *Baltic Journal of Road & Bridge Engineering*, 11(1).

Domaneschi, M., and Martinelli, L. (2015). "Earthquake-resilience-based control solutions for the extended benchmark cable-stayed bridge." *Journal of Structural Engineering*, 142(8), C4015009.

Domaneschi, M., Sigurdardottir, D., and Glišić, B. (2017). "Damage detection based on output-only monitoring of dynamic curvature in concrete-steel composite bridge decks." *Structural Monitoring and Maintenance*, 4(1), 1-15.

Domaneschi, M., Pellecchia, C., De Iuliis, E., Cimellaro, G. P., Morgese, M., Khalil, A. A., Ansari, F. (2020), "Collapse analysis of the Polcevera Viaduct by the Applied Element Method", Accepted (April 14, 2020) for publication in *Engineering Structures*, Elsevier.

Duong, K. V., Sheikh, S. A., and Vecchio, F. J. (2007). "Seismic behavior of shear-critical reinforced concrete frame: Experimental investigation." *ACI Structural Journal*, 104(3), 304.

Fahmy, M., and Wu, Z. "Retrofitting of existing RC square bridge columns using basalt FRP rebars." *Proc., Proceedings of the 6th International Conference on FRP Composites in Civil Engineering*.

Fahmy, M. F., and Wu, Z. (2016). "Exploratory Study of Seismic Response of Deficient Lap-Splice Columns Retrofitted with Near Surface–Mounted Basalt FRP Bars." *Journal of Structural Engineering*, 142(6), 04016020.

Fahmy, M. F., Wu, Z., Wu, G., and Sun, Z. (2010). "Post-yield stiffnesses and residual deformations of RC bridge columns reinforced with ordinary rebars and steel fiber composite bars." *Engineering Structures*, 32(9), 2969-2983.

FEMA (2006). "HAZUS-MH 2.0 advanced engineering building module (AEBM) technical and user's manual." ⟨www.fema.gov/plan/prevent/HAZUS⟩.

Fischer, K., Hiermaier, S., Riedel, W., and Häring, I. (2018). "Morphology Dependent Assessment of Resilience for Urban Areas." *Sustainability*, 10(6), 1800.

Griffin, M. J. (1998). "A comparison of standardized methods for predicting the hazards of whole-body vibration and repeated shocks." *Journal of sound and vibration*, 215(4), 883-914.

Griffin, M. J. (2012). *Handbook of human vibration*, Academic press.

Häring, I., Ebenhöch, S., and Stolz, A. (2016). "Quantifying resilience for resilience engineering of socio technical systems." *European Journal for Security Research*, 1(1), 21-58.

Häring, I., Sansavini, G., Bellini, E., Martyn, N., Kovalenko, T., Kitsak, M., Vogelbacher, G., Ross, K., Bergerhausen, U., and Barker, K. (2017). "Towards a Generic Resilience Management, Quantification and Development Process: General Definitions, Requirements, Methods, Techniques and Measures, and Case Studies." *Resilience and Risk*, Springer, 21-80.

Häring, I., von Ramin, M., Stottmeister, A., Schäfer, J., Vogelbacher, G., Brombacher, B., Pfeiffer, M., Restayn, E.-M., Ross, K., and Schneider, J. (2018). "Validated 3D Spatial Stepwise Quantitative Hazard, Risk and Resilience Analysis and Management of Explosive Events in Urban Areas." *European Journal for Security Research*, 1-37.

Homam, S., Sheikh, S., and Mukherjee, P. "Durability of fibre reinforced polymers (FRP) wraps and external FRP–concrete bond." *Proc., Proceedings of the 3rd international conference on concrete under severe conditions*, 1866-1873.

Hori, M., and Ichimura, T. (2008). "Current state of integrated earthquake simulation for earthquake hazard and disaster." *Journal of Seismology*, 12(2), 307-321.

Ibrahim, A. M., Fahmy, M. F., and Wu, Z. (2016). "3D finite element modeling of bond-controlled behavior of steel and basalt FRP-reinforced concrete square bridge columns under lateral loading." *Composite Structures*, 143, 33-52.

Ibrahim, A. M., Wu, Z., Fahmy, M. F., and Kamal, D. (2015). "Experimental study on cyclic response of concrete bridge columns reinforced by steel and basalt FRP reinforcements." *Journal of Composites for Construction*, 20(3), 04015062.

Ibrahim, H. A., Fahmy, M. F., and Wu, Z. (2018). "Numerical study of steel-to-FRP reinforcement ratio as a design-tool controlling the lateral response of SFRC beam-column joints." *Engineering Structures*, 172, 253-274.

Kharal, Z., and Sheikh, S. A. (2018). "Seismic Performance of Square Concrete Columns Confined with Glass Fiber–Reinforced Polymer Ties." *Journal of Composites for Construction*, 22(6), 04018054.

Kilanitis, I., and Sextos, A. (2018). "Integrated seismic risk and resilience assessment of roadway networks in earthquake prone areas." *Bulletin of Earthquake Engineering*, 1-30.

Lin, W., Lam, H., Yoda, T., Ge, H., Xu, Y., Kasano, H., Nogami, K., and Murakoshi, J. (2016). "After-Fracture Redundancy Analysis of an Aged Truss Bridge in Japan." Structure and Infrastructure Engineering, 13 (1), 107–117.

Lu, X., and Guan, H. (2017). *Earthquake disaster simulation of civil infrastructures: from tall buildings to urban areas*, Springer.

Lu, X., Han, B., Hori, M., Xiong, C., and Xu, Z. (2014). "A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing." *Advances in Engineering Software*, 70, 90-103.

Lu, X., and Wu, Z. (2018) *Proceedings of the Second International Workshop on Resilience* (In Press).

Lu, X. Z., McKenna, F., Cheng, Q. L., Xu, Z. , Zeng, X., and Mahin, S. (2020). "An open-source framework for regional earthquake loss estimation using the city-scale nonlinear time-history analysis." *Earthquake Spectra*. DOI: 10.1177/8755293019891724.

Lu, Y., Gu, A., and Xiao, Y. (2018). "Shake-table test on a low-damage concrete wall building: building design." *Proceedings of the 11th National Conference in Earthquake Engineering*Earthquake Engineering Research Institute, Los Angeles, CA.

Mohamed, F. M. F. (2010). "Enhancing recoverability and controllability of reinforced concrete bridge frame columns using FRP composites." 茨城大学.

Morgese, M., Ansari, F., Domaneschi, M., Cimellaro, G. P. (2020). "Post-collapse analysis of Morandi's Polcevera viaduct in Genoa Italy", *Journal of Civil Structural Health Monitoring*, 10, 69–85.

MRl, H. (2003). "Multi-hazard loss estimation methodology: Earthquake model." *Department of Homeland Security, FEMA, Washington, DC*.

Mufti, A., Bakht, B., and Tadros, G. (2010). "GFRP Reinforced Corrosion-Free Bridge Deck Slabs Based on ISIS Winnipeg Principles." *Advances in Structural Engineering*, 13(5), 773-782.

Mufti, A. A., Bakht, B., Tadros, G., Horosko, A. T., and Sparks, G. (2007). "Civionics—a new paradigm in design, evaluation, and risk analysis of civil structures." *Journal of Intelligent Material Systems and Structures*, 18(8), 757-763.

MWD—Merriam-Webster.com Dictionary (2020). s.v. "resilient," accessed April 14, 2020, https://www.merriam-webster.com/dictionary/resilient.

Nawari, N. O. (2018). *Building Information Modeling: Automated Code Checking and Compliance Processes*, CRC Press.

Peng, W., Ding, R., Xu, W., Xu, X., Dai, F., and Taciroglu, E. (2020). A forensic analysis of the Florida International University pedestrian bridge collapse using incident video footages, *Engineering Structures,* 200(1), 109732.

Renschler, C. S., Frazier, A. E., Arendt, L. A., Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010). *A framework for defining and measuring resilience at the community scale: The PEOPLES resilience framework*, MCEER Buffalo.

Rivera, E., Mufti, A., and Thomson, D. (2007). "Civionics for structural health monitoring." *Canadian Journal of Civil Engineering*, 34(3), 430-437.

Shultz, S. (2017). "Accuracy of HAZUS General Building Stock Data." *Nat. Hazards Rev.*, 18(4): 04017012.

Sheikh, S. A., and Homam, S. M. "A decade of performance of FRP-repaired concrete structures." *Proc., Proceedings of the ISIS-SHM 2004 Workshop. Winnipeg, Manitoba, Canada*.

Sheikh, S. A., and Yau, G. (2002). "Seismic behavior of concrete columns confined with steel and fiber-reinforced polymers." *Structural Journal*, 99(1), 72-80.

States, E. O. o. t. P. o. t. U. (2018). "Summary of the 2018 Critical Infrastructure Security and Resilience Stakeholder Workshop, Subcommittee on Critical Infrastructure Security and Resilience, Comimittee on Homeland and National Security of the National Science and Technology Council."

Stewart, J.P., Zimmaro, P., et al. (2019). Reconnaissance of 2016 Central Italy Earthquake Sequence, *Earthquake Spectra*, 34(4), 1547-1555.

Takahashi, T., Saito, T., Azuhata, T., and Ohtomo, K. (2004) "Shaking table test on indoor human response and evacuation action limit in strong ground motion." *Proc., Proc. of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada*.

Takahashi, T., Suzuki, T., Saito, T., Azuhata, T., and Morita, K. (2011). "Shaking Table Test For Indoor Human Response And Evacuation Limit." *7th International Conference on Urban Earthquake Engineering & 5th International Conference on Earthquake Engineering*Tokyo, Japan, 187-193.

Thoma, K., Scharte, B., Hiller, D., and Leismann, T. (2016). "Resilience engineering as part of security research: definitions, concepts and science approaches." *European Journal for Security Research*, 1(1), 3-19.

UNESCO, I. O. C. o. "Indian Ocean Tsunami Warning and Mitigation System." <http://www.ioc-tsunami.org/index.php?option=com_content&view=article&id=8&Itemid=58&lang=en>. (2019-01-15).

Vogelbacher, G., Häring, I., Fischer, K., and Riedel, W. (2016). "Empirical Susceptibility, Vulnerability and Risk Analysis for Resilience Enhancement of Urban Areas to Terrorist Events." *European Journal for Security Research*, 1(2), 151-186.

Yu, Q., Wang, C., Cetiner, B., Yu, S.X., McKenna, F., Taciroglu E., and Law, K.H. (2019). "Building Information Modeling and Classification by Visual Learning At A City Scale." arXiv preprint arXiv:1910.06391.

Wu, P., and Ou, J. (2015). "Seismic Performance Analysis and Design of High-Rise Structures under Very-Rare Earthquake." *6th International Conference on Advances in Experimental Structural Engineering*UIUC, USA.

Wu, Z., Fahmy, M. F., and Wu, G. (2009). "Safety enhancement of urban structures with structural recoverability and controllability." *Journal of Earthquake and Tsunami*, 3(03), 143-174.

Xiong, C., Lu, X., Guan, H., and Xu, Z. (2016). "A nonlinear computational model for regional seismic simulation of tall buildings." *Bulletin of Earthquake Engineering*, 14(4), 1047-1069.

Xiong, C., Lu, X., Hori, M., Guan, H., and Xu, Z. (2015). "Building seismic response and visualization using 3D urban polygonal modeling." *Automation in Construction*, 55, 25-34.

Xiong, C., Lu, X., Lin, X., Xu, Z., and Ye, L. (2017). "Parameter determination and damage assessment for THA-based regional seismic damage prediction of multi-story buildings." *Journal of Earthquake Engineering*, 21(3), 461-485.

Xu, Z., Lu, X., Guan, H., Tian, Y., and Ren, A. (2016). "Simulation of earthquake-induced hazards of falling exterior non-structural components and its application to emergency shelter design." *Natural Hazards*, 80(2), 935-950.

Young T (1807). A Course of Lectures on Natural Philosophy and the Mechanical Arts, Vol I, London, Printed for J. Johnson, St. Paul's Church Yard by W. Savage and B. Bury (availiable at https://books.google.com/books?id=lyQEAAAAQAAJ&oe=UTF-8).

Zeng, X., Lu, X., Yang, T., and Xu, Z. (2016). "Application of the FEMA-P58 methodology for regional earthquake loss prediction." *Natural Hazards*, 83(1), 177-192.

Zhou, Y., Gu, A., Lu, Y., Xiao, Y., Henry, R., Elwood, K., Rodgers, G., Yang, T.Y. (2018). "Large-Scale Shake-Table Test on a Low Damage Concrete Wall Building: Numerical Modeling and Analysis." *Eleventh U.S.*

National Conference on Earthquake Engineering - Integrating Science, Engineering and Policy, June 25-29, 2018, Los Angeles, California.