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## **Abstract**

Built environment constitutes the fundamental layer for many services and functions of our society. Many physical infrastructures are vulnerable to natural hazards (e.g. earthquakes, floods, tornados) as well as man-made hazards, and the risk of catastrophic damage due to hazardous events continues to increase worldwide. Considerable progress has been made towards risk management and mitigation, however, in particular the earthquake engineering community still faces many new challenges.

Focusing principally on seismic resilience, the objectives of the workshop have centred on (i) how we use resilience-based engineering to steward our built environment and make it safer, resilient and sustainable, and (ii) how to assess and develop strategies to improve community resilience against a major disruptive event.

The workshop has comprised presentations and discussion sessions. The state of knowledge regarding disaster resilience has first been examined in the light of the lessons learnt from recent major earthquakes. Then the views and approaches were solicited with contributions from Japan, Asia, Europe, North and South America on the new directions for Resilience-Based Design (RBD) in an effort towards catalysing and elaborating a comprehensive, collective and integrated approach to resilience. Currently running research projects on resilience, funded by the EU, were also presented.



## Introduction

Despite the substantial progress made in science and technology towards improved performance of the built environment, natural disasters, accidents and acts of terrorism have persistently been responsible for loss of life, disruption of commerce and financial networks, damaged property, and loss of business continuity and essential services during the last decades. Many physical infrastructures are vulnerable to natural hazards (e.g. along coastlines and in earthquake-prone regions) as well as man-made hazards, and across the world the risk of damage due to hazardous events continues to increase.

Major research activities on resilience-based earthquake engineering have been supported and coordinated by large research groups and networks. However, even with this progress the earthquake engineering community is facing many new challenges. The recent devastating earthquakes remind us that destructive events still threaten the lives of millions, their property, the social structure, and economic wellbeing of individuals, communities, and countries all over the world.

Today, the main question is: how do we use resilience-based seismic engineering to steward our built environment and make it safer, resilient and sustainable in the future? Our aim is to develop a common global vision for earthquake engineering and resilience design, while recognizing unique regional traditions. It has been the overarching objective of this workshop to assess and develop strategies on how to improve community resilience. Within this broad scope the intention was to chart a path for tackling new challenges in evaluation and repair of existing structures, design of new structures and infrastructure, in cost-effective risk management and in reducing disruption impact on society and economy in order to increase the resilience of the communities in which we live.

The workshop has comprised presentation and discussion sessions. The state of knowledge regarding disaster resilience has first been examined in the light of the lessons learnt from recent major earthquakes. Then the views and approaches were solicited with contributions from Europe, Japan, Asia, North and South America on the new directions for Resilience-Based Design (RBD). In these path-forward sessions, the group coordinator and six or seven speakers from each region presented their vision of where seismic engineering needs to be in order to enable the profession to better steward the built environment and make our society more resilient to natural disasters, and what needs to be done to get there. Small-group discussions were also fostered on: design and improvement of new and existing structures and infrastructure, implementation in engineering practice of research results and development and adoption of new civil/structural technologies and modelling tools.

As resilience is a re-sounding theme worldwide in diverse fields, it is worth noting that in the framework of the Europe 2020 strategy<sup>1</sup> the European Commission has been working in numerous policy areas related to resilience. These include developing new frameworks for disaster risk reduction and civil protection (i.e. forest fires, floods, droughts and other hazards), food security and other humanitarian crises – especially in Africa, structural measures and instruments to improve financial and economic stability within the EU, responding to epidemics and pandemics, stress tests for nuclear plants, the safety of critical infrastructures, etc.

Despite these laudable efforts, it is judged that “current investments and policy responses remain insufficient to effectively address existing risks, let alone to keep pace with emerging challenges”<sup>2</sup>. For a more resilient Europe, it is considered essential to set the right priorities and to focus scarce resources on key vulnerabilities. Scientific

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<sup>1</sup> COM(2010) 2020 final, ‘EUROPE 2020. A European strategy for smart, sustainable and inclusive growth’

<sup>2</sup> COM(2014) 216 final, ‘The post 2015 Hyogo Framework for Action: Managing risks to achieve resilience’, page 4

knowledge can play an important role in this regard by supporting policy- and decision-makers.

Transdisciplinary scientific and technical know-how has proven particularly useful in building resilience capacity, given the interconnectivity between our social, economic and ecological systems, on the one hand, and the need for multi-hazard approaches to tackle separate but often compounding risks, on the other. In this respect, representatives of projects on resilience of the EU Horizon 2020 programme presented their objectives and activities.

It is believed that the Workshop has created a successful forum where the different resilience approaches in the world and their eventual synergetic effects on future development were examined and discussed, as well as ideas on how to coordinate efforts among the world-leading engineering communities.

The First International Workshop on Resilience was co-organised by the Technical University of Turin and the Joint Research Centre. It was sponsored by the American Society of Civil Engineering (ASCE) and the Pacific Earthquake Engineering Research Centre (PEER).

# **OPENING LECTURES**



## **Resilience: The Structural Engineering Dilemma**

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The concept of seismic resilience formulated by MCEER and its affiliated researchers in 2003 (Bruneau et al. 2003) has been progressively more broadly endorsed over the years. This has happened in parallel with an at-large shift towards resilience across a large number of disciplines, focused or not on disaster preparedness and response, to the extent that the word “resilience” has permeated into everyday conversation, sometimes only abstractly (when not outright misused). Key to the original definition of resilience (including dictionary definitions), resilience is essentially and fundamentally the quality of being able to return quickly to a previous good condition after problems have occurred – which, with respect to the field of disaster mitigation, must therefore address both loss and recovery of functionality over time.

In other words, “functionality” is at the core of a workable definition of resilience that can be quantified. In that perspective, functionality can be defined in a number of ways that vary as a function of the services that are provided. In some engineering application, this information can be readily acquired, for example when the identification of functionality is a service and its measure is embedded into a metered distribution network (such as electricity, or water), even though these measures can at times be faulty or misleading for a number of reasons. Not surprisingly, a dominant segment of all resilience studies have focused on such distribution networks.

However, when it comes to individual engineered structures, the achievement of a resilient design is less directly obvious, particularly given that considering resilience from its greater context can effectively void efforts invested in making more resilient a single structure that is part of the total urban landscape (as the Christchurch earthquake demonstrated well). With some notable exceptions, such as lifeline bridges along major evacuation and supply routes or hospitals designed by strict state-enforced guidelines, community efforts at enhancing resilience at times are counter to the best intentions of structural engineers – hence the resilience dilemma.

In essence, structural engineers focusing on buildings face at least three resilience dilemma that can be enunciated as follows:

1) Resilience of the engineered infrastructure is something that most people do not care about, until after a disaster.

The problem is partly compounded by the fact that the design philosophy embedded in building codes is one of “life safety”, not “damage prevention”. This philosophy is often justified, by analogy, by the rational decision to buy a car with good crash-test ratings that would provide high expectations of survival of passengers in a major collision but where the car itself would be “totaled.” The fatal flaw in the analogy lies in the fact that car collisions, most of the time, involve no more than a few vehicles. When the majority of buildings in an urban area are designed following the life-safety perspective, the proper analogy should be that of a massive car pile-up involving hundreds of vehicles (the type that sometimes happen on icy roads in foggy driving conditions), where everybody ends-up in the same car-crash at the same time. When it comes to buildings, such widespread damage can lead to paralysis of a region or urban center, as happened following the Christchurch earthquake where the entire central business district was

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evacuated, cordoned, and then fenced-off for months to all except professionals involved in authorized response and recovery activities.

2) How can a structural engineer contribute to quantifying resilience?

If engineers are to contribute to such quantification/measurement, then it implies:

- A resilience framework that both defines resilience and what is to be measured;
- A method to quantify resilience;
- Strategies to enhance resilience (i.e., to engineer greater resilience), and;
- Multidisciplinary collaborations to comprehensively address the problem.

Some good strategies have been proposed to address these issues, but no consensus has been reached.

3) Making a Disaster Resilient Community Requires Multiple Owners and Stakeholders (with Varied Priorities, Values, and Interests) to Similarly Embrace Resilience

Much of the work on the quantification of resilience has been done on network systems. These typically have single owners or a few interdependent owners sharing a common infrastructure and common goals. This is not the case with buildings: there is generally a large number of different owners with different objectives within a specific community. As such, the concept of a "lifeline building" does not exist, unless that building is surrounded entirely by lifeline buildings, on a self-sufficient "lifeline island." Even if a single building had been made resilient to earthquakes, it could suffer damage from other surrounding buildings. Again, many buildings have performed well during the Christchurch earthquake but were rendered inaccessible (and therefore has no functionality) when owners were kept out of the Christchurch Business District after the earthquake. For these reasons, truly resilient communities may be decades away for some hazards.

Therefore, if resilience is to be achieved, there needs to be a mechanism to ensure that resilience is part of the discussion in the design of all buildings. Given the unlikelihood that building codes and specifications will require resilient design in the foreseeable future, and given that the interest in achieving resilient infrastructure has a tendency to subside as time from past damaging earthquakes increases, it is not clear how such a discussion will proceed.

In the meantime, while waiting for better solutions, the authors advance that a solution might be to create the "Lifeline (Resilient) Building District" concept. Figuratively speaking, such a community would be a self-contained "island" of buildings all having 5-Stars USRC resiliency rating, connected to transportation lifeline (to prevent Christchurch-type "encapsulation" and to link to critical facilities if needed), and having emergency back-up power generation, independent water purification and waste-treatment capabilities, and (possibly if too close to other non-resilient communities) its own security forces.

Keywords: resilience, structural engineering, multidisciplinary, buildings, functionality, loss.

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Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W. and von Winterfelt, D. 'A framework to quantitatively assess and enhance the seismic resilience of communities', *Earthquake Spectra*, Vol. 19, No 4, pp. 733-752.

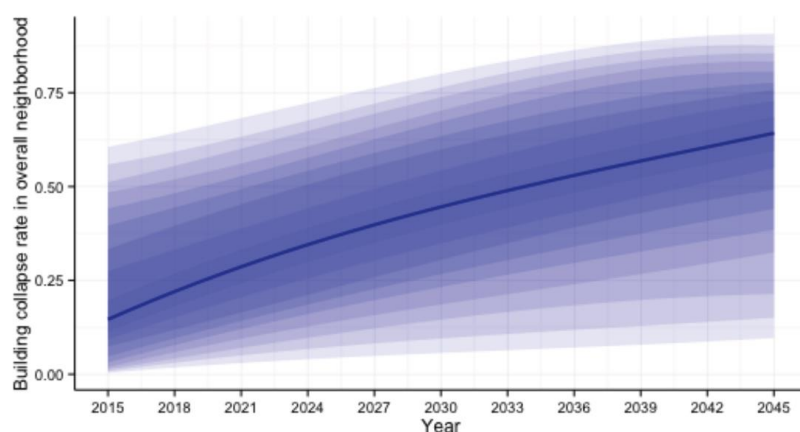
## Time Dependent Risk Assessment for Resilience Modeling

Anne Kiremidjian<sup>1</sup>, Luis Ceferino, David Lallemand and Gregory Deierlein

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One of the key components in urban resilience modelling is time. There are several time scales that need to be considered. These include the time when the event occurs in the future and the time that the urban region takes to recover. While the time to the next event is typically measured in terms of tens or hundreds of years, the time to recovery is measured in terms of months to at most several years. In this research the time to the next event is studied as it affects the size of the earthquake occurrence and thus the risk. Previous studies by Lallemand et al. (2017) have demonstrated that the risk to an urban region grows exponentially over time when the time since the last event, population growth and urban infrastructure growth are considered. Figure 1 shows the time dependent risk growth and the confidence bounds on the risk estimate. This growth in exposure and overall risk has direct effect on the ability of an area to respond, as the greater the risk the greater the demand for resources and reconstruction after an earthquake potentially increasing the time to recovery. Evaluation of this risk can help with the development of appropriate mitigation strategies to change the growth trajectory and increase the resilience of a community.



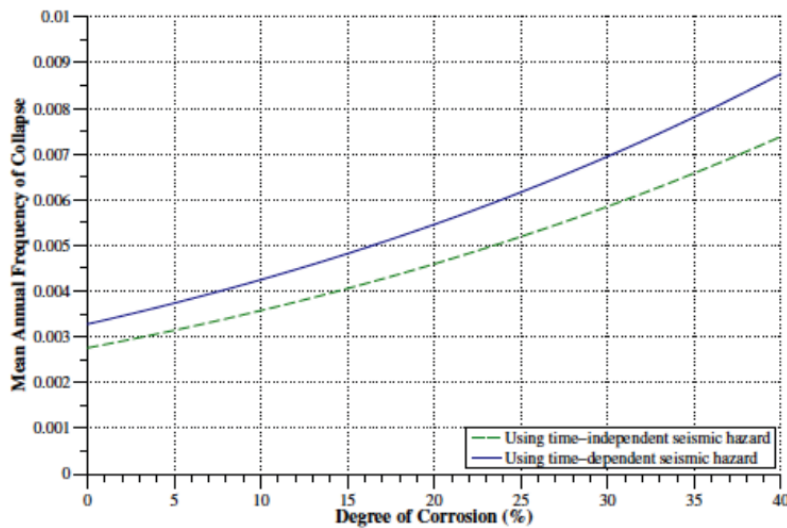
**Figure 1.** Increase in earthquake risk from building collapse as a function of time due to infrastructure growth, population growth, and increased vulnerability from incremental construction. Estimates for a neighborhood in Kathmandu, Nepal due to a reproduction of the 1934 Great Nepal--Bihar Earthquake (from Lallemand et al. 2017). Shaded areas correspond to different confidence bands.

The first step in the time dependent risk estimation is the development of time dependent earthquake occurrence models. Time dependent models are particularly important for regions where large earthquakes occur infrequently and the last event has occurred in a time long before the forecast time. The increase in risk with increased elapsed time since last earthquake was studied (Rao et al., 2017). Figure 2 shows the increase in risk from time independent to time dependent events.

We are currently working on an earthquake resilience model for medical response of an urban region during the emergency period following the event. The model considers scenario events and incorporates historical and physics based earthquake occurrence models. The resilience is measured by quantifying the demand resulting from injuries due to damaged and collapsed buildings over a region and the capacity of the system is represented by the ability of medical facilities to treat the injured.

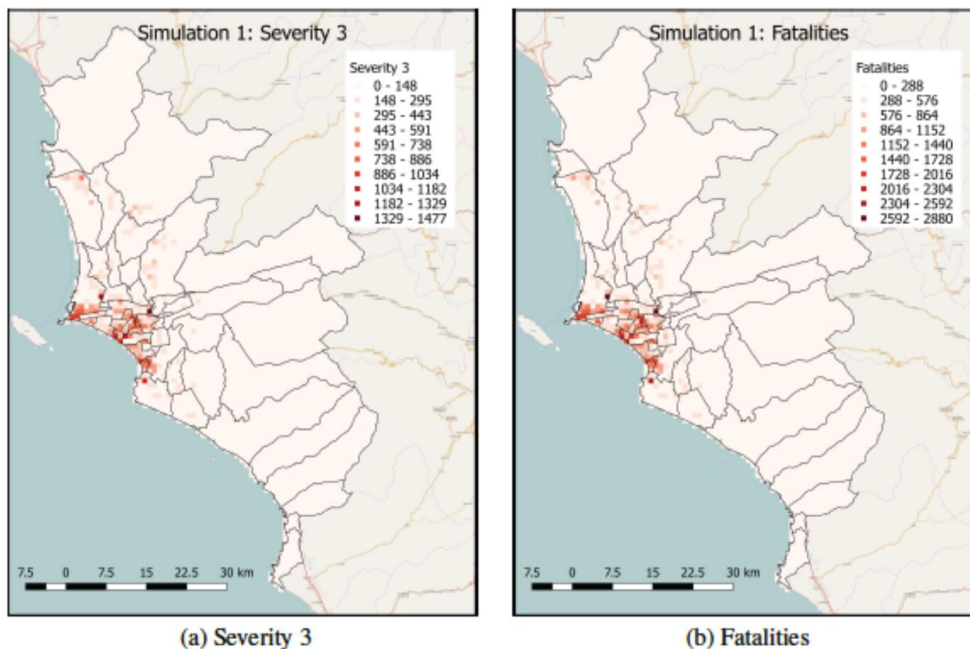
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**Figure 2.** Effect of time dependence on risk to reinforced concrete columns (from Rao et. al, 2017)

A stochastic model is developed to capture the number of injuries in different severity categories. The model takes into consideration the distribution of buildings over the region, their structural typology, and number of occupants (day/night) per building. Correlated ground motions are simulated for the scenario earthquake and the damage to buildings is estimated using fragility functions. Casualties, categorized from none to Severity Level 3 plus fatalities, are modeled by a multinomial distribution providing information on the number of injuries in each category over the affected region. Monte Carlo simulation and Central Limit Theorem (CTL) solutions are developed demonstrating that for a large region the CTL model provides reliable estimates of the casualties and their severities. The model is tested with data from Lima, Peru. (See Ceferino et al., 2017 for detailed description of the model.) Figure 3. Shows an example of the distribution of casualties and Fatalities in Lima, Peru for a magnitude 9 scenario event on the subduction zone off the coast of Peru.



**Figure 3.** Spatial distribution of casualties per square kilometer in Lima, Peru after a magnitude 9 scenario earthquake on the subduction zone off the coast of Peru.

The capacity of health facilities to respond are modeled by estimating their residual capacity after an earthquake that may have caused damage to the structures and utilities essential for functionality. Inventory of personnel and essential treatment material and equipment is estimated and a discrete--event model is developed to estimate the number

of injured that can be treated. A transportation network analysis model is incorporated for the transit of injuries from damaged buildings to health care facilities. The capacity component of the model is currently under development.

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## **The Social Landscape of Disaster Resilience**

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There is increasing interest in the resilience concept as a mechanism for moving from disaster risk reduction to sustainability. Efforts supported by the UNISDR to the US National Academies, to the UK Government Office for Science established priorities for policymakers in achieving disaster risk reduction through resilience. At the same time the philanthropic community in the form of the Rockefeller Foundation provided the financial means to create and support 100 global resilient cities. These activities were a precursor to the 2015 UN World Conference on Disaster Risk Reduction and its goal to reduce hazard exposure and vulnerability to disaster, increase preparedness, response, and recovery, and strengthen resilience. This keynote presentation reviews social science perspectives on disaster resilience. Taking the perspective of community resilience, the paper highlights what is known and not known conceptually about disaster resilience, how resilience knowledge is translated into practice, and innovations in measuring and modeling community resilience.

There are many definitions of disaster resilience, but the one that is the most expansive states that resilience is the “ability to prepare and plan for, absorb, recover from or more successfully adapt to actual or potential adverse events” (US National Research Council 2012:3). Disaster resilience sits at the intersection of natural systems, human systems, and the built environment (or engineered systems). It can be an outcome (its static dimension), a process (a dynamic dimension), or both. Resilience can be an inherent property within a system with pre-existing qualities, or it can adapt to changes in conditions. Resilience can be applied to multiple geographic scales from the local to global, and to multiple units of analyses such as individuals (people, structure), groups (e.g. elderly, sectors such as water, power), or spatially-defined entities (e.g. ecosystems, communities, cities).

The theoretical origins for disaster resilience and its measurement is in the disaster resilience of place (DROP) model which posits that antecedent conditions exist within communities where there are inherent vulnerabilities as well as inherent resilience. It should be noted that while there is a small degree of overlap between resilience and vulnerability, they are not the inverse of one another (Cutter et al. 2008). An event coupled with the coping responses of a community produces the hazard or disaster impact. If such an event (and the lack of coping responses) exceeds the capacity of the community to absorb the impact, then some form of improvisation, social learning, and adaptive resilience actions can take place to affect the degree of recovery which in turn influences the longer term mitigation activities post-event as well as the preparedness for the next event, thus altering the antecedent conditions and the cycle continues. While useful as a theoretical construct, the actual measurement of resilience is less advanced.

The development of resilience indicators in the US is a messy landscape of indices, tools, and scorecards, often focusing on different aspects of resilience (Cutter 2015). The measurement schemes employ qualitative to quantitative assessments and include top down to bottom up approaches. Spatially, there is local to global coverage in the tools and units of analysis ranging from the individual to the whole community. The focus of measurement either describes specific assets of resilience or else determines broader

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baselines for places. Finally, there are differences among the measurements which concentrate either on the characteristics or attributes of places that foster resilience or on the capacities within those places to undertake resilience. Specific examples include the Resilience Capacity Index (RCI) which is a top down quantitative tool based on census information. It is oriented towards metropolitan areas in the US and focuses on the capacity of cities to respond to stress (SUNY Buffalo Regional Institute 2017). Another example is NOAA's Coastal Resilience Index which is a locally-based bottom up qualitative tool designed to help communities assess how well they will function after a disaster (Sempier et al. 2010). The self-reported tool covers assessments of critical infrastructure and facilities, transportation, community plans and mitigation, business plans, and social systems.

The missing link among the measurement tools is the lack of a baseline—the starting point for assessment. How can you measure progress if you don't have a starting point? More importantly, how do you know if programs have been effective or whether resilience targets were reached without some initial point of reference? The challenge for any resilience measurement is the need for simplicity, the ability to replicate over time, meaningful inputs from local to national scales, and reliance on strong empirically-based evidence. One example of a tool that meets these requirements is the Baseline Resilience Index for Communities (BRIC) (Cutter et al. 2010; Cutter et al. 2014). Based on the disaster resilience of place (DROP) model, BRIC includes six different capitals for measuring resilience (social, economic, infrastructure, institutional, community capacity, and environmental) at the US county scale. It uses existing data from government agencies including the US Census for the 49 input variables and then creates a sub-index mean score for each of the capitals and then sums the average of each for the total score. The overall scores are then mapped by standard deviation to show regions of high and low resilience across the US. Each individual sub-index can also be mapped to illustrate the spatial variability in the components of resilience at the county scale, depicted from low to high areas of resilience.

A resilience measurement tool is useful for assessing and prioritizing goals. A baseline measurement tool helps to monitor progress and recognize success and is useful in understanding the costs and benefits of interventions to improve resilience. However, a single one-size fits all metric fits may not work for all places. Communities have the potential to develop or adapt simple measurement systems or tools to gauge their own baselines. While there are lots of tools out there for communities to choose from, few are used because they are too complex, unknown to citizens, or largely irrelevant to the community needs and expertise. Measurement tools cannot create a resilient community, but they can help show the pathway for becoming safer, stronger, and vibrant in the face of unanticipated events.

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# **CODES AND STANDARDS**



## **Holistic Design of Concrete Structures for Resilience to Blast, Impact, Fire and Earthquake**

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For an engineering system resilience can be mathematically defined as the functionality (percentagewise) of the system, integrated over time after the shock. In essence, Resilience-based-Engineering adds recovery time as another dimension to be catered for, besides the functionality retained right after the shock, which is the focus of Performance-based-Engineering. The design should then strive to: i) limit the instant loss of functionality by maximising robustness, and ii) facilitate and hasten recovery to full functionality.

The emphasis of resilience research placed on the scale of the community and on the economic, social and organisational facets of disasters may be warranted for major earthquakes, floods or CBRN (chemical/biological/radiological/nuclear) threats. However, it can be argued that the best means for resilience to extreme natural or man-made hazards (fire, blast, earthquake, etc.) are on the micro/meso-scale and derive from engineering:

- robustness and redundancy of individual physical infrastructures in order to minimise instant loss of functionality;
- efficient repair and recovery schemes.

Thus, new structures should possess by design robustness and redundancy for various threat scenarios, alongside coherent plans for repair and recovery. The huge inventory of existing and vulnerable structures can also profit to a limited extent from targeted retrofitting [6-8]. Hence, repair and recovery plans need to be in place.

The Structural Engineering community is not well-prepared for this new paradigm of design and retrofitting for resilience to extreme threats. Moreover, defining the probability of occurrence of such extreme threats may be a futile attempt, whereas quantifying their consequences is more tractable. Based on such considerations, the project PRESCIENT has been carried out at the Structures Laboratory of the University of Patras, which has focused on the technical consequences of the threats for structures, in order to limit them. Specifically, the project aspired to develop and promote a holistic paradigm for design of new structures and retrofitting of existing ones for resilience to postulated extreme threats, emphasising the two technical attributes of robustness and recovery.

A central idea has been that for a conceptual design against a portfolio of extreme threats one needs to achieve a single-concept holistic design, not a juxtaposition of multiple ones for different hazards, and for this it is necessary to know which structural features do favour resilience to all hazards and which ones help for some but hurt for others. Although the focus of the project was on concrete structures, which form the majority of new construction in Europe and of the vulnerable existing stock in need of protection from extreme loadings, PRESCIENT has also produced fundamental knowledge applicable to other construction materials.

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An overview and sample results of this project will be presented which derive from a concerted experimental and analytical /numerical investigation of the behaviour of critical components, subassemblies thereof and whole concrete structures of various types under simulated blast or impact, loss of columns due to these types of extreme events, or under exposure to fire or earthquake loading. Design measures which promote resilience to some types of extreme events, such as base isolation, uplifting and dry joints for earthquake, have been evaluated for blast or progressive collapse. The role of masonry infills against progressive collapse is also investigated. On the basis of the outcomes, structural features which are beneficial for one type of hazard but adverse for others are contrasted to those which favour resilience to multiple hazards.

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## **Resilient Seismic Codes in Chile: a Possible Challenge**

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Chile is characterized by the largest seismicity in the world which produces strong earthquakes every  $83 \pm 9$  years in the Central part of Chile, where it is located Santiago, the capital of Chile.

This short interval between large earthquakes magnitude 8.5 has conditioned the Chilean seismic design practice to achieve almost operational performance level, despite the fact that the Chilean Code NCh 433 "Earthquake Resistant Design of Buildings" declares a scope of life safe performance level due to legal liability.

The earthquake experience has shown that the response of the Chilean buildings has been close to operational. This can be attributed to the fact that the inter story drift of most engineered buildings designed in accordance with Chilean practice falls below 0,5%. (Lagos et al.2012). This operational performance is achieved at economic level accepted by the community.

Chile is unique in that it has a separate standard for industrial structures NCh 2369. Of 2003: "Earthquake - Resistant Design of Industrial Structures and Facilities" (Soules et al. 2016). This code declares a scope of operational level, which was successfully observed during the El Maule 2010 Chile earthquake magnitude 8.8.

However, during the 2010 Chile earthquake 189.451 dwelling – houses reported damage to insurance companies, 19.7% of the insured dwelling, mainly due non-structural damage. The total cost was U\$ 1256 million (Technical Report 2010).

Chilean people after 2010 Chile earthquake do not accepted the seismic design of life safe considered by engineers, despite its operational performance level, they look for a resilient design that guarantees fully operational performance after earthquake. This new requirement means a challenge that requires to evolve from the actual Chilean seismic codes of operational performance to resilient performance.

This is very important, since all seismic codes in Chile are enforced by law with liability implications.

In this paper are discussed the main code changes required to reach this new level, in particular the behavior of lintels in reinforced concrete buildings which actually are accepted in the design to be seismic fuse. The failure of lintels fuse in 2010 Maule earthquake produced that people was locked in their own apartments. They could not escape during aftershocks due to broken lintels, which did not allow to open doors of apartments.

The seismic non-structural elements behavior was partially corrected after the 2010 Chile earthquake in the new code 3357 "Seismic Design of non-structural components and systems", however it requires revision to achieve the resilient standard.

The new resilient code will not guarantee the good performance of building content. For that scope Chilean code NCh 2375 of 2003 (NCh 2003) of seismic isolation must be considered.

A resilient design code is not a chimera considering that overland zone of Santiago subway performed fully operational after 1985 and 2010 Chile earthquake. See Figure 1.

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An additional limitation to introduce a vanguard code based in resilience is the liability of structural engineers, matter that also reviewed in this paper since it will produce natural opposition of professional community.

Despite the limitations indicated above it concludes that it is possible to develop in Chile a future resilient seismic code.

**Figure 1.** Seismic fully operational performance of overland zones of Santiago Metro (subway) after 1985 and 2010 earthquakes.



Keywords: resilient code, Chile. Maule earthquake 2010.

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## **Building Resilient Communities: A Systemic Approach based on Lessons and Challenges from Grass Root Level Initiatives in India and Japan**

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Chile Disasters especially the large scale and catastrophic ones significantly shift bio-physical systems and create economic crises that cascade across national and regional borders. The resultant processes of change, their cascading effect and the thresholds they set for response, challenge the risk governance systems and their capabilities at all levels. The local communities are always the worst hit. Failures in disaster response, the experience the world over show, are invariably due to weak or practically non-existent resilience systems at the local government and community levels.

Generally disaster response is taken to be the responsibility of the government sector. City government disaster response is normally based on the national or regional government policies and action. City governments' disaster response actions, experience show, remain largely ineffective in meeting the emergent needs of the local communities. The common problem is lack of understanding of the community level needs and priorities at the government level and a general dominance of top-down approach by the government coupled with the apathy towards community capabilities to reduce risk and enhance resiliency.

We know from large number of field experiences over the world that local communities can play a critical role in reducing risk to disaster and also create structural resilience and be pro-active to reduce all impact of disasters. It is common knowledge that over 90% of lives saved in disasters is due to the local level initiatives and response actions.

There is a global trend now to plan for synergy interface between the top-down government disaster response and the bottom-up community based disaster response. It is also well realized how essential it is to create resilient communities and resilient local governments through the process. Related important question need to be answered. What mechanisms can help to tie up better all actions of the government and of the community in disaster response? What are the processes and mechanisms that are best to create resilient communities in a given socio-economic scenario? Can scientific and systemic search in this aspect provide some norm or guideline to design the mechanisms and processes?

The paper draws on lessons learnt from real world field situations in India and Japan in order to arrive at answers to the above questions. The reference is to the four year (2009-13) project, Community-Led Disaster Management (CLDM) in Mumbai mega city supported by Kyoto University and the Govt. of Japan. Other reference is to grass root initiatives in disaster risk reduction, community organization for resiliency in Kyoto and Nagoya cities in Japan. In these projects the author has been closely involved. A systemic search is focused on vulnerability assessment at the micro level, promotion of sustainable core leadership for action, technical knowledge building for scientific decision making and conflict resolution, enhancing capability to prepare local resiliency plan and designing mechanisms to implement the plan and promotion of community level bargaining power to work together with the city government for disaster risk reduction.

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## **Sustainability and Resilience in Seismic Areas: an Exciting Challenge for Civil Engineers**

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The constant search for a satisfactory economic development contrasts with the respect of the environment. The main categories of problems that arise are pollution and environmental degradation, depletion of natural resources and waste accumulation, chaotic urban growth. The construction industry is the most important responsible, directly and indirectly, of the destruction and degradation of natural resources, of the production and accumulation of waste and environmental impact. The challenge for civil engineers, involved in designing systems of infrastructures, is looking for new solutions for an effective sustainable development.

First question: can sustainability exist without safety? Obviously it cannot. There is neither development nor meeting of needs if the human life is not adequately protected. Among the most important causes of victims are the natural disasters such as earthquakes, which cause damage and collapse of buildings and other structures. So the good quality of the structures assumes an important role in the sustainable development.

Second question: can safety be acceptable if resilience is low? Obviously it cannot. It is very important to be able to recover in short time the previous situation, or even a better one, after a disaster. Resilience should be guaranteed by means of the good quality of all the structures but also by means of a suitable organization of the urban territory. The first aspect can be guaranteed by means of a good evaluation of the actions to be considered in the structural design and in suitable conservative structural choices. The second should include a suitable organization of the internal transportation systems and of the external connections, but also a sufficient number of anti-seismic buildings to be used also just after an earthquake. These should not be built on purpose but could be structures with dual use, i.e., normally used as such as schools or sports hall or gyms, but useful for the strategic functions or for the homeless in case of natural disasters.

In order to contribute to the discussion about sustainability and resilience the definition of the seismic input and the hypotheses about the structural behaviour beyond the elastic range are analysed in detail.

The correct and complete description of the seismic input for structural design is given by the acceleration components along three orthogonal axes, two horizontal and one vertical, recorded during a suitable number of real events at the site. Technical codes usually give horizontal and vertical elastic response spectra, which are used to determine directly the maximum seismic effects on structures when using linear analysis, and are the reference spectra for the definition of a suitable set of synthetic accelerograms. The horizontal acceleration response spectrum, usually given for a rigid soil with horizontal surface, is defined by means of the horizontal peak ground acceleration ( $PGA_A$ , i.e., the value at the period  $T = 0$ ; the subscript "A" indicate rigid soil, according Eurocode 8), the maximum amplification  $F$  (i.e., the ratio between the maximum amplitude of the spectrum and that at  $T = 0$ ), and the value  $T_{CA}$  (we use this symbol for the period  $T_C$  on rigid soil) of the period that is the upper limit of the range in which the spectral acceleration is constant. All the other parameters, such as the values of the periods that separate the different portion of the spectrum,  $T_B$  and  $T_D$ , can be derived from these.

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How are defined these hazard parameters? Usually the probability of exceedance  $P_{NCR50} = 10\%$  is assumed for ordinary buildings, as recommended also by Eurocode 8. This choice entails a certain risk. For example, in the Italian territory the ratio between the  $PGA_A$  relative to  $P_{NCR50} = 10\%$  and those relative to  $P_{NCR50} = 2\%$  is quite variable and assume an average value of about 0.55. It is worth reminding that the seismic waves can be amplified due to site effects. Therefore an accurate seismic local response is recommended especially for strategic and relevant structures (Clemente et al., 2015).

A suitable prevention policy should impose the assumption of the most severe seismic actions for the structural design. This translates in considering for the design the seismic actions corresponding to the minimum value of the probability of exceedance in 50 years  $P_{NCR50} = 2\%$  or to the maximum credible earthquake (MCE), for the ultimate limit state checks (no-collapse). The damage limit state checks should be done with reference to lower earthquake intensity, accounting for a credible and suitable ductility, which should also guarantee a low level of damage.

Designing traditional structures in the elastic range has always considered not convenient, both for economic and architectural considerations. A maximum design spectral value  $S_{d,max}$  could be suggested, based on economic and architectural considerations, for which the linear elastic design is requested. It is a function of the materials and the structural type and can be individualized as the value of  $S_d$  beyond which the cost increases significantly. For the design the assumed  $S_{d,max}$  should be compared with the elastic spectral amplitude the fundamental period  $T$  of the structure: if  $S_e(T) \leq S_{d,max}$ , then the elastic value  $S_e(T)$  should be assumed as design value; if  $S_e(T) > S_{d,max}$ , then  $S_{d,max}$  should be assumed as design spectral value, and the structure should be able to dissipate energy corresponding to the required behaviour factor.

As a result, the behaviour factor will depend on the ratio between the actual elastic spectral amplitude  $S_e(T)$ , which is a function of the seismic hazard at the site and of the fundamental period of vibration of the structure, and  $S_{d,max}$ . So it is variable also for a given response spectrum. The suggested procedure is usual when designing base isolated buildings, for which the period is chosen in order to reach a spectral amplitude low enough to design the superstructure in the elastic range (Clemente and Buffarini, 2010).

In order to guarantee the elastic design also in high seismicity areas, a suitable limitation of the building height, with respect to the size in plan, could be considered and, alternatively, the use of new anti-seismic technologies.

After any natural disaster the next phases follow each other: i) the emergency phase, in which the civil protection system intervenes immediately after the event and organizes the housing in tents or hotels in nearby areas, if available; ii) the post-emergency, in which containers or temporary houses are used for the homeless, often single-storey wooden houses but sometimes multi-storeys wooden, concrete or steel buildings; iii) the reconstruction phase, at the end of which people are transferred in buildings repaired or rebuilt.

The recent experiences demonstrated that, in developed countries, the emergency phase can be organized in few hours, while the construction of temporary houses or buildings requires few weeks or months. The reconstruction phase could require several years. The cost of the emergency phase is always quite high as well as the cost of the temporary housing and containers, almost never reusable after reconstruction, or permanent buildings, whose reuse requires additional costs for the adaptation. It is obvious that an effective accommodation and a rapid reconstruction reduce time and costs. Earthquakes strike suddenly and organization of emergency and post-emergency is always difficult. The preparation of emergency plans would be an important step forward for the system of civil protection. It appears useful the choice and predisposition, in "peacetime", of areas to accommodate temporary housing, equipped with the necessary infrastructure. The production and the assembly of these housing should be possible in the shortest time after the event. Furthermore, each municipality should have public constructions, such as schools, sports halls and public buildings in general, designed with adequate safety

factors or equipped with modern seismic protection systems, to be used in the emergency phase. These should be designed suitably flexible or able to contain tents.

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# **EUROPEAN FRAMEWORKS**



## **Operationalize European Resilience Management Guidelines in Urban Transport Systems: the RESOLUTE Project Approach**

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Increasing resilience to critical events is a topic of highest political concern in the EU. Regarding the case of transport systems, operations have developed a prominent safety and business critical nature, in view of which current practices have shown evidence of important limitations in terms of resilience management. Enhancing resilience in transport systems is considered imperative for two main reasons: such systems provide critical support to every socio-economic activity and are currently themselves one of the most important economic sectors and secondly, the paths that convey people, goods and information, are the same through which risks are propagated.

The RESOLUTE EC-funded project, based on the vision of achieving sustained adaptability of UTS (Urban Transportation System) to enhance resilience, is tackling these challenges. The final goal of RESOLUTE is to adapt and adopt the identified methods for the operationalization of the European Resilience Management Guidelines and for their evaluation when addressing UTS as a Critical Infrastructure.

The resilience is considered an emergent property of a complex system and it is about managing high variability and uncertainty in order to continuously pursue successful performance of a system. Understanding the sources of operational variability, the mechanisms through which it may potentially propagate and the impact on the system performance, are at the core of RESOLUTE approach. The resources and system capacities needed to manage and cope with operational variability are the main drivers of the analysis.

The issue at hand is to deliver management guidance on such human, technical and organisational elements, aiming to respond to different and possibly conflicting local operational needs, whilst achieving fundamental system level synchronisation and coordination that, as best possible, ensures successful operation. This requires three fundamental methodological stages:

(i) system analysis and understanding in support of the identification of relevant aspects and critical functions through the application of tools like FRAM, RAG and Network analysis/science techniques that also permit to infer, model, simulate and predict possible events propagation, preventing/mitigating cascading behaviour in the Network-of-Networks (NoN).

(ii) (Big) Data (i.e. from the smart city) gathering, semantic processing and mining to connect data flows to the models. Such a data driven analysis provides the means to assess the levels of criticality of interdependencies at evidence and quantitative level and seeks to enhance the capabilities of UTS to take right decision at strategic, tactical and operational level, with the aim of maintaining operations under continuously changing conditions;

(iii) a Collaborative Resilience Assessment and Management Support System able to adopt an highly synergic approach towards the definition of a resilience model for the next-generation of collaborative emergency services and decision making process. Within this framework, it can be stated that the pursuit of RESOLUTE objectives faces the challenge of relating dynamic and emergent system features, to a wide diversity of

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human, technical and organisational elements that at each time and place, generate equally diversified operational needs.

## **Application of Resilience Concepts to Critical Infrastructure in the IMPROVER Project**

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The impact of disasters and crises in Europe is characterised by a highly interconnected society - a society which is increasingly reliant on critical infrastructures providing centralised services. Through cascading failures through interdependent systems the indirect consequences of natural and man-made disasters may be more severe than expected.

Traditionally, the prevalent strategy to reduce the risk to critical infrastructure exposed to natural and man-made hazards has been to protect it. However, the very nature of crises means that they are initiated by low probability events or sequences of events. Such rare events rarely unfold in the way you expect them to, and protecting infrastructure against all types of incidents ranges from difficult or costly to technologically impossible or prohibitively expensive. Recent years have therefore seen a shift in focus – not only in policy and technological analysis but also on the political level, including the EU - from protection of critical infrastructure to resilience of critical infrastructure.

Despite this change and the increasing interdependencies, there is no common European methodology for measuring or implementing resilience, and different countries and sectors employ their own practices. Neither is there a shared, well-developed system-of-systems approach, which would be able to test the effects of dependencies and interdependencies between individual critical infrastructures and sectors. This increases the risk as a result of reliance on critical infrastructures, as well as affects the ability for sharing resources for incident planning due to the lack of a common terminology or common means of expressing risk.

The IMPROVER project (Improved risk evaluation and application of resilience concepts to critical infrastructure) aims at contributing to improving infrastructure resilience through the implementation of resilience concepts to real life examples of pan-European significance, including cross-border examples. The project aims to develop a risk based methodology, compatible with the EU risk assessment guidelines, for operationalising resilience for critical infrastructure. The project addresses both the infrastructure itself as well as the population, trying to understand their expectations of critical infrastructure performance in times of crises.

This presentation will give an overview of the progress within the project to date and will introduce some of the novel techniques and applications which we are working with for assessing the resilience of critical infrastructure within Europe. Building on work presented elsewhere, the presentation will include an application of the IMPROVER Critical Infrastructure Resilience Indicator (CIRI) to critical infrastructure in Europe. We

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will also present current work on the role of CI operators in responding to crises to improve their organisations resilience and include this in the application shown.

Keywords: resilience, critical infrastructure, interdependencies, engineering resilience, organizational resilience

## **A New Approach to Quantify the Resilience of a Community within the PEOPLES Framework**

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The multiple uncertainties of both natural and man-made disasters have prompted increased attention in the topic of resilience engineering (Wagner and Breil 2013). Several solutions for measuring resilience are available in the literature (Cimellaro 2016; Cimellaro et al. 2014). In this paper, an indicator-based approach for measuring urban community resilience within the PEOPLES framework is proposed. PEOPLES is a framework for defining and measuring disaster resilience of communities at various scales (Cimellaro et al. 2016). It consists of seven dimensions, each of which is split into several components. Relevant indicators have been selected from the literature to describe the framework's components in details. To do so, resilience indicators found in the literature have been collected and then filtered with the purpose of obtaining mutually exclusive indicators. This has necessitated rejecting a number of indicators either because they are not relevant or because they overlapped with other indicators. Each indicator has been associated with a measure allowing it to be quantified. The interdependency between the framework's variables (indicators, components, dimensions) has been tackled by introducing an interdependency matrix technique (CCSF Lifelines Council 2014; NIST 2015). The proposed interdependency technique returns as an output a weighting factor for each variable indicating its importance towards the resilience evaluation. For the purpose of the analysis, the variables of PEOPLES are classified into three major groups as follows:

1. Indicators that fall within a component are considered as a group;
2. Components classified under a dimension are taken as a group;
3. PEOPLES seven dimensions fall in one group.

Variables in the same groups are put together in a  $[n \times n]$  square matrix, where  $n$  is the number of variables in the analysed group. The cells in the matrix can take the values 0 or 1. The value 0 means that the functionality of the variable in the row does not depend on the variable in the column, while the value 1 means that the variable in the row depends on the variable in the column. The importance factor of the each variable is obtained by summing up the numbers in each column of the matrix. A high value implies high importance of the corresponding variable. The interdependency analysis is done in a hierarchical manner. That is, an interdependency matrix is built for each group of variables so that each variable is analysed within the group it belongs to. The matrix can be filled using a walk down survey. The evaluation is performed through an expert and the information is readily provided in a (yes/no) or (1/0) form. The experts will be able to employ their knowledge to decide whether the answer should be yes or no (1 or 0). The interdependency between the variables is greatly related to the community type. For instance, urban communities usually have more interdependencies between its different sectors than other types of communities given a specific hazard. The effects of the hazard type and the temporal variation of the community's characteristics have also been discussed in the paper.

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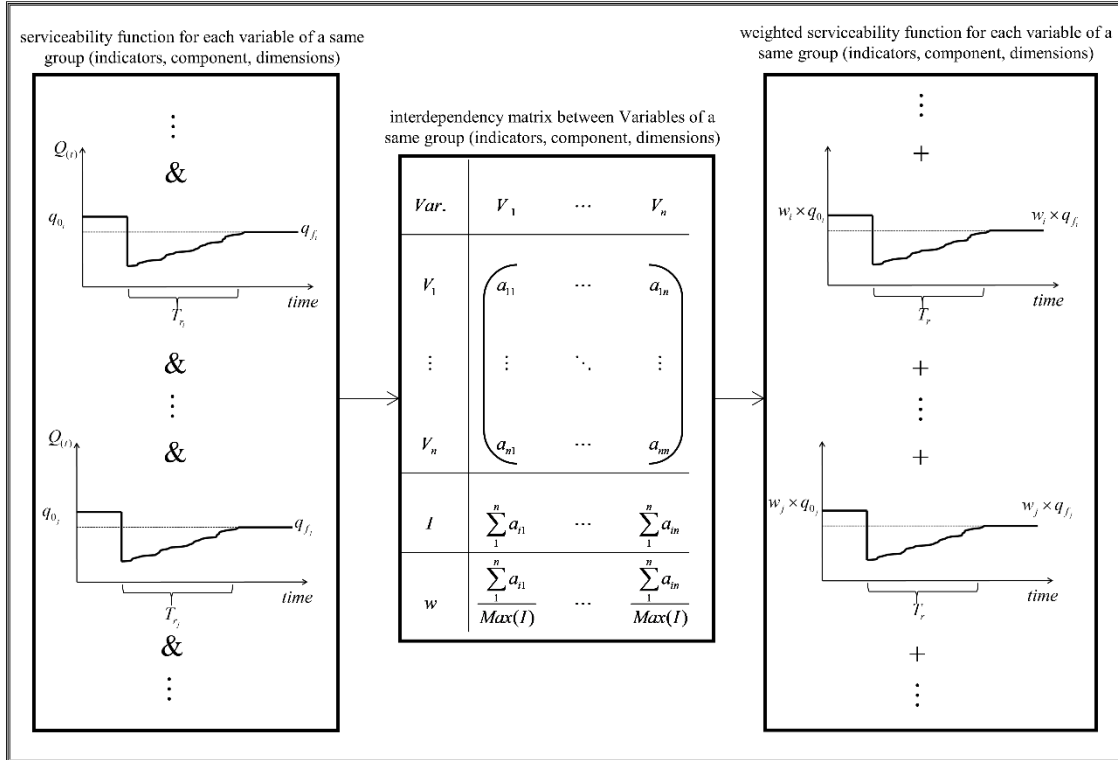
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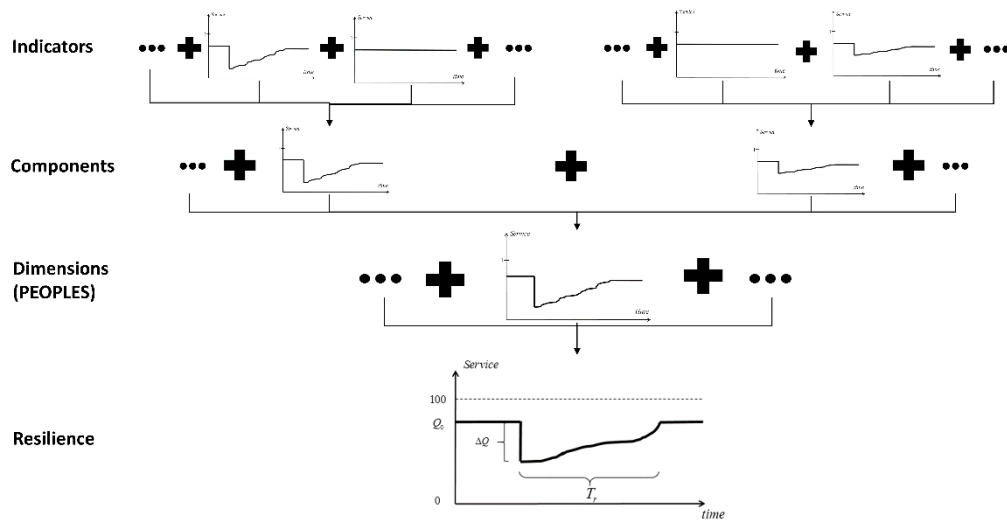
After obtaining weighting factors for the variables of the PEOPLES framework, a serviceability function is built for each variable. The serviceability function can be defined using a set of parameters that mark the outline of the serviceability function (e.g. initial serviceability  $q_0$ , post disaster serviceability  $q_1$ , restoration time  $T_r$ , recovered serviceability  $q_f$ ). These parameters can be obtained from the past events and/or by performing hazard analyses specific to each variable. Afterwards, all serviceability functions are weighted based on their contribution in the resilience assessment using the weighting factors obtained from the interdependency analysis described before. Figure 1 provides a schematic representation of the introduced methodology. Finally, the average of the weighted serviceability functions of the variables in the same group is considered to move to an upper layer (Figure 2). That is, to obtain the serviceability function of component  $i$ , the average of the weighted serviceability functions of the indicators under component  $i$  is considered. Similarly, to obtain the serviceability function of dimension  $i$ , the average of the weighted serviceability functions of the components under dimension  $i$  is considered. Finally, the serviceability function of the community is the average of the weighted serviceability functions of the seven dimensions. The resilience index of the community is then evaluated as the area under the final serviceability function.

**Figure 1** A schematic representation of the methodology introduced to compute community resilience



The introduced method is a decision making tool and the usefulness of the final resilience metric is to give an indication whether the community needs to improve in terms of the resilience by comparing it to a given acceptable level. Using this metric, the user can identify immediately if the community is experiencing a high serviceability deficiency, then the user can decide to look into specific components and indicators that are found to cause the highest impact on resilience. The significance of the proposed methodology lies in its graphical representation that helps communities take proper actions to improve their resilience. While all previous works generally provide a single index to measure community resilience, the proposed method indicates in details whether the resilience deficiency is caused by the system's lack of robustness or by the slow restoration process.

**Figure 2** Deriving the serviceability function of the community



The proposed method identifies where exactly resources should be spent to efficiently improve resilience. The final resilience index allows the user to have a broad picture about the resilience of the community, while the functionality curves of single indicators are used for analyses that focus more on specific resilience issues of the community. As a case study, the proposed methodology has been applied to the city of San Francisco for which the serviceability curve and the resilience metric have been derived.

## Acknowledgment

The research leading to these results has received funding from the European Research Council under the Grant Agreement n° ERC\_IDEAL RESCUE\_637842 of the project IDEAL RESCUE—Integrated Design and Control of Sustainable Communities during Emergencies.

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## **The RESILENS Project Approach**

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The rapid expansion of cities in recent decades is exposing a larger number of people and critical infrastructures to the threat of disasters and crisis events, and posing additional challenges for the design, planning and management of urban areas. Indeed, a number of recent high impact crisis events have highlighted the vulnerability, complexity and interdependency of contemporary urban infrastructure systems. In light of these developments, the capacity of cities to mitigate, prepare, respond or recover from these challenges, and how such capacities can be enhanced, has become a critical urban policy question. As such, concepts like 'urban resilience' - typically presented as the ability of cities to 'bounce back' or even 'bounce forward' from a disturbance or crisis event - have grown in importance. Indeed, ideas connected to the 'resilience' concept continue to permeate through a range of disparate disciplinary areas, a range of policy narratives, worlds of professional practice and the popular media.

Within the sphere of urban decision making, 'resilience', has entered into discourse with different orientations. Although the focus has traditionally been placed on environmental issues, in particular the reduction or mitigation of environmental risks such as earthquakes, floods, and global warming, there has been a rather rapid increase of the fields where the concept is used. The expansion of the concept has also inevitably led to problems of certainty and clarity around what sense and meaning the concept actually assumes, as well as in its translation into urban policy and practice. Thus, there remains debate around how 'resilience' can be best operationalised by decision makers in practice. This contribution is particularly concerned with the resilience of critical infrastructure (CI), and the ways in which urban decision makers (planners, engineers, infrastructure operators etc.) can be best supported in seeking to enhance the security and resilience of such developments. In doing so, it presents the ongoing progress and emerging findings from European Commission, H2020 funded project RESILENS (Realising European ReSILience for Critical INfraStructure) which is coordinated by Future Analytics Consulting and will run for three years – between 2015-2018.

CI provides essential functions and services that support European societal, economic and environmental systems. As both natural and man-made threats, disaster and crisis situations become more commonplace, the need to ensure the resilience of CI so that it is capable of withstanding, adapting and recovering from adverse events, is paramount. Moreover, whilst a breakdown in any CI alone can bring about catastrophic consequences, it is the interdependency of these systems, and by extension, the cascading effects of a breakdown in one system on other interconnected systems, which is of most significant concern. As an example, a fault in the electricity transmission network in Northern Germany in 2006, resulted in a blackout for more than 15 million people across Western Europe, triggering cascading effects on transport, healthcare systems, financial services and societal security and safety. Thus, moving resilience from a conceptual understanding to applied, operational measures that integrate best practice from the related realm of risk management and vulnerability assessment an the important focus of the RESILENS project.

The project defines resilience in the following manner:

"Resilience is the ability of a system or systems to survive and thrive in the face of a complex, uncertain and ever-changing future. It is a way of thinking about both short term cycles and long term trends: minimizing disruptions in the face of shocks and

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stresses, recovering rapidly when they do occur, and adapting steadily to become better able to thrive as conditions continue to change”

Over the course of the project, RESILENS will develop a European Resilience Management Guideline (ERMG) to support the practical application of resilience to all CI sectors. Accompanying the ERMG will be a Resilience Management Matrix and Audit Toolkit which will enable CI systems (encompassing assets and organisations) quantitatively and qualitatively index their level of resilience. The proposed toolkit will also allow for the quantitative analysis of the resilience of the CI systems at different spatial scales (urban, regional, national and trans-boundary), which can then be iteratively used to direct users to aspects of their systems where resources could be concentrated in order to further improve their resilience levels. The ERMG and resilience management methods are being tested and validated through ongoing stakeholder engagement, table-top exercises and three large scale pilots (transport CI, electricity CI and water CI) in three different European contexts – Ireland, Portugal and Germany. The finalised ERMG and accompanying resilience methods will be hosted on an interactive web based platform, the RESILENS Decision Support Platform (RES-DSP). The RES-DSP will also host an e-learning hub that will provide further guidance and training on CI resilience. Overall, RESILENS will aim to further advance the state of the art in CI resilience management and intends to increase and optimise the uptake of resilience measures by CI stakeholders.

For more information, please visit our project website – [www.resilens.eu](http://www.resilens.eu).

## **DARWIN – H2020 Project - Expect the Unexpected and Know How to Respond - Current Findings and Way Forward**

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In recent years, crises and disasters (Eyjafjallajökull and Deepwater Horizon 2010, Fukushima Daiichi 2011) have made it obvious that a more resilient approach to preparing for and dealing with such events is needed. DARWIN aims to improve response to expected and unexpected crises affecting critical infrastructures (CI) and social structures. It addresses the management of both man-made events and natural events. The main objective is the development of European resilience management guidelines. These will improve the ability of stakeholders to anticipate, monitor, respond, adapt, learn and evolve, to operate efficiently in the face of crises.

The DARWIN Resilience Management Guidelines (DRMG) are currently in the process of being developed on different formats including a WIKI platform intended for both easy access by potential end users and continuous improvement, with the help of interested stakeholders. The DRMG are guiding principles to help or advice CI stakeholders in the creation, assessment or improvement of their own guidelines or procedures, as well as in developing a critical view of their own crisis management activities, based on resilience management concepts. The target beneficiaries are crisis management actors and stakeholders responsible for public safety, such as critical infrastructures and service providers, which might be affected by a crisis, as well as the public and media. The DRMG are evaluated in the context of in depth pilot-exercises with involvement of stakeholders from different sectors, reflecting around examples of crisis scenarios originated in the Air Traffic Control and Healthcare domains. To enable a dynamic, user-friendly usage of guidelines, the project also adopts innovative tools (e.g. serious gaming) and establish knowledge about how organizations can implement guidelines to improve resilience.

To ensure transnational, cross-sector applicability, long-term relevance and uptake of project results, a DARWIN Community of Practitioners (DCoP) has been established, including stakeholders and end-users from a wide variety of domains, not limited to Air Traffic Control and Healthcare. The DCoP members are involved in an iterative development and evaluation process, which make them co-creators of the guidelines.

### **Acknowledgements**

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**Keywords:** Resilience, Resilience Engineering, Community Resilience, Crisis Management, Air Traffic Management, Health care, Critical Infrastructures

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## **Project SMR – Smart Mature Resilience**

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### **A Holistic Approach to Resilience**

Smart Mature Resilience is a multi-disciplinary research project working for more resilient cities in Europe. It is a research project aiming at delivering a Resilience Management Guideline to support city decision-makers in implementing resilience measures in their cities. The Resilience Management Guideline is a set of practical tools piloted in a core group of cities and shared with a wider group of cities, strengthening the nexus of Europe's resilient.

Actually, SMR is focused to a holistic approach to urban resilience assessment, considering all the aspects of the matter (namely, critical infrastructures, social dynamics, and climate change, including natural and man-made risks). SMR objectives can be summarized as follows:

1. Develop and validate a Systemic Risk Assessment which can assist in determining the resilience maturity level.
2. Develop and validate a Resilience Maturity Model defining the trajectory of cities through measurable resilience levels.
3. Develop a portfolio of Resilience Building Policies that enable progression towards higher maturity levels.
4. Develop and test a System Dynamics Model to diagnose and monitor resilience building policies.
5. Develop a Resilience Engagement and Communication Tool to integrate citizens in community resilience.

### **Urban Resilience**

The field of application of SMR research and results is closely connected to urban resilience, since urbanization is a definite trend and cities are particularly sensitive environments in terms of exposure to natural and man-made risks and to social and political issues. SMR aims to analyze cities from the perspective of serving their citizens and their metropolitan areas from a multi-level governance perspective. For this purpose, networking among cities involved in the project is of paramount importance.

Participants of the project are grouped in a consortium made of 4 Universities (University of Navarra-ES, as coordinator; CIEM University of Agder-NO; University of Strathclyde-GB; Linköping University-SE); 1 Local Government network (ICLEI European Secretariat-DE); 1 Standardization Institute (DIN- Deutsche Institut für Normung-DE) and 7 City Local Governments (Kristiansand-NO, Donostia-ES, Glasgow-GB, Vejle-DK, Bristol-GB, Rome-IT, Riga-LV).

The definition of the aforementioned Maturity Model is the first outcome of SMR. It classifies cities into five levels of resilience, according to well-known and recognized

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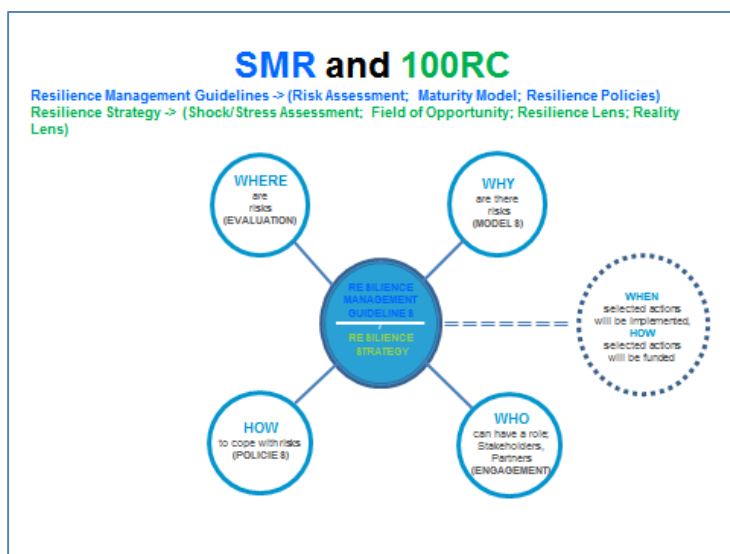
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indicators. The Maturity Model is the most important step for the development of the Resilience Management Guidelines, final goal of the project.

### Integration and synergies with other projects on Urban Resilience: the case of Rome

The city of Rome can benefit from a twofold approach to the study of Urban Resilience. Generally speaking, resilience is a quite new science and its definition, its functions and applications are still developing themes. This is particularly true for Urban Resilience, which requires a multi-functional and multi-disciplinary approach. The second ongoing project for the City of Rome is the 100 Resilient Cities initiative (100RC), an important international project funded by the Rockefeller Foundation to develop resilience strategies in very different urban frameworks.



The methodology adopted by 100RC is to some extent different from that of SMR, since it is more focused on communication and participation of stakeholders. Nevertheless, it aims at outlining a Resilience Strategy, likewise SMR. Hence, the added value is the opportunity to work on Urban Resilience by two slightly different approaches.

In the case of Rome, as a preliminary result coming from both the projects, 8 major challenges (or Focus Resilience Areas) have been identified:

1. Abandoned Public/Private Real Property (abandoned Real Property is a cost and a constraint to urban development; this should lead to a re-thinking of public services and new forms of housing and productive activities)
2. Cultural Heritage and Natural Resources (Rome has a high number of resources, sometimes poorly integrated into the life of the city; moreover, the impact of climate and anthropogenic risks on fragile, unique and, above all, unreplaceable assets must be considered)
3. Vulnerable Population (terms are those of social-demographic challenges, such as aging population, new immigrants, exclusion, poverty, family ties changes)
4. Critical Infrastructures (the city's infrastructure system – namely the public transport system – is highly vulnerable due to uninterrupted heavy stress conditions and the lacking of sufficient redundancy)
5. Immigration (the challenge arises from the impact of immigration waves on the ordinary urban management, putting pressure on a public service system already under heavy stress conditions)
6. Terrorism (the city has got high symbolic value, because of its touristic appeal and its proximity to immigration routes. However, compared to other EU capitals, Rome has no secluded communities, easing a more effective intelligence activity).
7. Climate Change (in the case of Rome, effects of climate change are relevant to increasing flash floods and heat waves. These two risks are amplified because of an aging population and the extremely fragile cultural-historic heritage)

8. Governance and Participation (a rational use of significant resources of data, experience, know-how must be developed; the social capital of the city, though abundant in forms of active citizenship, is neither systemic nor adequately recognized)

The process is now ongoing to assess priorities (according to real needs, relevance and urgency) and to define opportunities (in order to validate the work with feasible policy directions and fund posting evaluation).

Aiming at the establishment of an operational Resilience Office within the City Council setup, it can be said that SMR and 100RC are milestones in the complex path to Urban Resilience assessment.

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## **Extreme Loading Analysis of Petrochemical Plants and Design of Metamaterial-based Shields for Enhanced Resilience: The Horizon 2020 Innovative Training Network Project XP-RESILIENCE**

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The tremendous impact of natural hazards, such as earthquakes, tsunamis, flooding, etc., which triggered technological accidents, referred to as natural-technological (NaTech) events, was demonstrated by: i) the recent Tohoku earthquake and the following Fukushima disaster in 2011 (Nakashima et al. 2014) as shown in Figure 1a; ii) the UK's 2015 winter floods which topped £5bn, with thousands of families and businesses that faced financial problems because of inadequate or non-existent insurance. The NaTech problem is quite relevant as up to 10% of industrial accidents, involving the release of Chemical, Biological, Radiological, Nuclear and high-yield Explosives (CBRNE) substances, were triggered by natural hazards (Campedel, 2008). Although the number of lives lost each year to natural disaster is reduced, the recovery costs of major disasters continue to rise. In fact, each year, NaTech disasters cause an estimated \$52 billion in damages in the United States in terms of life lost, disruption of commerce, properties destroyed, and the costs of mobilizing emergency response personnel and equipment. Similar figures apply to Europe. To implement and support the Seveso III Directive 2012/18/EU which regulates the control of major accident hazards involving dangerous substances (European Parliament and Council, 2012), XP-RESILIENCE intends to establish a network of individual research projects working towards Advanced Modelling and Protection –via metamaterial-based isolators/layouts- of Complex Engineering Systems for Disaster Reduction and Resilient Communities. See, for instance, innovative solutions for existing and new tanks in Figure 1b and Figure 1c/1d, respectively. In fact, today there is a stronger need than ever to grow researchers that combine a robust academic foundation in reliability/resilience with practical experiences, technological expertise with awareness of the socio-economical context and conviction to furthering research with an entrepreneurial spirit. Hence, the objective of XP-RESILIENCE is to offer innovative research training ground as well as attractive career development and knowledge exchange opportunities for Early Stage Researchers (ESRs) through cross-border and cross-sector mobility for future growth in Europe. In fact, the ESRs will be seconded to organisations of the consortium with long-standing experience and expertise in the project topics to enrich their skills. XP-RESILIENCE is an inter/multi-disciplinary and intersectoral programme as it includes seven academic partners, one Institute of Applied Science and seven private companies from ten different European countries. It represents international excellence in risk-based simulation/development of “special risk” petrochemical plants, vibration reduction and community disaster resilience subjected to earthquakes, blast, fire, flooding, winterization, etc. Owing to the intense competition from countries such as USA, Japan, Korea, Taiwan, etc., the training of ESRs in such a network is timely and of strategic importance in Europe. The fourteen recruited ESRs will be exposed to all knowledge domains along the risk chain in continuous contact with both the industrial world and community needs. This is part of innovative methods that are not currently offered in Europe. Finally, XP-RESILIENCE will provide training-through-research in: i) controlling resilience planning at the plant level and nearby built environment; ii) designing metamaterial-based vibration shields; iii) quantifying resilience for facility/community performance during and after a hazard event; iv) setting concepts of recovery and functionality; v) interacting with academic and industrial partners.

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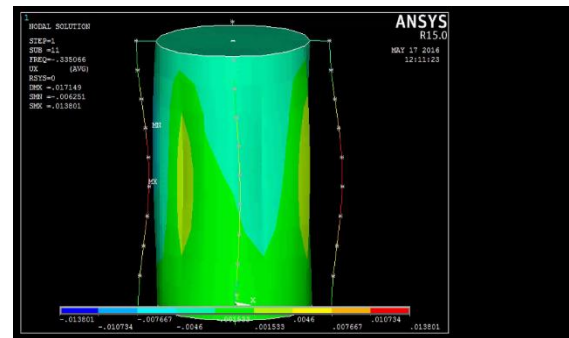
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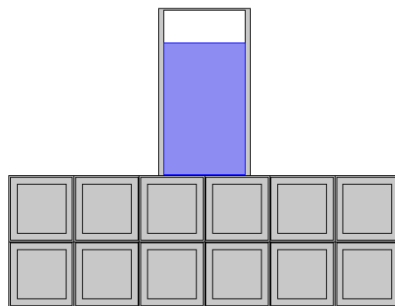
**Figure 1a.** Earthquake consequences on a petrochemical plant (Japan, 11/03/ 2011)



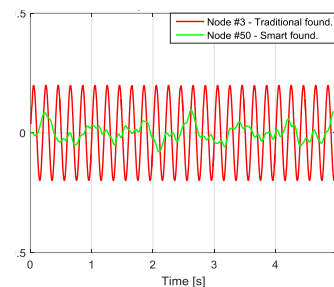
**Figure 1b.** High-contrast resonators based on metamaterials for vibration isolation of existing petrochemical tanks (Carta et al., 2016)



**Figure 1c.** 2D layout of a smart foundation for new tanks



**Figure 1d.** acceleration reduction due to non propagating band effects.



Keywords: risk-based framework, special risk facilities, community disaster resilience, metamaterial based shields, second generation of EN Eurocodes

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## A Compositional Demand/Supply Framework to Quantify the Resilience of Civil Infrastructure Systems (Re-CoDeS)

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Civil infrastructure systems (CISs) are the backbones of our communities. Thus, CISs meeting demand requirements, even when under disaster loads, or in the aftermath of disasters, are essential for safe communities. However, not only the vulnerability of CISs towards disaster loads needs to be accounted for, but additionally a resourceful and rapid recovery is important. Therefore, their resilience is central. CISs which are not able to meet the demand, thus showing a supply deficit, can induce large indirect costs (e.g. costs related to business interruptions caused by power blackouts), often overpassing direct costs related to direct damage.

In contrast to the supply, which is generally expected to drop after a disaster (especially due to damaged components), the demand to some CISs can increase after a disaster. This is especially true for the cellular communication (cellphone) network or hospitals, which are challenged with large increases in demand (e.g. because of injuries, or a high rate of emergency calls) in post-disaster situations. After the 2015 Gorkha (Nepal) Earthquake, the local demand to the cellphone network raised (according to expert interviews) up to 7 times the usual service demand. It is, thus, crucial to account explicitly for such changes in demand to detect possible *Lack of Resilience* consistently.

The *Re-CoDeS* (Resilience – Compositional Demand Supply) framework (Didier et al., 2017a), developed recently at the Chair of Structural Dynamics and Earthquake Engineering at the Swiss Federal Institute of Technology (ETH) Zurich, allows to account for the evolution of both the demand and the supply at the different locations in CISs over time. The framework is based on demand and supply layers, linked by a system service model. The system service model regulates the distribution of the system's service supply to satisfy the demand at the different nodes, depending on the technical functioning and the topology of the CIS, and on the dispatch/allocation strategy or policy of the CIS operator.

In contrast to traditional functionality-based frameworks that focus on the evaluation of the performance (i.e. the supply) of the CIS, the *Re-CoDeS* framework is designed to account for dynamic adaptations of the post-disaster demand and supply situations.

In particular, a *Lack of Resilience* at component level  $i$  ( $LoR_i$ ) occurs, if the demand of the component cannot be satisfied with the available supply. This can be defined over an assessment period  $t_0 \leq t \leq t_f$  by (Figure 1):

$$LoR_i = \int_{t_0}^{t_f} \langle D_i(t) - S_i^{av}(t) \rangle dt = \int_{t_0}^{t_f} (D_i(t) - C_i(t)) dt \quad (1)$$

where  $D_i(t)$  is the demand to the CIS at node  $i$  and time  $t$ ,  $S_i^{av}(t)$  is the available supply at node  $i$  and time  $t$ ,  $C_i(t)$  is the service consumption at node  $i$  and time  $t$  and  $\langle \cdot \rangle$  is the singularity function.  $t_0$  and  $t_f$  are the start and end time of the resilience assessment, respectively. Depending on the scope of the resilience assessment, different values can

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be chosen for  $t_0$  and  $t_f$  (e.g. the moment when a disaster hits the community and the lifespan of the system).

The obtained  $LoR_i$  can be normalized by the node demand to obtain the normalized Lack of Resilience of a node  $i$ ,  $\widehat{LoR}_i$ , allowing a direct comparison of the resilience across different nodes and CISSs. The normalized system Lack of Resilience ( $\widehat{LoR}_{sys}$ ), which is based on the aggregation of the *Lack of Resilience* of the components  $i \in \{1, I\}$  of the assessed system can then be written as:

$$\widehat{LoR}_{sys} = \frac{\sum_{i=1}^I LoR_i}{\sum_{i=1}^I \int_{t_0}^{t_f} D_i(t) dt} = \frac{\sum_{i=1}^I \int_{t_0}^{t_f} (D_i(t) - S_i^{av}(t)) dt}{\sum_{i=1}^I \int_{t_0}^{t_f} D_i(t) dt} = \frac{\int_{t_0}^{t_f} (D_{sys}(t) - C_{sys}(t)) dt}{\int_{t_0}^{t_f} D_{sys}(t) dt} \quad (2)$$

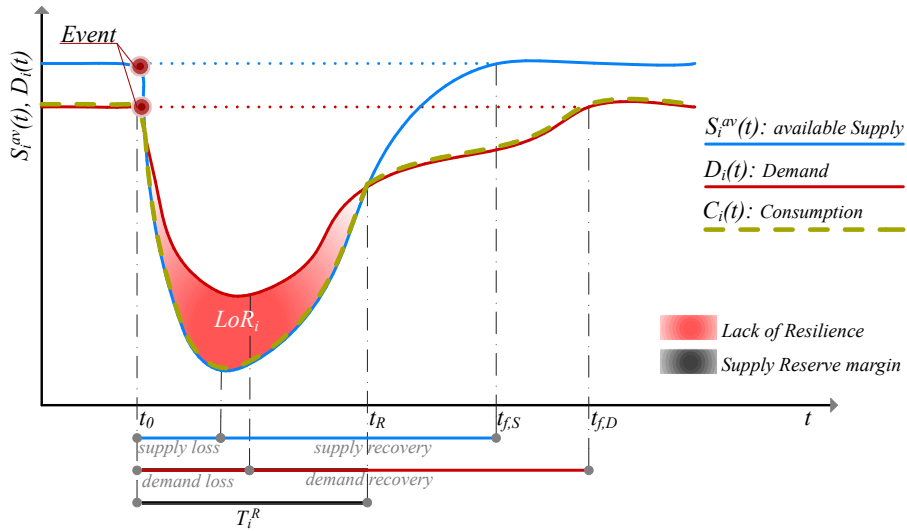
where  $D_{sys}(t)$  is the aggregate demand at a system level and  $C_{sys}(t)$  is the aggregate consumption at a system level. The resilience  $R_i$  of the component or node  $i$ , and the resilience  $R_{sys}$  of the investigated system, over an assessment period  $t_0 \leq t \leq t_f$ , are, finally:

$$R_i = 1 - \widehat{LoR}_i \quad (3)$$

$$R_{sys} = 1 - \widehat{LoR}_{sys} \quad (4)$$

Note that  $0 \leq R_i \leq 1$  and  $0 \leq R_{sys} \leq 1$ . In particular,  $R_i = 1$  and  $R_{sys} = 1$  correspond to full resilience (i.e. the demand can always be completely covered after an event), and  $R_i = 0$  and  $R_{sys} = 0$  correspond to full lack of resilience (i.e. the demand can not be covered).

**Figure 1.** Lack of resilience at a component  $i$  level (Didier et al., 2017)



The *Re-CoDeS* framework can be used to optimize post-disaster recovery by minimizing the *Lack of Resilience* under resource and time constraints. It can account for different recovery priorities and different rates of recovery of different systems to possible new post-disaster demand and supply patterns, and allows, thus, to plan for a better allocation of sparse resources and to prepare better for potential future disasters.

The *Re-CoDeS* framework was used to analyze the resilience of the electric power supply system in Nepal after the 2015 Gorkha earthquake (Didier et al., 2017a), and to model the post-earthquake recovery of a virtual CIS-community systems using Monte-Carlo simulation (Didier et al., 2015). Possible challenges and potential future fields of research

include especially the estimation of the evolution of the post-disaster service demand (Didier et al., 2017b), and the possible interdependencies between CIs.

Keywords: resilience, civil infrastructure system, recovery, vulnerability

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# **NORTH AMERICA: NIST FRAMEWORK**



## **Introducing the NIST Center of Excellence for Risk-Based Community Resilience Planning: Part I: Center of Excellence Overview, Objectives, and the Community Resilience Modeling Environment**

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Community resilience depends on the performance of the built environment and on supporting social, economic and public institutions which, individually and collectively, are essential for immediate response and long-term recovery within the community following a disaster. The social needs and objectives (including post-disaster recovery) are not reflected in codes, standards and other regulatory documents applied to design of individual facilities, necessitating an approach which reflects the complex inter-dependencies among the physical, social and economic systems on which a healthy community depends. Thus, modeling the resilience of communities and cities to natural disasters depends on many disciplines, including engineering, social sciences, and information sciences. The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado and involving ten universities, was established by The National Institute of Standards and Technology (NIST) in 2015. A two-part presentation is requested; the first will provide an overview of the Center, its objectives, and progress in the development of the NIST Community Resilience Modeling Environment known as NIST-CORE, while the second will focus on community resilience testbeds, climate change modeling, and upcoming activities within the Center for years 2-5. The anticipated presenter is underlined below with additional authors contributing.

The Center's overarching goal is to establish the measurement science for understanding the factors that make a community resilient, to assess the likely impact of natural hazards on communities, and to develop risk-informed decision strategies that optimize planning for and recovery from disasters and are consistent with financial constraints and local values and preferences. To accomplish this goal, the Center is engaged in three major research thrusts aimed at (1) developing a community resilience modeling environment (NIST-CORE) to quantitatively assess alternative community resilience strategies; (2) instituting a standardized data ontology, robust architecture and management tools supporting NIST-CORE; and (3) performing a comprehensive set of disaster hindcasts to validate this advanced modeling environment. This presentation presents an overview of the Center's current research activities, focusing on multiple hazards and their cascading effects on infrastructure, the role of supporting economic networks and social systems on community resilience, aging infrastructure, uncertainty analysis and propagation, standardization of databases, incorporation of open-source interfaces, and articulation of performance metrics and requirements. NIST-CORE, the Community Resilience Modeling Environment being developed as part of the Center of Excellence will be demonstrated as an illustrative example for earthquakes and tornadoes.

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## **Introducing the NIST Center of Excellence for Risk-Based Community Resilience Planning: Part II: Center of Excellence Community Resilience Testbeds, Climate Change, and Upcoming Center Research Activities**

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The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado, was established by The National Institute of Standards and Technology in 2015. The Center's overarching goal is to establish the measurement science for understanding the factors that make a community resilient, to assess the likely impact of natural hazards on communities, and to develop risk-informed decision strategies that optimize planning for and recovery from disasters. The community resilience modeling environment, Interconnected Networked Computational Environment for Community Resilience (IN-CORE), is the major measurement science product of the Center.

As part of the Center's research program, a number of site- and hazard-specific community resilience testbeds were designed to allow research teams to examine varying degrees of dependency, to stress analysis modules in IN-CORE in a controlled manner and to facilitate interdisciplinary approaches to community resilience assessment at an early stage in the development of the IN-CORE platforms and its embedded decision algorithms. In this presentation, several examples of the community resilience testbeds will be presented. In the first, a virtual community of approximately 50,000 people in an area of the central United States that is susceptible to earthquake and tornado hazards is considered. This testbed allows issues of scalability in community infrastructure modeling to be addressed, and informs the subsequent development of more refined community resilience assessment methods used for planning and decision purposes. In the second, the impacts of earthquake and cascading tsunami hazards on a small tourist community situated in the Pacific Northwest of the United States arising from an offshore

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seismic event in the Cascadia Subduction Zone is examined. Finally, many of the most challenging hazards worldwide are exacerbated by climate change and its effect on sea levels, flooding and the severity and frequency of coastal storms. This presentation will summarize the Center's activities related to the inclusion of the effect of climate change on community resilience modeling. The presentation will conclude with an identification of significant challenges facing the Center and a summary of projected Center research activities designed to address them.

Keywords: resilience, natural hazards, risk-informed decision

## **Functionality Fragility Assessment in the Context of Community Resilience**

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A methodology for developing functionality fragility curves of individual buildings is developed and proposed in this study to evaluate the community resilience after the occurrence of natural hazards. The proposed methodology is comprised by four main steps including the: (i) development of isolated component damage fragility curves, (ii) aggregation to repair estimation level for sub-assemblies (SA), (iii) development of functionality fragility curves for each SA and (iv) development of building system functionality fragility curves. Fundamental component of this methodology is to estimate the repair times needed for various damage classifications and components. In this study, the proposed methodology is applied to assess the functionality of concrete tilt-up industrial facilities subjected to extreme ground shaking. The findings of this study are expected to be significant for evaluating the recovery and resilience of a typical community in the United States.

**Keywords:** Functionality; Fragility curves; Repair times; Resilience

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## **Earthquake and Tsunami Fragility Surfaces for a Masonry Infilled Reinforced Concrete Building Structure**

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Recent catastrophic events such as the Tohoku Earthquake and Tsunami in Japan (2011) have raised the global awareness for the urgent need to understand the response of the built environment to multi-hazard extreme events. With respect to earthquake and tsunami cascading hazards, catastrophic damage to coastal infrastructure has been observed within the past 10 years due to extreme events such as the Indian Ocean (2004), Samoa (2009), Chile (2010) and Japan (2011). The US faces a similar multi-hazard threat from the Cascadia Subduction Zone (CSZ), a fault that runs from Northern California to British Columbia and is less than 160 km (100 mi) offshore in most places. Recent paleoseismic studies have shown that there is 7-12% chance of magnitude 9.0 earthquake along this fault in next 50 years which will trigger peak ground accelerations of up to 0.50 g, a massive tsunami over 10 m (33 ft) high and will hit the Pacific Northwest coast within 20 to 40 minutes. For the tsunami, when insufficient time and geographical conditions or urban development prevent evacuation to high ground, an alternative is to move to a high elevation climbing up to a top floor of a building that has sufficient robustness to withstand the earthquake and subsequent tsunami forces.

To develop mitigation strategies for existing structures and to enable immediate life safety based on building vertical evacuations for near-field tsunamis, the assessment, design and placement of vertical evacuation structures requires reliable performance-based earthquake and tsunami engineering assessment of existing structures. In addition, a high degree of confidence in the inundation levels and flow velocities for a particular site, and confidence in the predictive equations building lateral strength to both seismic and tsunami loadings is crucial in order to obtain reliable estimates of building performance.

In this study, a framework for developing physics-based multi-hazard earthquake and tsunami fragility surfaces for near-field earthquake and tsunamis is proposed. The framework is exemplified on the development of earthquake-tsunami fragilities for a reinforced concrete infilled moment frame. Since component failures have been identified in the literature as being of utmost importance when modeling structures to tsunami loading, state-of-the-art phenomenological models for infills and RC column shear failures are explicitly considered in the nonlinear finite element model developed using OpenSees. Uncertainty in the earthquake and tsunami intensity measures as well as in model parameters are accounted for through the use of importance sampling methods of the basic variables of the problem analyzed. Results provide a first set of curves for this building typology that can be incorporated in robustness and resilience assessment of coastal communities.

**Keywords:** multi-hazard, earthquake, tsunami, cascadia subduction zone, fragility surfaces

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# **NORTH AMERICA: OTHER FRAMEWORKS**



## **Risk Management Considering Resilience and Environmental Impact**

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Due to the concerns associated with the sustainable uses of Earth's resources and adverse consequences of structural failure under extreme events, the significance of resilience and environmental impact assessment of infrastructure systems under hazard effects has increased. The United Nations Office for Disaster Risk Reduction (UNISDR) reported that in 2011 natural disasters (e.g., earthquakes and tsunamis) resulted in \$366 billion of direct economic losses (Ferris and Petz, 2011). Additionally, with increase in the global mean annual temperature under climate change, the concerns associated with the severity of seismic hazard, storm intensity, sea levels, and coastal erosion become bigger. Consequently, it is of vital importance to incorporate resilience and environmental impact within the risk mitigation and management procedure at the component and network levels (Frangopol, 2011; Dong and Frangopol, 2016; Padgett JE, and Li, 2016). Moreover, bridge management planning and optimization under a constrictive budget and performance constraints associated with resilience and sustainability should be established in a probabilistic manner.

Resilience as a performance indicator should be incorporated within the disaster recovery process in order to minimize social disruption and mitigate the adverse consequences from the future extreme events (Dong and Frangopol, 2016). In general, resilience in civil engineering can be defined as (Bruneau et al., 2003) "the ability of social units (e.g., organizations and communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes". Presidential Policy Directive (PPD, 2013) defined resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover from disruptions". Considering the effects of uncertainties, it is crucial for the quantification of resilience at the holistic level to be processed through a probabilistic framework. Several deterministic and few probabilistic studies have been reported in the literature to analyse the resilience of civil infrastructure systems (Dong and Frangopol, 2016; Cimellaro et al., 2010; Bocchini et al., 2012; Decò et al., 2013), among others.

Due to the fact that infrastructure systems account for a paramount portion of greenhouse emissions, the environmental impacts should be considered within the building rating systems (LEED, 2008). Generally, the CO<sub>2</sub> emissions of the embodied of infrastructure materials contribute significantly to the total emissions associated with hazard repair actions. The incorporation of sustainability in the life-cycle performance assessment and management procedures allows for the effective integration of economic, social, and environmental aspects. Overall, these two indicators, resilience and environmental impact, should be quantified and accounted in the hazard management procedure and integrated for a more comprehensive performance-based assessment and hazard management process. This paper aims to put emphasis on the development of a rational approach to risk management of infrastructure systems considering resilience and environmental impact in a life-cycle context.

**Keywords:** resilience; risk management; environmental impact; CO<sub>2</sub> emission

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## **Acceptable and Tolerable Levels of Risk: The Role of Immediate Impact, Resilience, and Human Rights**

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The impact of hazards is a result of dynamic interactions between the built-environment and the socio-economic characteristics of the society. Assessing the societal impact of hazards is crucial both for pre-event mitigation planning and post-event optimal resource allocation. Three important challenges in societal risk assessment are to 1) determine what consequences should be considered; 2) develop a mathematical formulation to quantify the consequences both in the immediate aftermath of a hazard and over time; and 3) define acceptable and tolerable levels of risk.

A time-dependent capability approach is proposed to quantify the impact of hazards. In this approach, the potential societal impact of hazards is evaluated in terms of individuals' capabilities, constitutive elements of well-being. Capabilities refer to the genuine opportunity open to individuals to become or achieve things of value such as being adequately nourished, having shelter, or being mobile. Probabilistic models are developed to predict the immediate impact of hazards on individuals' capabilities as functions of the state of the built-environment and the socio-economic characteristics of the society. Models are also developed to describe the recovery process as capabilities are restored over time. Such recovery process is a function of the infrastructure resilience (namely the resilience of the impacted built environment - structures and infrastructures) and of the societal resilience. Infrastructure resilience refers to the ability of the built environment to recovery from the structural and functional damage imposed by a hazard. Societal resilience refers to the ability of communities to recovery from adverse events. To determine risk levels, the individuals' capabilities attainment is compared over time in the aftermath of a hazard with two critical thresholds, the acceptability and the tolerability thresholds. An important consideration in defining the capabilities' thresholds is human rights that specify the minimum moral thresholds all individuals are entitled by virtue of their humanity.

Keywords: acceptable risk, tolerable risk, immediate impact, resilience, human rights

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# **A Community Model for Residential Sector Recovery: An Integrated Engineering and Social Science Perspective**

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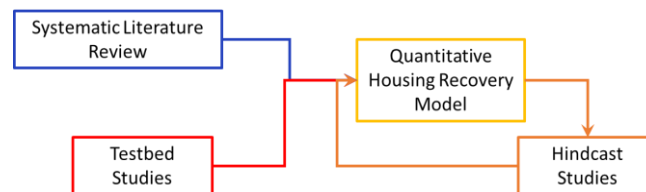
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Community resilience and recovery go hand in hand, and both are complicated problems that need more focused research. This work takes the approach that a major stride forward in community recovery can be achieved once the residential sector recovers (Zhang and Peacock, 2010). And, through modelling recovery, communities can make risk-informed decisions to improve resilience. In most cases, a person's home comprises the majority of that household's financial assets (Ellingwood et al. 2004). Thus, if major damage is caused to the home it can be very difficult for the household to recover. If the event is large enough to cause widespread damage to many homes, then the disaster recovery time can last for years (e.g., Hurricane Katrina).

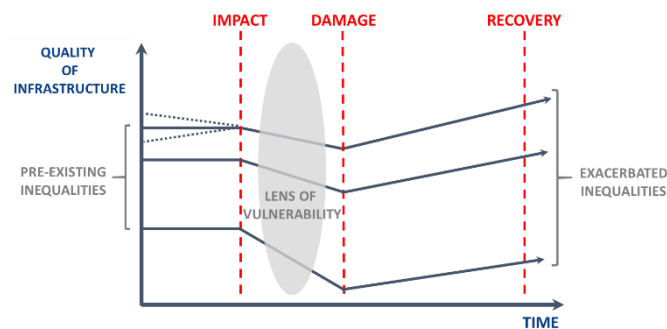
The intention of this research is to develop a quantitative housing recovery model for communities to use before the event, and during recovery, to make risk-informed decisions. The model is informed by a systematic literature review, built off of data from testbed studies, and calibrated using data from hindcast studies. The general process for the model development is provided in Fig. 1.

**Figure 1.** Housing recovery model development process



The model's purpose is to improve community-level recovery by improving differential recovery across the community. Figure 2 provides a conceptual model of how community-level inequalities can be exacerbated through the recovery process (adapted from (Peacock et al. 2014)).

**Figure 2.** Conceptual model of community-level inequalities



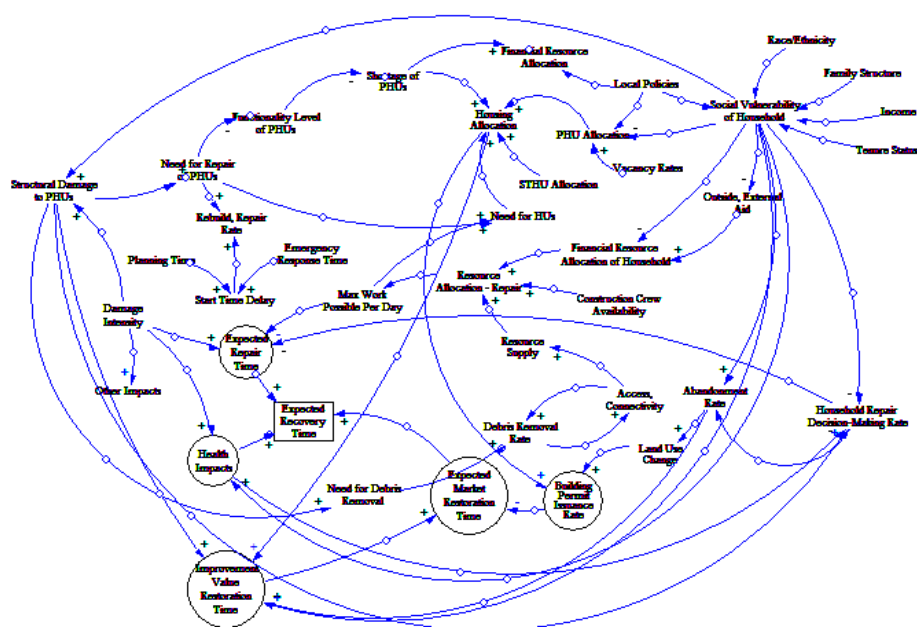
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The vertical axis in Figure 2 is labelled as Quality of Infrastructure. This could be replaced by Social Capital, or Community Functional Capacity, for example. In each case, there are subgroups in a community that have pre-existing, differing levels of inequalities, as highlighted by the lens of vulnerability. The housing recovery model developed here addresses these inequalities in an effort to eliminate the exacerbated inequalities post-disaster.

Through the literature review and testbed studies, residential sector recovery was identified to have many causal factors and indicators. Based on these, the model includes the initial residential building stock quality, the level of damage, the number of permanent housing units needing repair, the accessibility to the damage units, the social vulnerability of the household, extent of health impacts caused by the disaster, the available resources at the community- and household-level, such as FEMA Minimal Home Repair grants, SBA loans, HUD Community Develop Block grants, and insurance, and existing pre-event policies, and newly developed post-event policies for building permits, zoning, and recovery funds, for example. Figure 3 provides a causal loop diagram of how these elements relate to each other, and the overall recovery time for the residential sector.

**Figure 3.** Causal loop diagram for residential sector recovery



The causal loop diagram in Figure 3 is a preliminary, conceptual model for residential sector recovery. Continued work of the authors includes the development of a quantifiable stock and flow system dynamics model that covers the causal factors and indicators of residential sector recovery. The stock and flow system dynamics model will additionally measure recovery through the return and/or exceedance of: (1) the percentage (relative to the number of households in need) and quality of permanent residential units reconstructed; (2) the rate of building permit issuance and new construction; and (3) the parcel-level tax assessed improvement value.

Keywords: housing recovery, community resilience, residential buildings, social vulnerability

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# **ASIAN FRAMEWORKS**



# **General Review on Damage Controllability and Resilience of Structures with FRP Composites**

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In modern seismic design codes, ordinary bridges shall be designed for the life safety performance objective, so the bridge has a low probability of collapse but may suffer significant damage and that significant disruption to service is possible. This study addresses the application of fiber reinforced polymer (FRP) composites in existing and modern bridges to enhance post-earthquake recoverability and to provide a new controllability-tool. A mechanical model describing the performance of a FRP-RC damage-controllable structure in comparison with the performance of a normal RC structure was proposed. Recoverability and controllability of existing RC bridge columns retrofitted with external FRP jackets was evaluated in the light of the proposed mechanical model. Application of bond-based near-surface mounted (NSM) retrofitting technique was also proposed and experimentally evaluated. An innovative hybrid reinforcement, steel fiber composite bars (SFCB), was proposed as alternative reinforcement for modern bridges 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. Furthermore, recently, a novel reinforcement details using both steel reinforcement and basalt FRP (BFRP) bars as well as external BFRP jacket was proposed for modern RC bridge columns. A systematic experimental study and detailed 3D finite study were carried out to evaluate the effect of several potentially influential parameters. Several key conclusion were drawn from these studies.

**Keywords:** Damage-control; Recoverability; FRP; RC bridges; Bond; Confinement; NSM; SFCB; Hbrid.

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# **Analysis of the Life Recovery Process of Local People in Iwaki City after the Great East Japan Earthquake Disaster Using Structural Equation Modeling**

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Through the experiences of severe earthquake events, such as the Great Hanshin Awaji Earthquake Disaster and the Great East Japan Earthquake Disaster, it is demanded for local communities to recover from disasters immediately. The Great East Japan Earthquake Disaster triggered by the 2011 Tohoku earthquake, which was one of the largest earthquakes in recorded history and caused catastrophic damage to the Tohoku region of Japan. In this study, we conducted a questionnaire survey in Iwaki City, Fukushima and analyzed the life recovery process of the local people. Iwaki City is located on the Pacific coast and suffered severe damage from both the earthquake and tsunami of March 11, 2011.

A structural equation model of the life recovery of the local people was built using the questionnaire survey data. Based on the model, we proposed a method to evaluate a life recovery index of local people. Factors of the life recovery model were chosen on the basis of the seven elements of happiness suggested by Layard (2011); the elements are (1) family relationships, (2) household income, (3) employment situation, (4) community and friends, (5) personal health, (6) personal freedom, and (7) personal values. In addition, the life recovery indices were compared based on differences in damage to personal health, living situation, and housing due to the earthquake.

Keywords: recovery process, local community, structural equation modelling, questionnaire survey

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## **Resilience of Concrete Frames with Damage-free Mechanism**

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Effective control of structural residual deformation will lead to less reparation time and cost. During the past few decades, earthquake resilient structures have gained widespread concern in both academia and industry. This new system can not only protect life safety by preventing structural failure under earthquake, but also restore its structural function immediately afterwards.

Conventional concrete frames are design to be ductile to prevent sudden collapse and dissipate energy under severe earthquakes. That means plastic hinges are expected to be developed on component ends. However post-earthquake investigation shows that, plastic hinges are difficult to repair and excessive residual deformation due to plasticity makes the structure irreparable. For this reason, to avoid plastic hinges on beam-column and column-base connections, the constraints on these connections are relaxed. The components are connected by post-tensioning rather than monolithically casting. By this way, the gaps between components are allowed to open when the structure deforms. The interfaces between components can take compression but no tension. Hence, the rebar avoid tensile yielding, and compression on compressive side of the section will be thus reduced, when the connection subjects to bending deformation. Post-tensioning strands which run through beams and columns will remain elastic by reasonable design, and the restoring force provided by strands will always pull the structure returning to its original position. Rubber is used in this kind of structures, for its outstanding deformation capacity and character of absolute elasticity unless ruptured. Rubber is padding in the clearance between columns and socket foundations as well as between slabs and beams. Rubber padding is used in socket foundations to protect the columns and provide additional rotational stiffness. As the structure deforms gap between beams and columns will open, the distance between column centreline will increase. This expansion will be restrained if the floor slabs are rigid connected to the beams, and the purpose of self-centring and damage avoidance will not be achieved. Thus a more complex connection between slab and column is needed. In the latest research, the slabs are connected to the beams by bolts with rubber padding between slabs and beams. Thus, the deformation due to gap expansion will be accommodated by the slab system.

To investigate the seismic performance of self-centring concrete frames, two large scale shaking table tests are conducted in Tongji University. First model is a two story one-bay one-span unidirectional 1/2 scaled model. Contact interfaces are protected by steel plates including contact surfaces between beams and columns and between columns and base. Top and seat steel angels are installed at ends of the beams to dissipate energy and prevent slipping between contact interface in case post-tension force is lost. Rubber padding is used at the clearance between column and socket foundation. The model is tested under El Centro record and Wenchuan Wolong record. The maximum interstory

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drift is up to 1/25. But no evident damage is observed in the model. Gap opening is obvious visible when input PGA is large, which indicate that the design purpose of release end moment by relaxing constrain is achieved. Second model is a three story two-bay two span bi-directional self-centring concrete frame. In this model, steel jacket is installed at the ends on components to protect the contact interface to avoid damage under point-contact for the deformation is bi-directional. Bracket is used at beam-column connection; hence only top angel is used to provide energy dissipating capacity. New slab to beam connection is used in this model to test its validity. Test result shows that the damage avoidance capacity of this model is even better than the first one. However, the constrain to the gap opening due to slab is bigger than expected, thus the interstory drift of the frame is comparably small, which may not be bad because non-structural components will thus be protected. The resilience of the self-centring concrete frame structures can be assessed by the following indices: the residual drift should be no more than 0.2%, and the rotational angle of the beam and column should be no more than 5.0% under major earthquakes.

**Figure 1.** Test models. (a) Test conducted by Liu and Lu (2015) (b) Test conducted by Cui and Lu (2017)



Design guidelines for seismic resilient structures under strong earthquakes are being developed in China. Four categories of seismic resilient structures (i.e. structures with replaceable members, structures with high-performance members, rocking wall and rocking frame systems, and self-centring structures) have been covered in the design guidelines. Specifically, structures with replaceable members include reinforced concrete shear wall with replaceable foot parts and coupling beams, and outrigger truss system. Structures with high-performance members include steel plate-concrete composite shear walls and shear wall with gaps. In addition, the design method for rocking wall, rocking frame, and self-centring structural system is also presented in the design guidelines. Moreover, the level of damage for various structural members (i.e. beams, columns, walls, and coupling beams) and repair cost are all related to the structural resilience, and the approaches for evaluating the resilience of these structural members are also included in the design guidelines.

Keywords: resilience; concrete frame; shaking table test, damage-free; design guideline

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## Structural Resilience Measurement of Buildings Subjected to Earthquakes

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In recent years, earthquake-resilient structure has become a research focus of the seismic engineering in China. New structural system, including replaceable structure, rocking wall, rocking frame and self-centering structure, is investigated through experimental and theoretical researches, and design methods of the new system are proposed. Meanwhile, methodology of measuring resilience has been studied as well. Reasonable resilience measurement can determine whether an existing or proposed building is safe enough or has satisfactorily low future earthquake repair costs.

This research summarizes the current achievement in the field of research, and introduces a method of resilience measurement considering structural performance, damage and loss evaluation. Structural resilience is focused on and measured in use of inter-story drift and structure residual displacement referring to FEMA P58. It is concluded that the method of structural resilience evaluation is capable of assessing the efficacy of building, and weighing the future recovery efforts.

The methodology is presented in a case study of an 11-storey police office building, built in 1990's in Dujiangyan City, Sichuan Province, damaged in the Wen-Chuan earthquake in China on May 12, 2008. Inadequate consideration during the design phase caused serious damages of both structural and non-structural components during the earthquake event. Most failures developed at the shear walls, frame beams, slabs, partition walls, and parapet walls. Fig. 1 shows the large cracks and damages sustained by the shear walls, stairs, and partition walls. X-shaped cracks were the most common mode of failure of the shear walls, especially at the first storey in the width of 10 mm. Shear failures developed at the ends of frame beams along the longitudinal axis of the building. Severe shear-torsion failure was observed in the platform beams and column-beam joints in stairs. Also, large levels of damage developed at the partition walls from the 1st storey to the 7th storey, with some collapse due to inappropriate construction. Fig. 2 shows the outline of the damaged building.

**Figure 1.** Damage details. (a) X-shaped crack in shear walls; (b) Stairs; (c) Partition walls.



(a)



(b)



(c)

Nonlinear response history analysis (NLRHA) are conducted with ground motions representative of the design-based earthquake (DBE) defined in current Chinese building codes, and the maximum considered earthquake (MCE) selected from the Pacific

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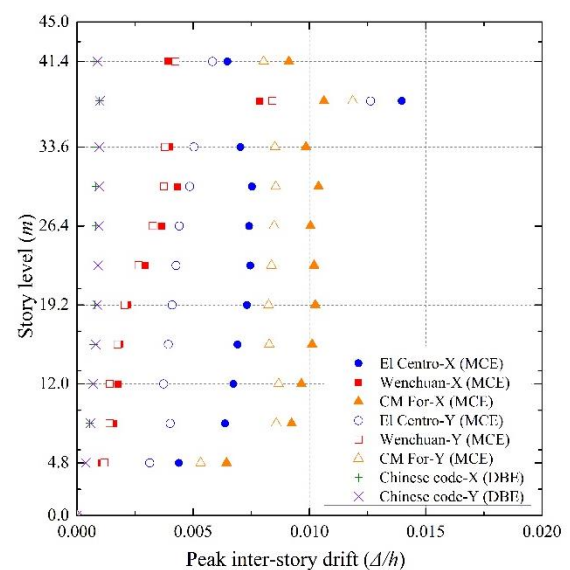
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Earthquake Engineering Research (PEER) database. Peak inter-story drift and residual drift are obtained from the NLRHA to judge the post-earthquake safety of the office building and the economic feasibility of repair. Figure 3 illustrates the peak inter-story drift at every storey under different ground motions. According to the classification of damage states in FEMA P58, the building is concluded to be the second damage state (DS2) with the residual drift ratio limit of 0.5%. Through the field investigation on the structural performance after the disaster, it was concluded that the police office building could be re-operated after the repairs of structural frame, and particular attention should be devoted to prevent shear wall failures, and guarantee the shear resistance of stairs and adequate construction of partition walls. Consequently, the NLEHA results agree with the conclusion from field investigation. In addition, strategies including structural retrofits, non-structural enhancements are also proposed in order to achieve increased resilience.

**Figure 2.** Outline of the damaged building



**Figure 3.** Peak inter-story drift



Keywords: new structural system, structural resilience, resilience evaluation

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# **ECONOMIC RESILIENCE**



## **Business Resilience to Earthquake Disasters: Observations from Past Earthquakes in Japan**

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This research deals with surveys pertaining to post-disaster business recovery, which were administered in recent years. These surveys were employed to determine the extent of economic losses or to monitor the recovery status. Using the survey data, basic statistical evidence is generated for appropriate public policies, such as financial aid and tax reduction, to be implemented during the recovery period. Moreover, to mitigate the economic impact of such disasters in future, it is important to understand the characteristics of different businesses during and after a disaster and reflect these characteristics in loss estimation models. For instance, collected datasets can be used to estimate the so-called "lifeline resilience factor" and "functional fragility curve" for each business type. These basic functions can be applied to forecast the magnitude of supply capacity loss at the time of a disaster, which is essential in analyzing the economic impact, especially in flow terms.

The lifeline resilience factor is defined as the remaining production capacity rate following single or multiple lifeline disruptions. In Kajitani and Tatano (2009), the lifeline resilience factors for 27 industrial sectors were estimated from empirical surveys administered to 562 businesses in Japan's Aichi and Shizuoka Prefectures. The surveys cover multiple lifeline disruptions (electricity, water, and gas) and the individual and compound effects of different types of resilience options (e.g., production rescheduling, inventories, and back-up generators). While these are not post-disaster surveys, the estimated results are confirmed as being consistent with those achieved based on post-disaster surveys administered for different regions.

The functional fragility curve is defined as the production capacity loss rate in relation to the size of ground motion or other hazards during a disaster. The function is an extension of the traditional fragility curve, which defines the damage patterns based on the lost stock values. In Nakano et al. (2013), the functional fragility curves for nine industrial sectors were estimated based on surveys administered to 849 businesses, following the 2004 Mid-Niigata Earthquake in Japan.

Using these surveys and analyses, Kajitani and Tatano (2014) developed a methodology to estimate the production capacity loss rate following a disaster. The model developed was applied to the 2011 Great East Japan Earthquake, demonstrating that the estimated production capacity loss was consistent with the observed production indices in severely affected regions.

Our research into understanding economic impacts relies on many lines of empirical evidence in jointly considering natural hazards and production damage to represent the initial shock in terms of economic modeling. Further analysis is thus indispensable for constructing a model that fully utilizes the insights from post-disaster business surveys.

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## Resilience-based Geotechnical Design: An Initial Insight

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The relevance of the quantitative estimation of resilience is increasingly recognized in the context of the virtuous management of human systems. The resilience of a geotechnical structure can be defined as a quantitative parameterization of its capability to sustain and restore a level of performance (e.g. structural integrity, serviceability, etc.) over a reference period. Temporal variations in performance can occur, for instance, as a result of the progressive deterioration of the soil-structure system, of phenomena which are typical of soil mechanics or of abrupt anthropogenic or natural events. Cimellaro et al. (2015) stated that the goal of resilience-based engineering design is “to make individual structures and communities as resilient as possible, developing technologies and actions that allow each structure and/or community to regain its function as promptly as possible”. As such, and specifically in the context of the geotechnical discipline, resilience-based design can be seen as an extension of current design approaches, which do not explicitly account for the variation of performance in time through a time-dependent functionality-performance function. As for other engineering disciplines, the traditional deterministic approach to geotechnical design is being progressively replaced by evolutionary methods which allow a more rational approach to ensuring safety and performance whilst attempting to limit excess conservatism and costs. This paper probes the unexplored topic of resilience-based geotechnical design by proposing a quantitative framework which links existing geotechnical design approaches to the new concept of geotechnical resilience.

Resilience is defined quantitatively as proposed by Bruneau and Reinhorn (2007):

$$R = \int_{t_0}^{t_0+T_{LC}} Q(t)/T_{LC} dt \quad (1)$$

in which  $Q(t)$  is the functionality-performance function, estimated quantitatively over the control time  $T_{LC}$  from an initial time  $t_0$ . The framework proposed herein allows the calculation of resilience by defining  $Q(t)$  in the context of four design approaches; namely: (a) deterministic; (b) load-resistance factor design [LRFD]; (c) reliability-based design; and (d) performance-based design. For all approaches, quantitative definitions of functionality are provided in terms of design parameters which are thus well known to geotechnical engineer. In deterministic geotechnical design, functionality (in terms of a specific failure model) can be defined as the ratio of the factor of safety at a given time  $t$ ,  $F_s(t)$ , to a target factor of safety  $F_{ST}$  as set by regulatory constraints or engineering judgment:

$$Q(t) = \frac{F_s(t)}{F_{ST}} \quad (2)$$

The concept of LRFD encompasses methods that require all relevant limit states to be checked using specific multiple-factor formats involving load and resistance factors. LRFD is conceptually affine to the partial factors approach which is increasingly used in Europe. Eurocode 7, for instance, deals with ultimate limit states (ULS) in persistent and transient situations and in accidental situations, and with serviceability limit states (SLS). For any given ULS or SLS, it is proposed here to define functionality as

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$$Q(t) = \frac{R_d(t)}{E_d(t)} \quad (3)$$

where  $E_d$  is the design effect of actions at a given time and  $R_d$  is the corresponding resistance to that effect at the same time. Design actions and design resistances are obtained by applying partial factors to characteristic values.

Reliability-based design entails a "full probabilistic" approach in which uncertainties in models and parameters are explicitly modelled and processed using suitable probabilistic methods. The proposed definition of time-dependent functionality is

$$Q(t) = \frac{\log_{10}[P_f(t)]}{\log_{10}(P_{fT})} \quad (4)$$

where  $P_f(t)$  is the probability of failure at time  $t$  and  $P_{fT}$  is a target/tolerable/acceptable probability of failure. Probabilities of failure can be calculated through probabilistic methods such as Monte Carlo Simulation, First-Order Second-Moment, Second-Order Second-Moment, etc. "Failure" is synonymous to "non-performance", and is thus applicable with full generality to any ULS or SLS for which a target probability can be set.

Performance-based geotechnical design can be defined as a design approach which goal is the rational quantification of the achievement of one or more specified target performance levels of a soil-structure system. Performance levels may be related, in the geotechnical discipline, to displacements, stresses, maximum acceleration, mobilized strength for one or more limit states. Functionality can thus be parameterized as

$$Q(t) = \frac{f_\theta(t)}{f_{\theta T}} \quad (5)$$

in which  $f_\theta(t)$  is the value of an engineering parameter  $\theta$  (or function thereof) at time  $t$  and  $f_{\theta T}$  is the target/tolerable/acceptable value for  $f_\theta$ .

Once time-dependent functionality is estimated for the period  $[t_0, t_0 + T_{LC}]$  through one of the available geotechnical design approaches as possible, appropriate or required, it is possible to calculate resilience using Eq. (1) and assess whether the calculated value exceeds a pre-defined threshold of acceptability. In addition to the resilience acceptability check, it is also necessary to check that functionality levels consistently reflect states of sufficient performance. This check relies on geotechnical experience, as it is possible that soil-structure systems may be able to bear temporal drops in functionality below unity (i.e., where design checks for some limit states may not be satisfied).

The above conditions should be checked for all relevant limit states. Resilience-based design is thus more stringent in requiring the explicit estimation and preservation of functionality over time. On the other hand, it accommodates a more in-depth understanding of a soil-structure system by allowing, if and where pertinent, time-dependent variations and/or temporary loss of functionality. The temporal variability of soil-structure systems is especially significant for engineering purposes. Soil are natural materials which in many cases display time-dependent behaviour. For instance, the strength of cohesive-behaviour soils generally increases in time due to the evolution of the consolidation process, so an increase in the bearing capacity of a shallow or deep foundation structure can be expected, leading to increases in functionality for the bearing capacity ultimate limit state. On another note, the bearing capacity of frictional soils may experience significant short-term decreases due to dynamic loading and liquefaction.

The resilience-based approach is thus very pertinent and promising for geotechnical design, and deserves further investigation and formalization.

Keywords: resilience, geotechnical design, functionality, uncertainty, performance, limit states

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# **EMERGING TECHNOLOGIES**



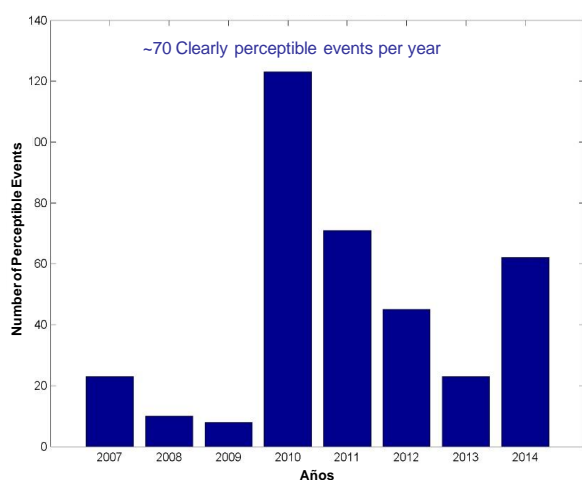
## Chile Resiliency: a Review of the Housing and Health Sectors

Ruben Boroschek<sup>1</sup> and Rodrigo Retamales<sup>2</sup>

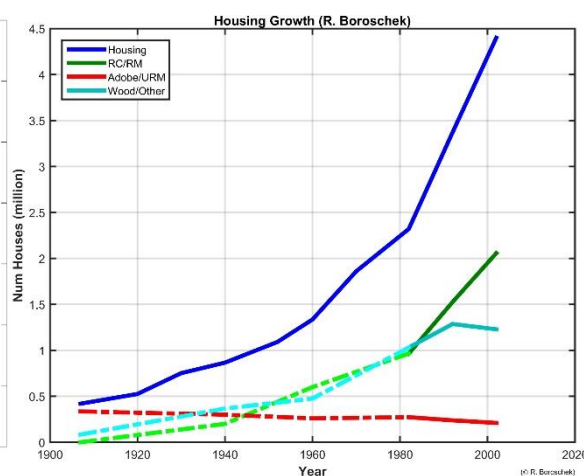
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Chile is one of the countries with the highest seismic activity in the world, primarily due to the subduction process of the Nazca Plate below the South American continent. From the late 16th century to the present, there has been a high-magnitude damaging earthquake ( $M_w > 7.5$ ) every 8 to 10 years on average throughout the Chilean territory. Figure 1 shows the statistics of seismic events with Modified Mercalli Intensities IMM greater than V occurred between 2007 and 2014 in the Chilean territory.

**Figure 1.** Number of events IMM>V.



**Figure 2.** Housing growth per construction material



### Design/Construction Techniques

The Chilean traditional design and construction practices consider the application and enforcement of strict seismic design codes. The present design practices for dwellings mainly consider the use of reinforced concrete or confined masonry walls. The use of non-seismic materials such as adobe or unreinforced masonry has decreased systematically since 1920, as illustrated in Figure 2. Non-engineered adobe and unreinforced masonry structures been severely damaged in all major earthquake in Chile,  $M_w > 8$  every 10 years in average, and the have been demolished and not reconstructed after past earthquakes, reducing the existing stock of risky structures (Figure 3). On the other hand, the good performance observed in engineered structures designed according to the Chilean code requirements during  $M_w > 8$  earthquakes is attributed to the used of structural walls, strict code compliance by the designer and contractor and mandatory peer review requirement for all structural design projects with more than 4 stories high. Additionally, the code strict inter-story drifts limits, which typically results in the need for using reinforced concrete shear walls or mixed systems composed by moment resistant frames and shear walls has contribute to a very low damage level. Moment resistant frames without shear walls are not feasible in the Chilean practice. Figure 4 shows the evolution with time of the ratio between the in-plan shear wall area and the total floor area, and the evolution with time of total building heights (after Calderon, 2007). It is observed historically the wall density ratio has fluctuated between 2 and 4%.

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**Figure 3.** Typical damage non engineered structure.



**Figure 4.** Evolution with time of wall area to floor area ratio and total building height (after Calderon 2007).

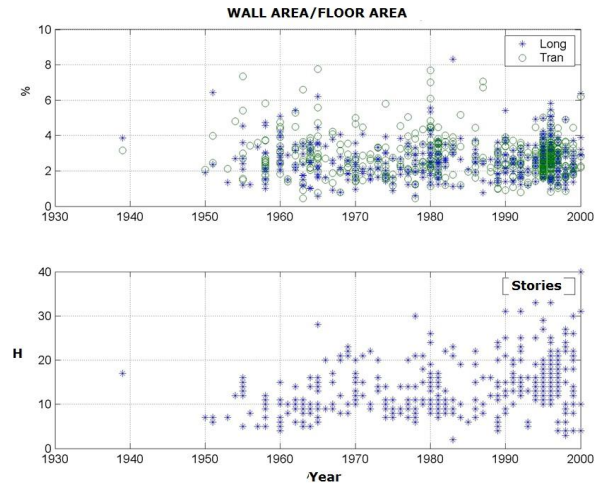
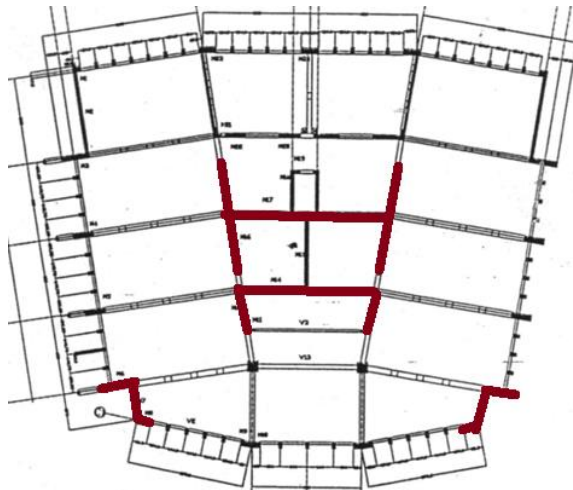


Figure 5 shows a plan view of a typical office building, the Chilean Chamber of Construction, a high rise 24-story building, 78 m in height, with wall density ratios equal to 2.3 and 4.6% in the longitudinal and transverse directions, respectively. The typical story height is 3.3 m. The fundamental period of the structure is 0.95 seconds. This building has been instrumented by the University of Chile (<http://terremotos.ing.uchile.cl/>) since the mid 90's, recording data during more than 80 strong motion events.

**Figure 5.** Chilean Chamber of Construction building. (S. Contreras)



Plan view structural system

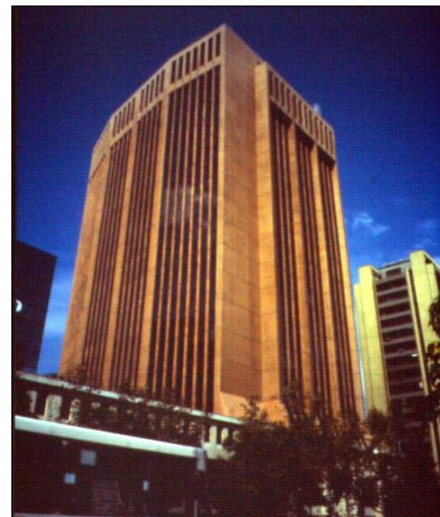
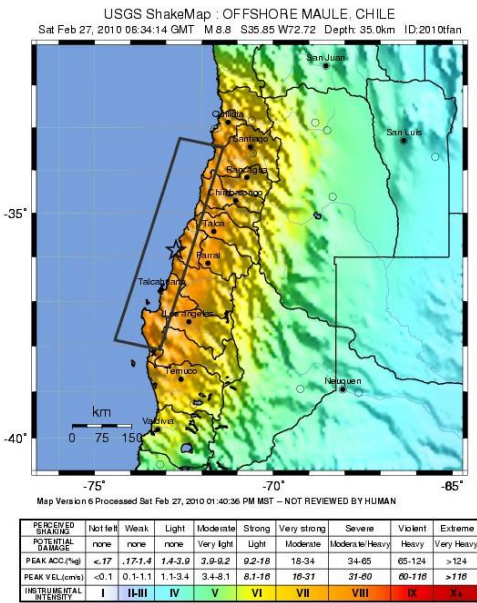


Photo modern construction

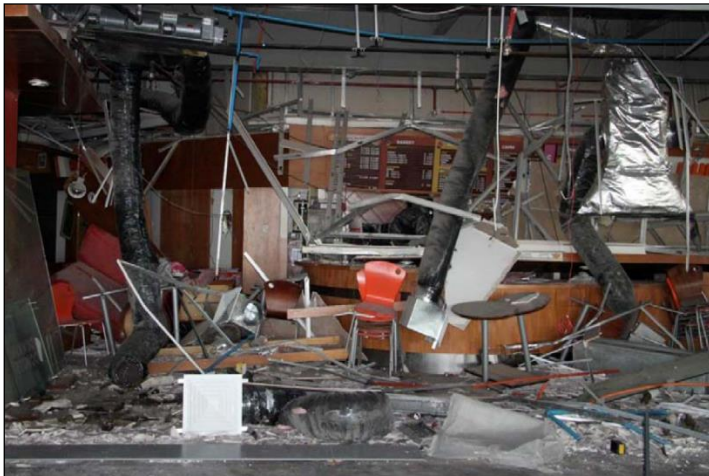
## THE 2010 Mw 8.8 MAULE EARTHQUAKE

The February 27, 2010 Mw 8.8 Maule earthquake (Figure 6) affected a significant portion (65% of stock, approximately) of housing and health infrastructures, causing economic losses exceeding 33 billion US dollars, equivalent to 15% Chile's 2010 GDP. Ninety percent of those losses were associated to non-structural damage (Figure 7).

**Figure 6.** Zone affected by 2010 Maule Earthquake (Source: USGS).

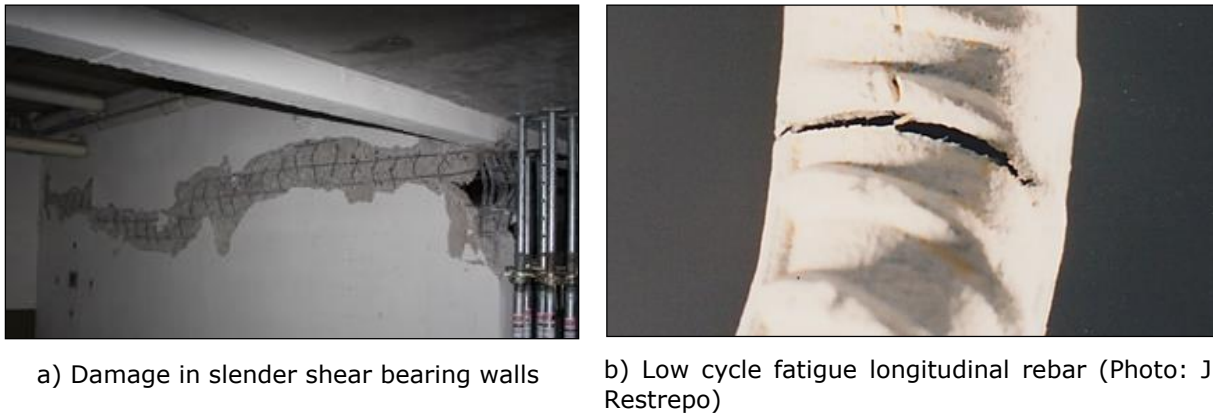


**Figure 7.** Example of generalized damage to non-structural components and systems (Miranda et al., 2012).



Structural damage was observed in approximately 0.5% of buildings, including damage to shear bearing walls due to deficient confinement detailing, excessive slenderness of the walls, low cycle fatigue of longitudinal rebar, excessive vertical compression loads, walls discontinuities and wall/slab interactions (Borosc hek et al. 2014). Figures 8 and 9 show examples of the observed structural damage. Ten percent of the losses (3.3 billion US dollars) resulted from direct damage to the 130 public health facilities affected. Among these hospitals, 83% lost partially or completely its functionality exclusively due to damage to non-structural systems and components, such as architectural elements, contents and electrical, and mechanical and medical equipment. Five hospitals needed to be evacuated due to severe structural and non-structural damage, twelve had greater than 75% loss of function due to non-structural damage, eight were operating only partially after the main shock, and eighty needed repairs or replacement. Figure 10 shows the statistics of damage in hospitals located in the epicentral area. Twenty two percent of the 19,179 beds in public hospitals were lost during the main shock and 18% continued out of service one month after the earthquake. Although structural damage was minimal in hospitals, most suffered non-structural damage and loss of utilities.

**Figure 8.** Damage to structural components

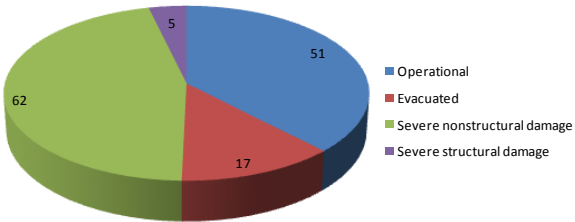


**Figure 9.** Damage to structural components: damage due to wall/slab interaction

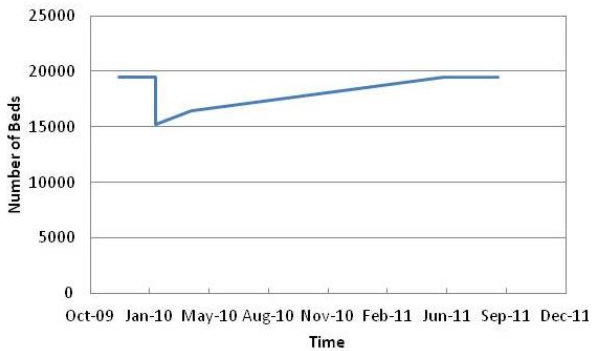


Figure 11 shows the recovery function of the number of beds available in the affected area. In Figure 11 it is observed that recovering the number of beds available before the Mw 8.8 earthquake took 14 months.

**Figure 10.** Statistics of damage in hospitals (Ministry of Health)



**Figure 11.** Recovery process for beds in affected area.

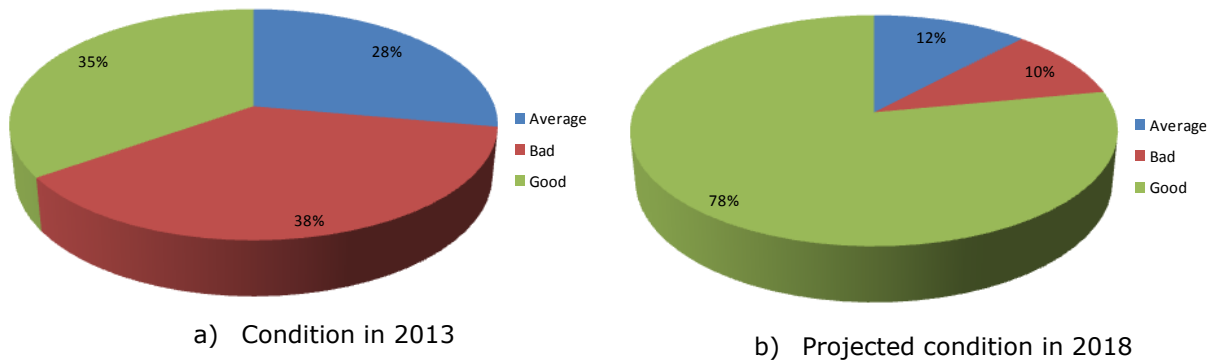


### Current and Future Trends

Following the 2010 Maule earthquake, significant efforts were made to introduce modifications into design codes and standards in order to improve seismic design practices, disseminate the use of seismic protection technologies, such as seismic isolation and energy dissipation (Retamales and Boroschek, 2014), promote the seismic design of nonstructural components and systems, and define minimum requirements for utilities, communication and access redundancy for critical facilities. All these actions aimed at improving the seismic resilience of new housing and health facilities. Figure 11 shows the condition in 2013 and the projected condition by 2018 of the public health infrastructure.

Currently, public investment plans for the next 5 years consider the construction of 8 new hospitals, with a total investment about 1.4 billion US dollars and 770,000 square meters to be built. All of them consider measures such as the use of seismic isolation, seismic design of non-structural components and system, and an extensive instrumentation and monitoring plan, oriented to increase the seismic resiliency of the public health net. The codes used for designing residential buildings have been also updated to include the lessons learned from the recent earthquakes.

**Figure 12.** Current (2013) and projected condition of public health infrastructure



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## **Emerging Technologies: Enablers of Resilience in Natural Disasters**

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Understanding how citizens and communities self-organize online to anticipate, mitigate, respond to emergency, and recover from the impact of natural disasters, is an emerging research agenda. Based on several research and dissemination initiatives related to the use of information communication technologies for disasters at the CIGIDEN. One research project has focused on the use of social media (particularly Twitter) by citizens after the occurrence of major natural disasters (earthquake, tsunami, floods, and fires) characterizing their online activity according to disaster resilience frameworks and their capacity to model mental health first aid principles. Another research project has studied the potential of UAVs (drones) for shaping community participation in a city impacted by floods. This paper highlights the potential use of emerging technologies in strengthening community resilience in the context of disaster relief, crisis, reconstruction, mitigation, and preparation.

Chile has been a pioneer in the adoption of information communication technologies. This historical patterns is reflected in the early adoption and high level of penetration of ICTs. (Haynes, 2016) 73,8% of the population uses internet; 79,5% access the internet via smartphones (SUBTEL, 2016). 96% of those who use the internet are also using social media apps (Commscore, 2015) like Facebook, Twitter, and private messaging tools (e.g., WhatsApp and Messenger). Chile is third in the ranking of Facebook adoption worldwide. Therefore, it is not surprise that most of internet users rank high the use of ICTs to connect with friends and family: 68% chats via WhatsApp, 65% use social networks, and 60% email (Subsecretaría de Telecomunicaciones, 2016). When disasters or emergencies occur, Twitter becomes a tool that is incorporated into the story of the event, and often influences the mass media agenda coverage (Valenzuela et al., 2017). The emergency personnel strategies have not been at to par with citizens mainstreaming of these technologies by citizens who are not only consuming information but also producing it simultaneously.

Digital volunteers have emerged with particular force since the 2010 earthquake and our research intended to track this trend to investigate their perception of how citizens connect during and after the occurrence of a socionatural disaster. According to our interviews with digital volunteers, an essential component in the social media activity is the emphasis on the social rather than the technology. Trusting that the information is not a rumor, for example, is based on having a relationship with the other. Digital volunteers that are activated during an emergency have developed a clear sense of what information is worth sharing via social networks. The crowdsourcing of big data is a powerful tool but the significance of particular data requires individuals who are able to judge the value of an account or a story. The development of hashtags, the tools that allow for the location of related information, is still in its very early developments. The exchange of information, though, is clearly perceived as central during the emergency and the ability of many individuals to participate in sharing information is also in itself a factor that has a positive impact since it creates networks of social support. Citizens are adopting these technologies, the question for emergency management institutions is how they will join that conversation rather than continuing using these technologies as simple modes of communicating to the community rather than engaging in a bidirectional interaction to support the efforts after a disaster strikes. Directly affected individuals and

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those witnessing the events from afar need to participate and end contributing through sharing information, curating, filtering, or reporting it. In this context, the institutional accounts play an important role in helping channel appropriate and accurate information, disarming inaccurate information or rumors (Conrado et al., 2016), and providing a framework for the exchange of information. Participation in social networks has a set of implicit and explicit rules that facilitate rumor control which are part of the digital culture that permeates social networks. Individuals who have a sizeable audience do care about the image and identity that they have developed. Accounts that grew into trusted sources of information become more verifiable and reliable with time, with users triangulating the information and often accessing information that the official channels are not able to. The institutional accounts, during an emergency, do have high levels of trust but often may not be providing enough information. The legitimacy of these accounts is not only developed in virtual relationships but also complementarily developed in face-to-face interactions. In sum, as our participants suggest, the adoption of disruptive technologies is a fact, how we respond requires an intentional strategy.

Unmanned Aerial Vehicles (UAV), drones, are becoming part of disaster management. UAV imagery is essential in obtaining a detailed vertical view of geographical objects. Its timely use may meaningfully influence communities' decision-making and their relationship with governmental and non-governmental organizations. As part of a community action research project, we examined the impact of UAV for community participation in an isolated northern city of Chile, affected by a catastrophic flooding in 2015. We analyzed how drone video images of this devastated zone and its urban and mountainous surroundings heightened community agency and participation in the shaping of reconstruction and mitigation efforts. We concluded that drone photography and video imaging can support community efforts and collaboration with local government to advocate for mitigation efforts and preparedness strategies in responding to natural threats. To investigate further the use of UAVs with communities, we began a study that supports community mapping in a multi-risk and highly vulnerable coastal community. This is a city that was devastated after a large fire and has traditionally used self-construction as a post-disaster strategy. We are employing drones to enhance the ability of the community to assess risk and to advocate for better reconstruction, mitigation, and preparedness strategies. Initial findings suggest that the use of cutting edge technology attracts a intergenerational section of the community to work collectively address and impacting their levels of community resilience.

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## Measurement-based Structural Identification for Robust Post-earthquake Vulnerability Predictions

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Current practice in earthquake-damaged-building assessment is to rely exclusively on visual inspection. However, the usually large number of buildings to inspect, as well as the potential need for multiple inspections of the same buildings, results in important economic losses due to production down-time and provisional housing. Vibration measurements may provide a meaningful and time-efficient complement to visual inspection. Indeed, measurement-based structural identification of buildings may reduce the time between a damaging earthquake and the clearance for occupancy of a building, while improving the knowledge of the residual capacity of the building to withstand future earthquakes. Therefore, measurement-based structural identification has potential to improve the resilience of buildings.

Post-earthquake vulnerability assessment of damaged buildings facing aftershocks involves some form of model-based identification. Predicting the behaviour of a building during future earthquakes is a prognosis task that involves extrapolation, hence model-free methodologies are not useful. Measurements are thus used to gain knowledge of parameters of non-linear models. Being an inverse task, structural identification intrinsically involves ambiguity. Therefore, methodologies that focus on providing a single deterministic answer are inappropriate, especially due to significant model uncertainty from simplified non-linear structural models that are used in earthquake engineering. Two methodologies, Bayesian Model Updating (BMU) (Beck and Au, 2002; Vanik et al., 2000) and Error-Domain Model Falsification (EDMF) (Goulet et al., 2013; Pasquier and Smith, 2016) that are not deterministic, and thus convey the concept of uncertainties, are compared. However, BMU and EDMF differ in the way uncertainties are taken into account.

BMU introduces uncertainty by relying on a likelihood function,  $p(\theta|y)$ , that can be related to the probability of predicting the measured value  $y$  using a model based on the parameter set  $\theta$ . Most applications define the likelihood function to be a zero-mean Gaussian distribution. Bayes' theorem is then used to calculate the posterior probability of the parameter set  $\theta$  based on the likelihood function and the prior probability of  $\theta$ . On the other hand, EDMF merges measurement and model uncertainty into a combined uncertainty distribution that is subsequently used to compute falsification thresholds. Thresholds that reflect a chosen target probability are used to falsify all the model instances of the initial model set sampled from the possible parameter values. The use of falsification thresholds is conservative when probabilistic models of uncertainty are poorly defined and uncertainty correlations between measurements are unknown (Goulet and Smith, 2013). Models that cannot be falsified by any of the measurements constitute the candidate model set and, due to little information about uncertainty distributions, are considered equally likely (Smith, 2016). In order to perform robust predictions of a quantity under conditions that differ from the measured conditions that are used for identification, the model uncertainty distribution needs to be added to the model predictions (Pasquier and Smith, 2015).

In order to compare the robustness of BMU and EDMF to perform prognosis tasks, a simple structure is used to predict post-earthquake vulnerability. The true structure that is used to simulate measurements is a four-storey lumped mass system with partial shear contribution and a non-linear base spring having a modified Takeda moment-rotation behaviour law. The model that is used to infer parameter values and predict the

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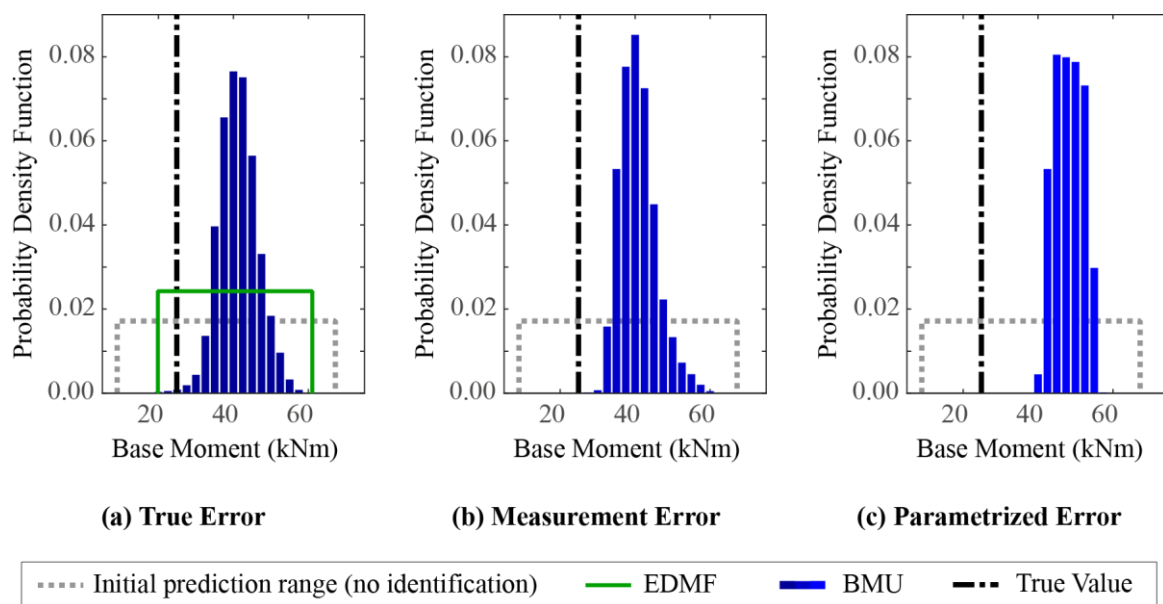
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base moment during an aftershock is a four-storey lumped-mass system without shear contribution and a Gamma moment-rotation law (Lestuzzi and Badoux, 2003). Natural frequencies and mode shapes of the three first modes before and after a main shock are used to infer parameter values. Three scenarios are compared: a) uncertainty distributions derived from the true model error, b) uncertainty distributions based on measurement error only (model error is ignored) and c) the standard deviation of the uncertainty distribution is parametrized and updated through BMU.

The results show that for predictions based on BMU, the true base moment falls outside three standard deviations for all three scenarios. EDMF, however, includes the true value for scenario (a). For scenario (b) that ignores model error, EDMF falsifies all model instances, which indicates a wrong model class or a misevaluated uncertainty distribution. BMU with a Gaussian zero-mean likelihood function fails to reject the model class based on under-estimated uncertainty, even if four modes (i.e. more measurement data) are used. Finally, despite providing good results for interpolation, parametrizing the uncertainty (scenario c) results in erroneous extrapolation results. As EDMF relies on engineering judgement to estimate uncertainty distributions, scenario c is not applicable to EDMF. Fig 1 summarizes the prediction results for aftershock base moments.

In summary, unlike traditional application of Bayesian Model Updating, EDMF is robust for prediction tasks. Furthermore, robust measurement interpretation has potential to improve resilience of structures under seismic risk.

**Figure 1.** Comparison between EDMF and BMU for the prediction of the base moment of a non-linear-spring supported four-storey lumped mass system during an aftershock



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# Novel Connection for Accelerated Bridge Construction with Dissipation and Recentering Capabilities

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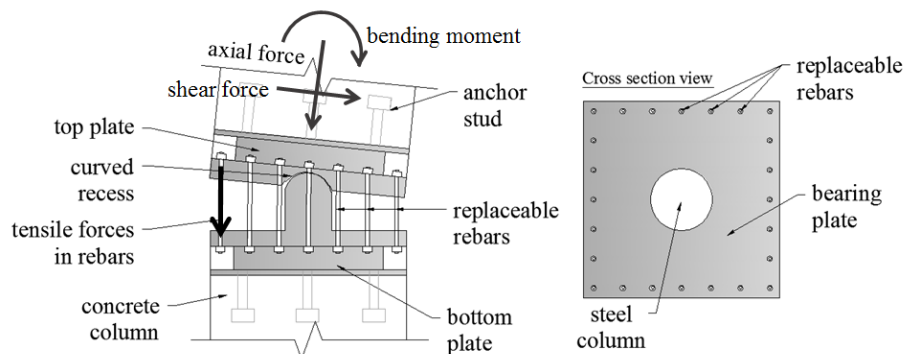
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Current seismic design codes for bridges prescribe the formation of plastic hinges at bridge piers to dissipate energy. However, it has been observed that this approach may result in severely damaged structures that need to be closed and for which repairs are not economically feasible. This paper presents a novel hinge design scheme, which is expected to provide a cost-effective low-damage solution that dissipates energy through bar yielding, provides recentering capabilities through non-yielding components, and reduces downtime due to ease of replaceability. Finite element models of single-column piers are analysed and compared against conventional reinforced concrete connections to investigate the efficiency of the resilient hinge. Nonlinear time-history analyses showed that large reductions of permanent drifts were expected when comparing the results of the resilient hinge and the conventional concrete piers.

## Description of the Resilient Hinge

The connection for segmental bridge construction is used at the positions where the bending moments of the piers are maximized, i.e. at the pier top and bottom. Similar techniques have been used before, (Mitoulis and Rodriguez, 2016; Nazari et al., 2014 and Pampanin, 2012). It links cast in situ or precast pier segments to the deck and/or to the footing of spread foundations or pile caps as shown in Fig. 1. The seismic connection shown in Fig. 1 includes a curved recess that allows the column to rotate, but restricts the horizontal relative displacements of the column to the top plate. The design of the connection was performed such that the bars receive tension only and no compression. These tensile forces comprise the bending capacity and the stiffness of the connection; thus these can be fully controlled by the rebar design, i.e. the material, the diameter, the length and the boundary conditions of the rebars.

**Figure 1.** Elevation and plan view of the proposed seismic connection



An important feature of the seismic connection is that for a given pier-to-foundation rotation, the bars at a greater distance from the bending axis are designed to yield. On the other hand, the bars that have smaller lever arms are designed to remain elastic and

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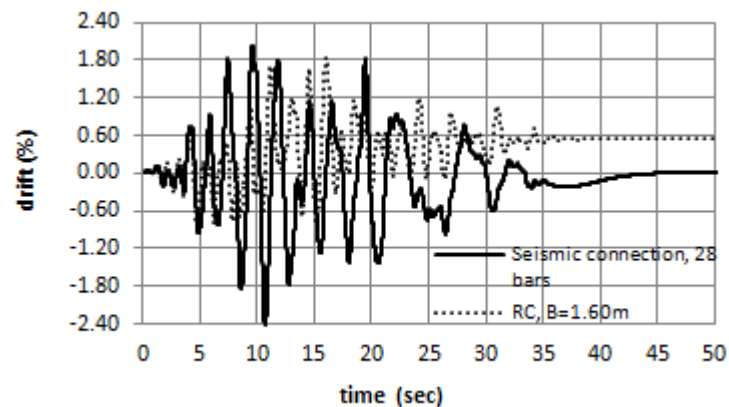
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hence provide recentering to the pier. Adequacy of this recentering mechanism was assessed based on the numerical models built in this research that included P-delta effects. Nonlinear dynamic time history analysis was performed for a set of accelerograms. All input motions were compatible with the elastic spectrum of Eurocode 8-1.

## Results and Discussion

The numerical results of the conventional and unconventional columns that have either a traditional reinforced concrete design and detailing or the proposed seismic connection detailing were compared. In Fig. 2 the drift-time histories have been superimposed for EQ1, showing the variation in response for the top column displacement. From Fig. 2 it can be observed that although the response varies, the general trend is that the piers with the seismic connection are able to recover the deflections and exhibit negligible permanent drift after the earthquake. Both maximum and residual drifts have been recorded for all accelerograms and results are summarized in Table 1. The areas of the table highlighted with grey provide a direct comparison between the maximum and mean residual drifts for the conventional pier and the novel connection. On average, the arrangement of 28 bars for P1 will reduce the residual drift up to 91%, i.e. from 0.22% to 0.02%, with respect to the concrete conventional column, leading to negligible residual drifts.

**Figure 2.** Drift-time comparison for EQ1 (P1,  $h=9.30\text{m}$ )



**Table 1.** Comparison of maximum/residual drifts between conventional and resilient pier designs.

	conventional pier, $b=1.60\text{m}$			seismic connection, 28 bars		
	residual drift (%)	maximum drift (%)	residual/maximum drift ratio	residual drift (%)	maximum drift (%)	residual/maximum drift ratio
EQ1	0.55	1.84	0.30	0.00	2.40	0.00
EQ2	0.15	1.72	0.09	0.05	2.88	0.02
EQ3	0.05	1.61	0.03	0.00	2.01	0.00
EQ4	0.17	1.69	0.10	0.02	2.51	0.01
EQ5	0.14	1.54	0.09	0.00	1.96	0.00
EQ6	0.24	1.62	0.15	0.06	2.82	0.02
Max Value	0.55	1.84	0.30	0.06	2.88	0.02
Mean Value	<b>0.22</b>	<b>1.67</b>	<b>0.13</b>	<b>0.02</b>	<b>2.43</b>	<b>0.01</b>

## **Conclusion**

A new connection was analysed for Accelerated Bridge Construction of piers and it was found that the connection offers recentering capabilities and minimal construction and re-construction times.

Keywords: bridge; pier; resilience; dissipation; recentering; hinge

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# **INFRASTRUCTURE RESILIENCE**



## **Re-conceptualizing Resilience in Disasters from Transdisciplinary Perspectives**

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Chile is characterized by the continuous occurrence of socio-natural disasters, including earthquakes, floods, fires, volcano eruptions, and tsunamis. Milliano et al.. (2015) argue for conceptualizations of disasters that take into account “multi-risk environments”, which include: “slow and rapid onset emergencies, violent conflict, climate change, and other global challenges such as pandemics and biodiversity loss, as well as chronic political, economic, and society fragility” (p.25). Furthermore, Wisner and Kelman (2015) argue that it is important to acknowledge at least four overlapping hazard categories when considering disasters, including: natural hazards (e.g. earthquakes, tsunamis, floods, fires, hurricanes, and volcanic eruptions); technological hazards (e.g. oil-spills, nuclear power plant disasters, and transportation-related crashes); violent social crisis (e.g. wars, terrorist attacks, gun massacres, gang-related community violence, assassinations, detentions, torture, and disappearances by state-led repressive regimes); and nonviolent social crisis (e.g. chronic poverty, structural discrimination, and the presence of slow yet continual socio-environmental changes that reduce accessibility and availability of key resources and human rights). Considering overlapping dimensions of disasters, it is important to understand the ways in which Chile is not only a nation impacted by natural hazards, but also by complex social inequities, such as, income inequality, structural racism, and gender-based oppression, which together overlap and challenge opportunities for resilience across multiple levels and domains (e.g. Agostini et al., 2010; Cabieses et al., 2016; Tijoux, 2016). Therefore, in this presentation, we at the Chilean National Research Center for Integrated Natural Disaster Management (CIGIDEN) argue that in each overlapping hazard category, it is imperative to consider the social conditions, which in fact determine the characteristics of the disaster (e.g. Atallah, 2016). Therefore, because of complex interactions between physical and social phenomena in disaster situations, we argue for a transdisciplinary approach toward attempting to understand and promote resilience related to these complex overlapping hazards.

CIGIDEN’s principal goal is to contribute to understandings and the development of policies and practices capable of promoting improved hazard prediction, prevention, and response to disasters locally and globally utilizing resilience as a core framework. In this presentation we share a table that we have developed at CIGIDEN grounded on our literature reviews, disaster preparedness and response practice experiences, and theoretical mapping of resilience constructs across disciplines and across “waves” or the trends frequently discussed by resilience researchers (e.g. Atallah, 2016; Milliano et al., 2015; Richardson, 2002; Wright et al., 2013). More specifically, we characterize and describe three waves in the literature. We demonstrate how in the first wave of resilience thinking, an emphasis is placed on better understanding how to protect the status quo and return functioning to an equilibrium – i.e. a system’s capacity

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**Table 1.** Three Waves of Resilience Thinking: Towards Transdisciplinarity and Social Transformation.

<b>"Wave" of Resilience Thinking</b>	<b>Dominant Paradigms</b>	<b>Definition of Infrastructure Resilience</b>	<b>Definition of Psychosocial Resilience</b>	<b>Strength of "Wave"</b>
<b>First Wave:</b> <i>Protection</i>  <b>Disciplinary-specific</b>	<b>"Bouncing Back" Paradigm Focusing on Functioning:</b>  Frameworks attempt to explain and understand how systems "bounce back" after exposures to external adversities, focusing on protecting and maintaining the status quo	Resilience is the <b>capacity</b> of an infrastructure or physical system to maintain its structure, form, or state of equilibrium despite the presence of adverse external events	Resilience is the <b>capacity</b> for restoring functioning after an overwhelming experience or exposure to potentially traumatic events	Helpful when it is possible to identify an optimum <b>equilibrium</b> or a desired "Status Quo" that should be protected to be able to persist over time
<b>Second Wave:</b> <i>Adaptation</i>  <b>Interdisciplinary</b>	<b>Paradigm shift toward Adaptation &amp; "Bouncing Forward":</b>  Frameworks attempt to explain and identify pathways toward improving conditions and adaptive capacities - seeking to understand and promote adaptive responses to constantly changing environments and punctuated equilibriums - "bouncing forward" after exposures to external adversities	Resilience is the <b>process</b> of a system to adapt its structure in response to episodic disturbances, reorganizing to increase adaptive potentials related to the probable presence of future adversities	Resilience is the <b>process</b> of people navigating toward resources for strengthening their adaptive capacities to "bounce forward" or even "grow" after exposure to hardship or trauma	Helpful to systems that are NOT at an equilibrium - suitable to adaptive systems that have <b>NO obvious best ending point</b> , that require constant change, growth, and amelioration
<b>Third Wave:</b> <i>Transformation</i>  <b>Transdisciplinary</b>	<b>Paradigm shift toward "Centering at the Margins":</b>  Frameworks begin to shift from majority groups' perspectives on disasters toward incorporating more perspectives of marginalized communities, thereby increasing understandings of overlapping disasters and viewing resilience as a metaphor for life-world outcomes shaped by unequal power relations	<b>Transdisciplinary Resilience Thinking</b>  Resilience is just <b>the name given to the outcome</b> of overlapping physical and social processes that effect systemic transformation in context-specific and culturally-meaningful ways and that increase human wellness, sustainability, and social justice		Helpful toward <b>transforming unjust social systems</b> and addressing the conditions of disasters, which are always present, especially at the margins

*Adapted from tables in Atallah (2016); Milliano et al. (2015); Richardson (2002); and Wright et al., (2013).*

to “bounce back” after an adverse experience, impacted by vulnerability and protective factors. The second wave of resilience thinking shifts from a focus on capacity to process, and emphasizes systemic adaptation or ameliorating functioning and “bounce forward” after exposure to an external stressor, impacted by previous notions of vulnerability and protection from the first wave. However, recent trends in resilience thinking caution that a given factor may be protective in one situation, and yet can cause vulnerability in another, whereby the conditions of both disaster and recovery are embedded in the social situation (Kirmayer et al., 2009). In this light, in the current “third wave” of thinking, resilience is not seen as something that describes the nature of a system, person, place, or a thing, but rather, as simply a name given to the outcome of many complex ecosystemic processes embedded in life-world situations whereby an emphasis should be placed on social transformation toward equity, environmental sustainability, and wellness (See Table 1 below for an outline of the three waves from “Protection” to “Adaptation” to “Transformation”).

In conclusion, resilience is much more than systemic protection, adjustment, and adaptation in response to sudden disasters. In fact, we argue that in the ongoing developing “third wave” resilience paradigm, the conditions of disaster are seen as always being present, especially at the margins. Disasters are determined by life-world conditions and caused by interplays between physical, psychological, and sociopolitical dynamics impacted by long-standing asymmetrical social power relations which create disproportionate adversities in marginalized communities. Therefore, when understanding resilience, we argue for the importance of “Centering at the Margins” (Hardeman et al., 2016), explicitly incorporating social justice frameworks with a focus on transforming social systems while more robustly including bottom-up participatory approaches, empowerment of local communities, and the inclusion of differently-positioned stakeholders in all stages of disaster risk reduction, preparedness, and response.

Keywords: resilience, transdisciplinary, disasters, hazards, social justice

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# Seismic Resilience of Isolated Bridge Configurations With Soil Structure Interaction

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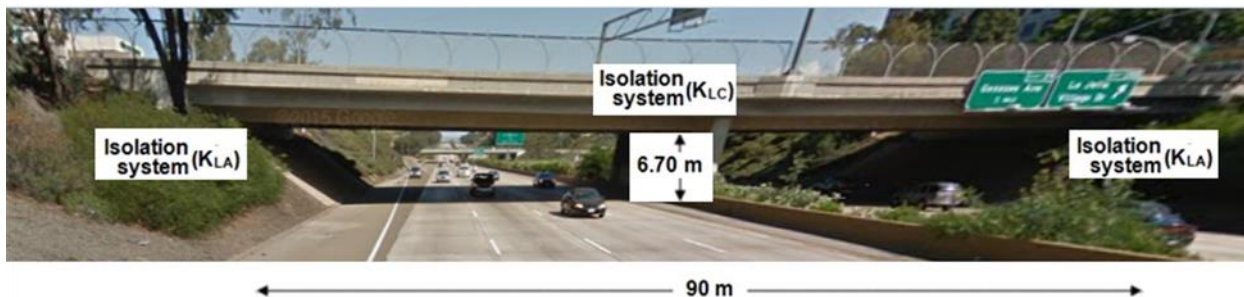
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Assessment of damage is one of the key points to define the Seismic Resilience (SR) of infrastructure systems. In particular, evaluation of the most proper countermeasure - such as retrofitting, recovery or reconstruction - to return to the original functionality is a crucial issue, which has to deal with economic limitations. In this regard, bridges are fundamental for the network serviceability and communities functionality during earthquakes and in case of emergencies, therefore their accessibility must be guaranteed.

In this background, the paper aims at evaluating SR of a benchmark bridge (Figure 1) improving its performance by means of isolation technique. The study is based on the application of a Performance-Based Earthquake Engineering (PBEE) methodology, proposed by the Pacific Earthquake Engineering Research (PEER) center. This approach is based on the definition of performance groups (PG), and consists of the association of various structural and non-structural components, using the most common repair methods. Each PG contains a collection of components that reflect global-level indicators of structural performance and that significantly contribute to repair-level decisions. The notion of a PG allows grouping several components for related repair work. Therefore, PGs are not necessarily the same as the individual load-resisting structural components. PGs damage is related to specific repair procedures and repair quantities that could be used for the estimation of cost and repair effort to return the bridge to its original level of functionality. Consequently, the platform defines discrete damage states and each of these has a subset of different repair quantities, associated to a given scenario. Once the repair quantities have been established for a given scenario (damage to different PGs), the total repair costs can be generated through a unit cost function (Mackie et al., 2008, 2010). Finally, for each repair quantity, an estimate of the repair effort can be obtained through a production rate.

**Figure 1.** Benchmark bridge.



The paper aims at integrating the soil-structure model with the assessment of base-isolation effects. In this regard, past earthquakes all over the world have proved the

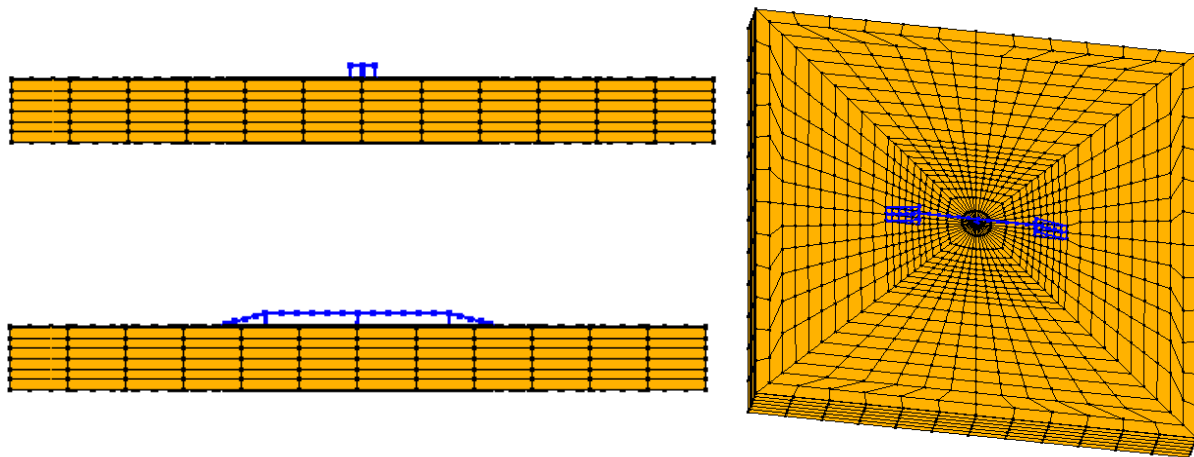
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benefits of isolation technique for pier protection. These effects can be strongly modified by soil deformability and energy dissipation in the ground, as shown in Vlassis and Spyarakos (2001), Tongaonkar and Jangid (2003), Ucak and Tsopelas (2008) and Forcellini (2016). In the paper, SR has been assessed by taking into account the effects of a set of motions by considering the soil structure interaction (SSI) on several isolated bridge configurations. In particular, the seismic response of the case-study has been represented through a numerical model (Figure 2) performed with OpenSees (Mazzoni et al., 2009), able to couple the structure together with the foundation soil. The results have been performed with the PBEE methodology in order to consider the damage in terms of economic consequences and to calculate recovery costs and time to reset the original level of functionality. The novelty of the paper consists of applying these outcomes to estimate the SR of the bridge and of applying this procedure to a real case study. In particular, recovery costs and time have been implemented inside the definition of resilience by Cimellaro et al. 2010. The analytical expression of system functionality has been modelled as a linear function. Other assumptions have been made in order to define the loss function and the recovery function.

**Figure 2.** Soil-Structure FE model: 3D and vertical views.



The mutual effect of soil and isolators non-linearities has been studied in order to assess the best isolated configuration able to fit the different non-linear conditions of the soil. In this regard, the parametric study on soil deformability allowed to assess the circumstances under which soil structure interaction needs to be considered. In particular, the selected soil profiles captured the effects of amplification and consequent accumulation of ground deformation (laterally and vertically) thanks to OpenSees potentialities in soil modelling (in particular non-linearity and hysteretic damping). Results show that total costs are affected mainly by abutment damage and effects of soil deformability. In this regard, the effects of various types of isolations have been evaluated. The final calculation of SR has been used in order to assess several scenarios. In conclusion, the paper provides an integrated procedure to assess bridge recovery under different soil conditions.

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## **A Network Model for Probabilistic Assessment of the Vulnerability of the Fuel Distribution System of Coastal British Columbia**

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The Western Coast of Canada is seismically active, and susceptible to both interplate (subduction) and intraplate (shallow) earthquakes. Models have shown the impact of a large quake (M7.3) directly below Vancouver would extensively damage or destroy some 30% of the buildings in the region (Province of British Columbia, 2015). Other studies suggest that such an earthquake should be expected within the next 50 years (AIR Worldwide, 2013).

The susceptibility of the region to major earthquakes is particularly concerning for its liquid fuel distribution system. Several coastal communities depend on maritime transportation to receive fuel shipped from a hub in the Greater Vancouver area, where all the fuel terminals are located. The integrity of this system is crucial, since fuel availability in the aftermath of a disaster severely impacts the capacity for effective recovery. Many communities also depend on liquid fuels for electricity generation and heating. This multi-level dependency creates a broader range of energy service disruptions when liquid fuels supply is disrupted.

This research assesses the vulnerabilities of the fuel distribution system of Coastal British Columbia employing a network-based approach to model the system using information collected from manuals, reports and interviews with key stakeholders. By identifying vulnerabilities, it contributes to the development of guidelines for contingency plans in the scenario of fuel shortages and, consequently, a more effective post-disaster response.

The models in this network can be separated into two categories: models for moving elements and models for fixed infrastructure. The models for moving elements are representative of the transportation modes on land and on water. The maritime shipping models are informed by data about the departure and arrival time, fuel capacity, type (e.g., barges, ferries, etc.) and specifications (e.g. single or double hull, hull draft, type of load-unloading system) of the vessels. The tanker truck models include similar information, as well as information about the bridges along the route from the fuel depot to point of delivery. Models for shipping channels impacts are still being developed and

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two categories of failures will eventually be considered: a) bridge collapses blocking a channel and, b) the channel walls collapse under accelerated ground motion.

The models for fixed infrastructure nodes, e.g. fuel terminals, bridges, ports and tank farms, represent members of the system that are susceptible to earthquake damage. The damage estimation on these nodes is performed in *Rts* (Adams and Halchuk, 2003) a software developed at the University of British Columbia. This software aggregates state-of-the-art models for natural hazards, structural response and damage and loss estimate.

The hazard models are based on information provided by the Geological Survey of Canada (Mahsuli and Haukaas, 2003), which lists 26 areas where potential earthquakes can happen in Western Canada. The intensity attenuation models are based on (Atkinson and Boore, 2003) for crustal and subcrustal earthquakes and on (Boore and Atkinson, 2008) for subduction earthquakes that can happen at the Cascadia Subduction Zone.

The structural damage estimation in *Rts* is based on fragility curves given by the HAZUS MR4 technical manual (HAZUS-MH, 2009). These fragility curves are specified in terms of peak ground acceleration (PGA) or permanent ground displacement (PGD), and the total damage is a combination of PGA- and PGD-related damage contributions. Based on the attenuation relationships and the fragility curves, the damage associated with the occurrence of an earthquake can be calculated for each fixed structure, i.e. each fuel terminal, port, bridge and tank farm. With this, the probability of disruption at node  $i$  given an earthquake at area source  $j$  defined by (Adams and Halchuk, 2003),  $P(D_i|E_j)$ , is determined. With these probabilities and the rate of occurrence of earthquakes in each area source,  $\lambda_j$  (Mahsuli and Haukaas, 2003), the rate of disruption for each infrastructure node is

$$\lambda_{D_{i,j}} = \lambda_j \cdot P(D_i|E_j) \quad 1)$$

Finally, to account for all area sources and obtain the probability of disruption at node  $i$  given an earthquake happening anywhere in the region, we recall earthquakes are modelled as Poisson processes for which the rates can be additively combined, thus

$$P_{D_i} = 1 - \exp\left(-(\lambda_{D_{i,1}} + \lambda_{D_{i,2}} + \dots + \lambda_{D_{i,N}})T\right) \quad 2)$$

Once these total probabilities of disruption are computed for each fixed infrastructure node in the network, the computation of the probability of a fuel shortage at each community can be solved as a system reliability problem.

With this, it is possible to identify which components of this system are more likely to fail in the aftermath of an earthquake and which communities are more susceptible to experience fuel shortages. This is essential for the development of measures that increase community resilience, such as local fuel storage, prioritised supply, modifications to health and safety regulations during emergencies and exploring alternative methods to energize critical infrastructure.

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# **Time-series Analysis for the Calibration of Causative Models Of Spatially Distributed Infrastructure Interdependencies in Post-disaster Recovery**

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The problem of properly capturing and predicting interdependencies among infrastructure components and systems in case of a disastrous event is one of the most challenging topics of current research in civil engineering and related fields of science. Some authors have proposed the use of “interdependency matrices” to describe how much one component/system can affect the recovery of other components/systems (Cimellaro and Solari, 2014). This approach is simple enough to become popular in practice, but the calibration of the entries of the matrix (i.e., the interdependency coefficients) is a challenging task in itself. In particular, it was attempted to use functionality recovery curves from past events to perform time-series analyses and calculate correlation coefficients among the recovery of different components/systems (or, at least, a proxy of such correlation coefficients) (Duenas-Osorio and Kwasinski, 2012, Cimellaro et al., 2014). This approach is certainly useful to validate models, but being phenomenological and based on statistical analyses of past events, its usefulness for predictive analyses performed at different locations and for different events may be limited. For this reason, recent research efforts are going in the direction of exploring mechanistic models of interdependencies, which may be more effective in predictive tools (PRAISys, 2016).

We present some ideas of a general strategy that aims at connecting all the previously mentioned approaches. Tools from time-series analysis and random function theory are combined to calibrate mechanistic models of the recovery of a simple system of infrastructures spread over a few districts. The use of a recovery simulator developed as part of the PRAISys project (PRAISys, 2016) allows to define a priori the interdependencies in the system, determine which features they yield in the recovery curves, and validate the outcome of the time-series analysis.

## **Introduction**

The goal of this case of study is to validate, through time series analysis, the interdependencies between infrastructural systems subject to an hypothetical seismic event. These infrastructures are spatially distributed and are functional to four districts: this type of configuration allows to analyze not only intra-district but also extra-districts interdependencies. The infrastructures considered in this study are transportation, power and communication systems.

The model generates recovery curves for each system in two different cases: with and without interdependencies. Starting from the recovery curves  $Q(t)$  of each system, it is possible to evaluate the Cross Correlation Function (CCF) that expresses the grade of correlation between a couple of infrastructural systems. Using the values of CCF we computed the interdependencies matrix  $S_{ij}$  for both intra- and extra-district

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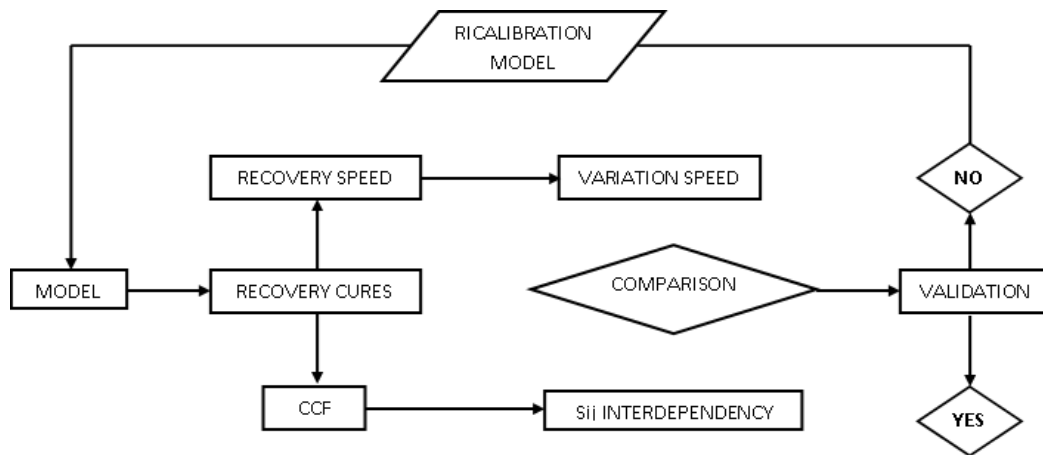
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infrastructures: the interdependencies index  $S_{ij}$  are the first important values for the assessment of the correlation.

Another parameter taken into account for the assessment of the interdependency is the Recovery Speed index of each infrastructure of the model. A comparison between the interdependency index  $S_{ij}$  and recovery speed index values allowed to understand and validate if the interdependencies assigned to the model are correct or not. Figure 1 illustrates the flowchart of the validation process starting from the recovery curves  $Q(t)$  generated by the model through the interdependencies.

**Figure 1.** Flowchart of the interdependency validation process.



### Model and assignment of interdependencies

Each infrastructural system is composed by a set of infrastructural components potentially vulnerable to seismic hazard: bridges were considered for transportation system, traffic lights and transmission towers for power system and communication towers for communication systems. Every system is built like a network of nodes and links in which the component of each infrastructure is located.

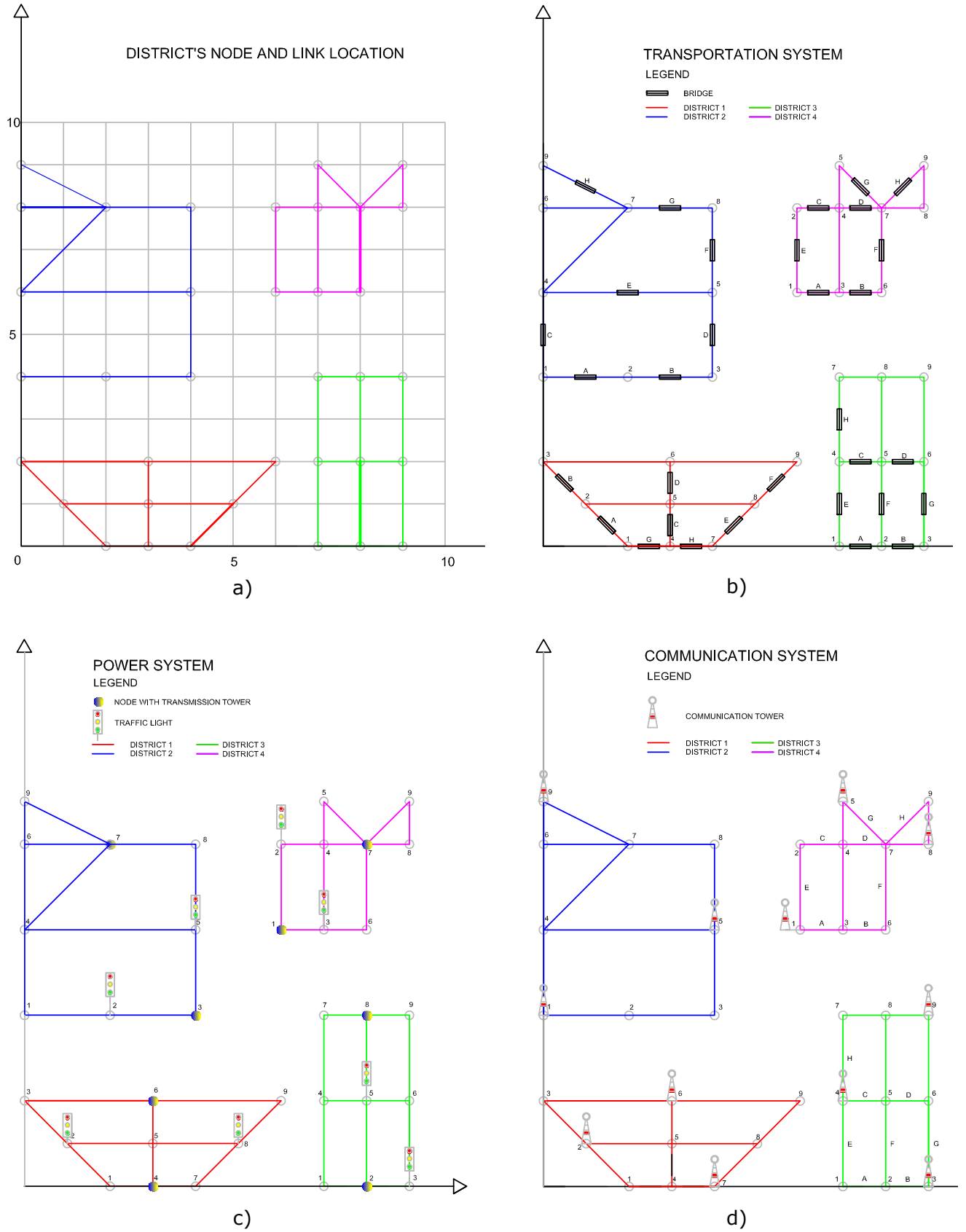
A key aspect for the setting of the model is the allocation of the interdependencies between infrastructures. At intra-district level, correlation between transportation and power system is through bridge and traffic light component: if the power system is not able to supply the electrical energy necessary for the operation of the traffic light also the bridge component is consequently affected. Its level of functionality will be reduced since the lack of traffic light control will cause a reduction of vehicular traffic through the bridge itself. The communication tower receives energy from the power system whereas no correlation between communication and transportation system was taken into account.

With reference to extra-district correlations, to obtain interdependencies we made the hypothesis of considering one power system for all the model and not a power system for each district: in such way, if there is a outage or lack of power, the systems of all district which are depending on it are consequently affected. Figure 2 shows the representation of the four districts considered as case study with nodes, links and components.

### Generation of restoration curves

A specific system recovery curve generator was developed for the random definition of the system functionality over time for power and communication systems. For the transportation system the functionality was instead computed as described in (Karamlou, 2016). Recovery curves express thus the daily residual functionality of each system for a total time window of one year.

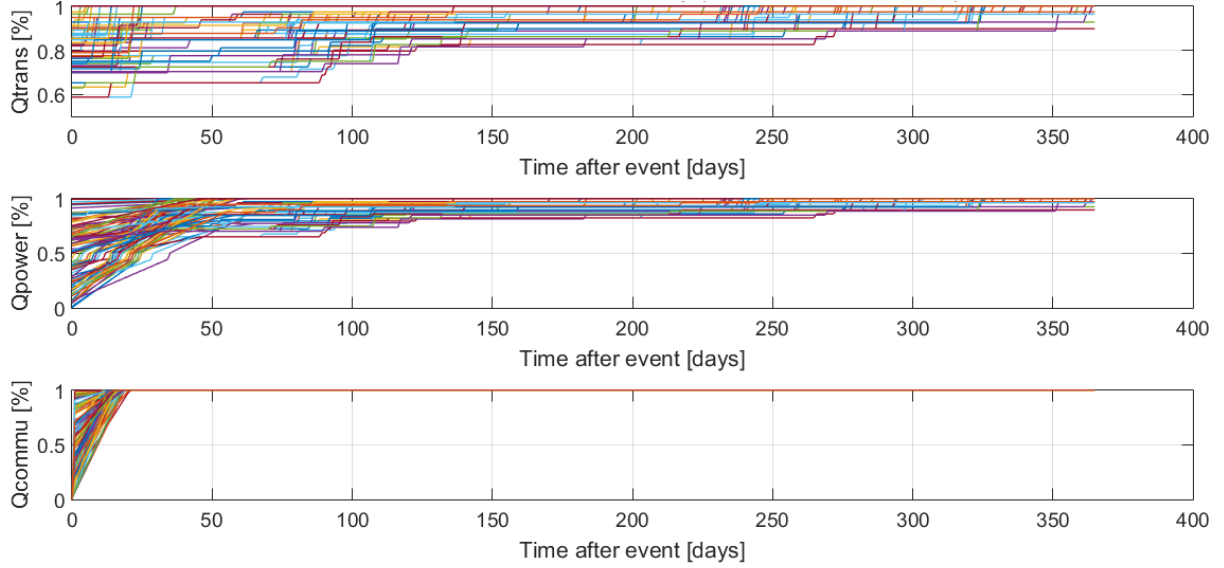
**Figure 2.** Topology description : district case study (a) and localization of infrastructural components (b - d).



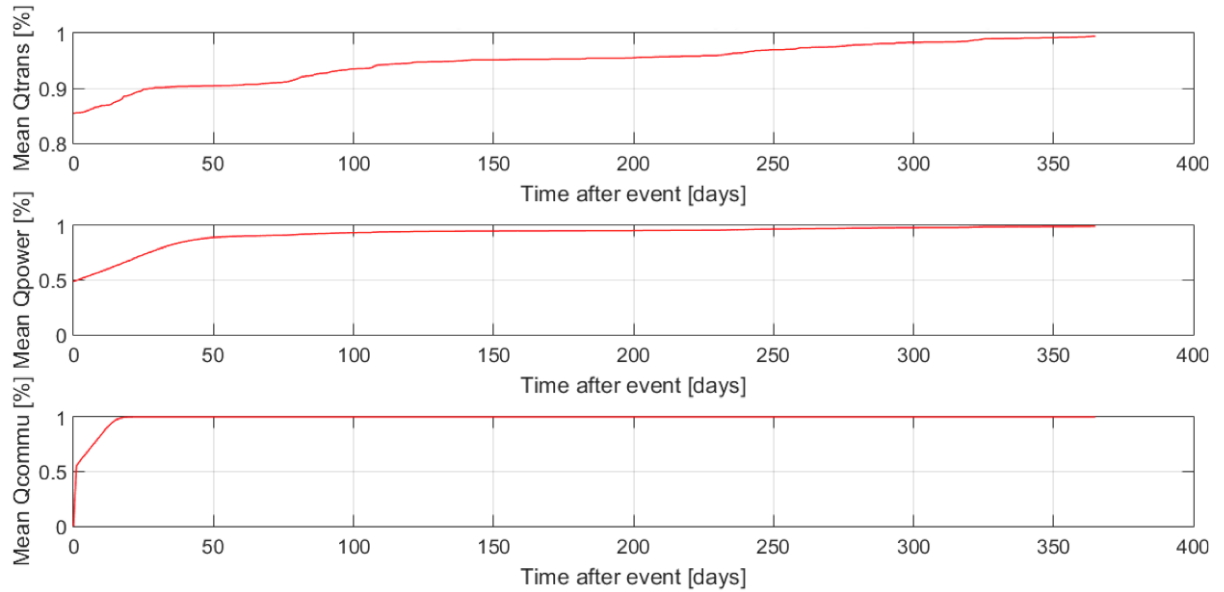
A total number of 100 recovery curve samples were generated for each system (Figure 3) taking into account interdependencies between systems. Figure 4 illustrates mean

functionality curves on the basis of the 100 curves previously defined for each infrastructural system.

**Figure 3.** Recovery functions sampled for each infrastructural system taking into account system interdependencies.



**Figure 4.** Mean recovery functions for each infrastructural system taking into account system interdependencies.



### Cross Correlation Function

Starting from the mean functionality values  $Q(t)$ , the cross correlation function  $CCF$  was derived with the aim to quantify the strength of coupling between infrastructural systems. The data  $Q(t)$  has got a trend of second order with non stationary behavior. A weakly stationary is obtained with a logarithmic transformation of  $Q(t)$  of values and the second differenced of them. Several relations for the assessment of the  $CCF$  function were proposed over the years in scientific literature: in this work, we used the relation described in (Duenas-Osorio and Kwasinski, 2012). Starting from the definition of the cross-covariance  $\gamma_{j,k}(h)$  between two infrastructural systems, as:

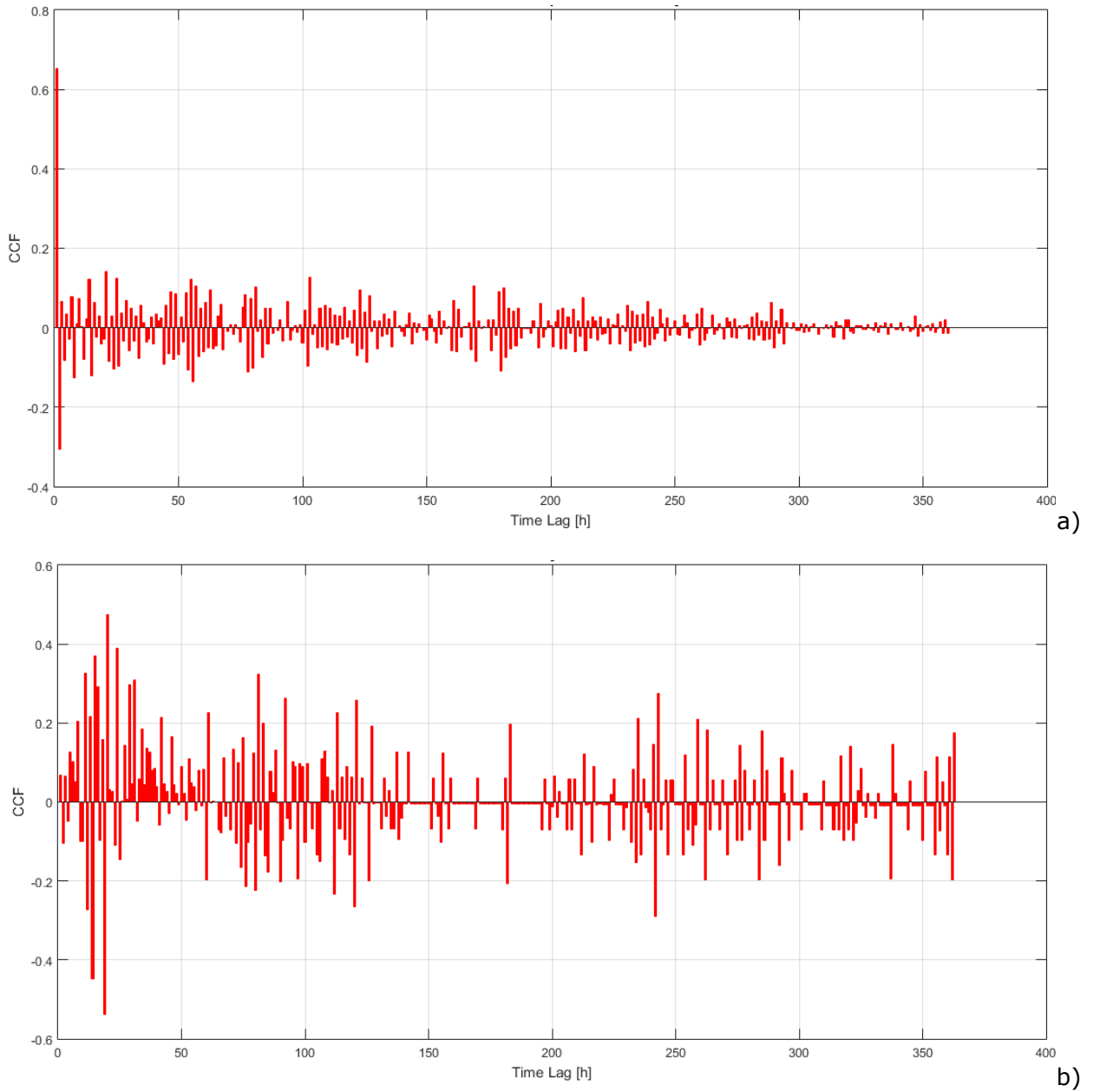
$$\gamma_{j,k}(h) = \frac{1}{1 + n_j} \sum_{t=0}^{n_j-h} (x_{t+h,j} - \bar{x}_j) (x_{t,k} - \bar{x}_k) \quad 1)$$

It is possible to derive the Cross Correlation Function  $\rho_j(h)$  as a function of time  $h$ , according the following expression:

$$\rho_j(h) = \frac{\gamma_{j,k}(h)}{\sqrt{\gamma_j(0) \cdot \gamma_k(0)}} \quad 2)$$

Figure 5 shows as illustrative examples CCF derived from two the systems comparisons.

**Figure 5.** CCFs between transportation and power (a), power and communication systems of district #1



### Evaluation of the interdependencies matrix $S_{ij}$

The evaluation of CCF function  $\rho_j(h)$  allows computing the daily degree of correlation between two infrastructures day by day. However, for summarizing this information, a global value of correlation in the observation period is needed. The synthetic estimation of correlation is thus performed via the interdependency index  $S_{ij}$  proposed by Duenas-Osorio and Kwasinski (2012):

$$S_{i,j} = \frac{1}{N} \sum_{k=1}^N \begin{cases} \frac{\rho_{i,j}^+(h)}{1 + \sqrt{|h_k|}} \cdot \text{sgn}(h_k) & \text{if } \rho(h_k) \geq \rho_{tr} \text{ e } h_k \neq 0 \\ \rho(h_k) & \text{if } \rho(h_k) < \rho_{tr} \text{ e } h_k \neq 0 \end{cases} \quad 3)$$

where  $\rho_{i,j}^+(h)$  is the CCF positive value which occurs to the peak lag time  $h$  with absolute value  $|h|$ ,  $\rho_{tr}$  is the positive threshold of statistical significance, and  $N$  represents the positive value that exceed the upper bound of statistical significance. The threshold value assumed in this work is equal to  $\rho_{tr} = 0.15$ . All interdependencies coefficient are summarized in sixteen matrices, 4 of them for intra-district and 12 for extra-district estimates. Table 1 lists the interdependencies coefficients  $S_{ij}$  derived from the analysis.

**Table 1.** The interdependencies coefficients derived for the analyzed infrastructural systems

	TS1	PS1	CS1	TS2	PS2	CS2	TS3	PS3	CS3	TS4	PS4	CS4
TS1	1	0.65	0	0.42	0.46	0.05	0.27	0.19	0.05	0.1	0.1	0.05
PS1	0.23	1	0	0.64	0.22	0.01	0.1	0.14	0.04	0.11	0.1	0.03
CS1	0	0	1	0	0	0.06	0	0	0.04	0	0	0.04
TS2	0.2	0.33	0	1	0.52	0.02	0.13	0.13	0.04	0.08	0.1	0.04
PS2	0.21	0.21	0	0.51	1	0.01	0.13	0.12	0.03	0.09	0.1	0.03
CS2	0.16	0	0	0	0	1	0	0	0	0	0	0
TS3	0.28	0.31	0	0.48	0.5	0.07	1	0.23	0.05	0.13	0.13	0.05
PS3	0.29	0.21	0	0.5	0.32	0.06	0.36	1	0	0.15	0.07	0.05
CS3	0	0	0	0	0	0	0	0.05	1	0	0	0
TS4	0.21	0.37	0	0.15	0.2	0.05	0.17	0.22	0.08	1	0.5	0.08
PS4	0.23	0.41	0	0.24	0.2	0.04	0.19	0.18	0.08	0.49	1	0.1
CS4	0	0	0	0	0	0	0	0	0	0	0	1

Results evidenced a strength correlation between transportation and power systems, both in the intra- and extra-district cases. The highest value is equal to  $S_{ij} = 0.64$ , when the transportation system lead the recovery process with respect to the power system in the district #1. As expected, a weak correlation between communication and the other systems was observed.

### Evaluation of the Recovery Speed Index and discussion

A novel parameter was set in this study for the analysis of the interdependencies: the recovery speed index, can allow to easily describe the level of correlation between different infrastructural systems.

The recovery speed index is easy to compute starting from the classic definition of velocity:

$$v = \frac{dx}{dt} \quad 4)$$

The equation can be considered in incremental terms considering in y axis the increasing of functionality  $\Delta F$  respect to the variation in time  $\Delta T$  in the x axis. The time variation chosen in this study for the analysis is the monthly variation of functionality: in such way the monthly recovery speed index can be expressed as:

$$v_{RC}^M = \frac{\Delta F}{\Delta T_M} \text{ [Functionality Recovery/month]} \quad 5)$$

Table 2 lists the monthly recovery speed index for each infrastructural system of the four districts. After finding all the monthly recovery speed values we made the comparison between the recovery speed index values for couples of infrastructures with the monthly values over one year. Figures 6, 7 show as illustrative examples respectively an intra- and an extra-district recovery speed index comparisons.

**Table 2.** Monthly recovery speed index values for the analyzed infrastructural systems.

Month	TS1	PS1	CS1	TS2	PS2	CS2
1	0.001557	0.009430	0.03324	0.001776	0.011144	0.033242
2	0.000141	0.003801	0	0.000169	0.003789	0
3	0.000714	0.000784	0	0.000727	0.000732	0
4	0.000583	0.000583	0	0.000584	0.000584	0
5	0.000155	0.000155	0	0.000223	0.000223	0
6	0.000058	0.000058	0	0.000072	0.000072	0
7	0.000140	0.000140	0	0.000119	0.000119	0
8	0.000262	0.000261	0	0.000266	0.000266	0
9	0.000329	0.000329	0	0.000354	0.000354	0
10	0.000272	0.000272	0	0.000285	0.000285	0
11	0.000246	0.000245	0	0.000228	0.000228	0
12	0.000102	0.000100	0	0.000124	0.000124	0

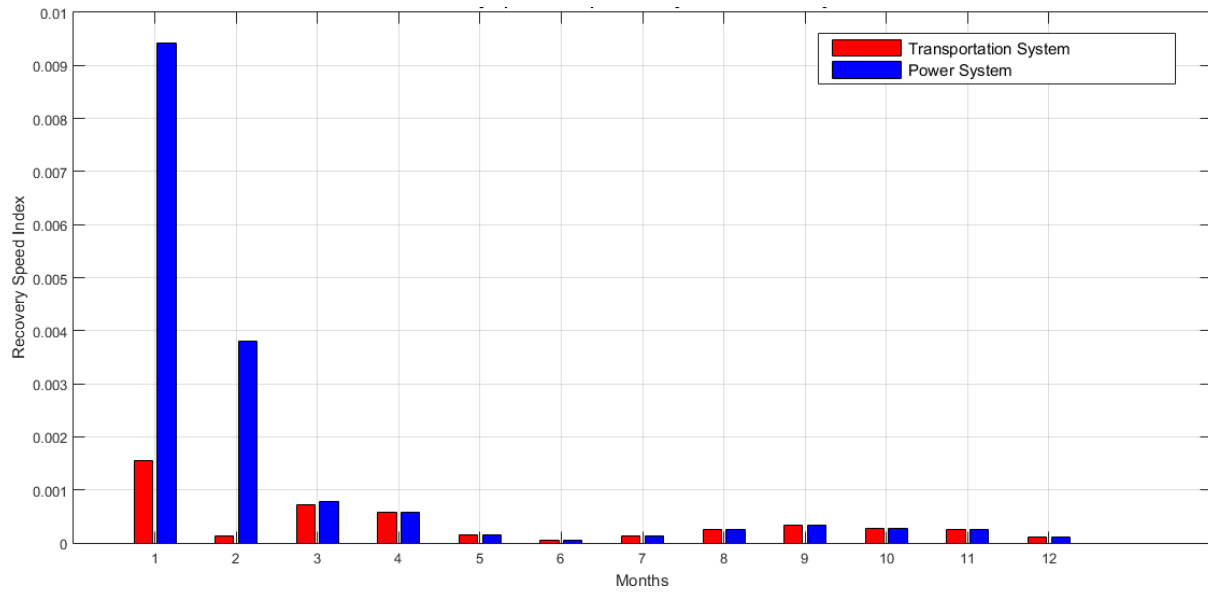
  

1	TS3	PS3	CS3	TS4	PS4	CS4
2	0.001860	0.011059	0.033242	0.001691	0.009893	0.033333
3	0.000126	0.004700	0	0.000108	0.003854	0
4	0.000564	0.000783	0	0.000649	0.000656	0
5	0.000468	0.000470	0	0.000501	0.000501	0
6	0.000124	0.000124	0	0.000180	0.000180	0
7	0.000048	0.000048	0	0.000062	0.000062	0
8	0.000105	0.000105	0	0.000119	0.000118	0
9	0.000229	0.000227	0	0.000269	0.000269	0
10	0.000229	0.000226	0	0.000270	0.000270	0
11	0.000210	0.000210	0	0.000229	0.000228	0

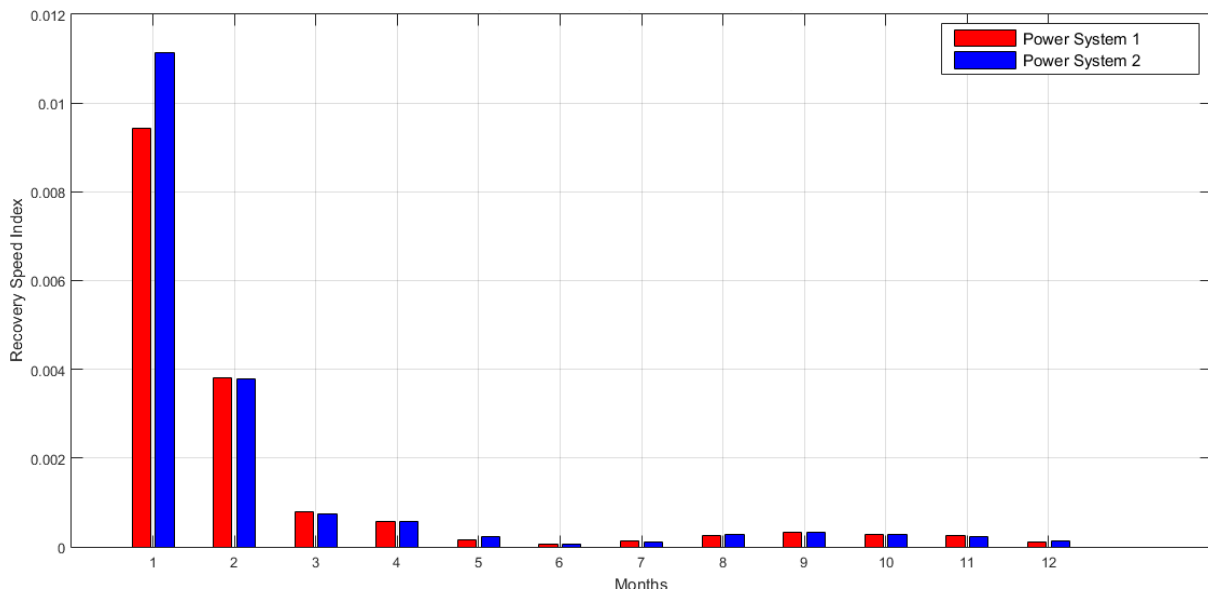
From the information derived from the recovery speed values it is important to consider, rather than absolute values, the monthly percentage changes between the two systems. The observation was therefore focused in the first three months which are the most crucial for a system interdependency analysis: after three months the recovery speed index significantly decreases and the percentage variation is therefore weak.

It was observed that if there is an high percentage variation of recovery speed index, infrastructures are strength correlated. In the case in Figure 6 there are high variations of recovery speed index and if we check the interdependency coefficient value  $S_{ij}$  previously derived, we see that is high and equal to 0.65. Figure 7 evidences a lower variation of recovery speed index, and the value of interdependency  $S_{ij}$  is equal to 0.21. Table 3 summarizes these outcomes.

**Figure 6.** Recovery speed index comparison for transportation and power systems of district #1.



**Figure 7.** Recovery speed index comparison between power systems of districts #1 and #2.



**Table 3.** Comparisons between recovery speed index variations in the first three months after the earthquake occurrence for couples of intra- and extra- district infrastructural systems

Comparison	$S_{ij}$	Var. Month 1	Var. Month 2	Var. Month 3
TS1 - PS1	0.65	505%	2586%	10%
PS1 – PS2	0.21	18%	0%	7%

Keywords: resilience, interdependencies, time-series analysis.

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# Derivation of Bridge Functionality Loss Curves for the Resilience Analysis of a Road Network exposed to Seismic Risk

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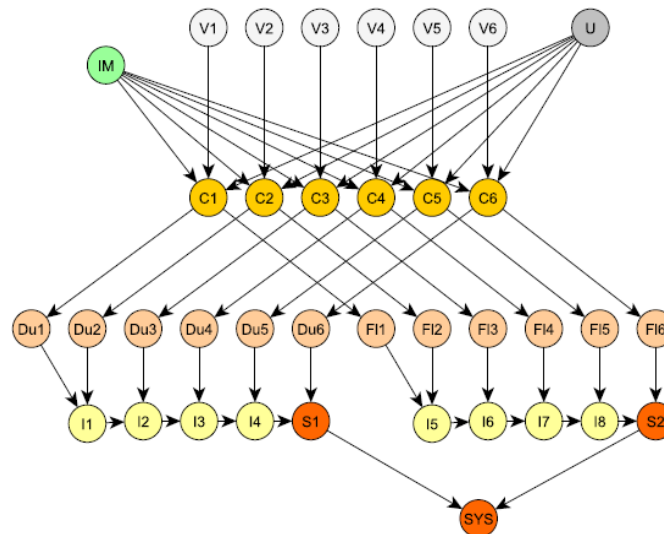
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An infrastructure is conventionally represented as a system of systems, where individual components are heavily interdependent. In this context, the assessment of the robustness or the resilience of an infrastructure requires to quantify a set of appropriate system performance indicators. The latter are usually accessed through the prediction of the functionality level of the components, and not only their physical damage states. Therefore the present study details a procedure for the derivation of probabilistic functionality loss curves, applied to the seismic fragility assessment of roadway bridges. The proposed approach may be decomposed into the following steps:

- Identification of the bridge's structural components and corresponding damage mechanisms (e.g. yielding of pier columns, deformation of bearings, deck unseating, etc.);
- Association of each component damage mode with a probabilistic distribution of functionality loss and repair duration, through an expert elicitation process;
- Construction of a Bayesian Network (BN) in order to update the probabilistic distributions of losses at the bridge level (see Figure 1), which result from the combinations of damage events at the component level (Gehl and D'Ayala, 2016).

**Figure 1.** Bayesian Network for the derivation of functionality curves for a six-component bridge. **IM** represents the seismic loading, **U** and **V<sub>i</sub>** are standard normal variables representing the statistical dependence between the component events, **C<sub>i</sub>** represent the component events (i.e. fragility of component failure modes), **Du<sub>i</sub>** and **Fl<sub>i</sub>** represent the associated functional consequences (repair duration and functionality loss, respectively) and **SYS** represents the aggregated functional losses at the bridge level.

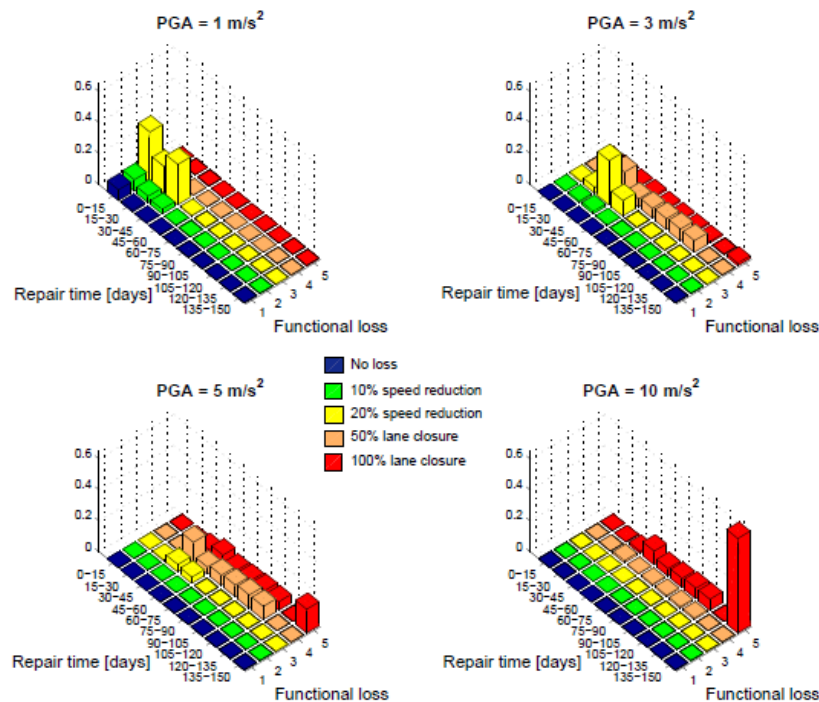


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The resulting curves directly express the probability of reaching or exceeding some predefined functionality levels given the seismic intensity at the bridge location. The use of BNs allows for the joint probability of functionality loss and repair duration to be accessed (see Figure 2), which constitute crucial information for the design of restoration strategies.

**Figure 2.** Joint distribution of the repair time and functional loss for different seismic intensity levels



The derived functionality curves are then applied to a simplified road network, where the aggregated inter-city travel time is selected as the system performance indicator. Thanks to the derived functionality loss curves, which provide both an estimation of the robustness and the recovery parameters at the bridge level, the resilience index (Cimellaro et al., 2006) with respect to the extra-travel time may then be derived. Based on activity parameters of a given seismic source area, thousands of probabilistic earthquake scenarios are generated in order to derive the distribution of the resilience index (i.e. derivation of the yearly probability of exceedance of the resilience loss). Finally, various restoration strategies are also tested (e.g. priority given to bridges with lightest damages, or bridges with heaviest damages, etc.), in the case of limited resources: a bridge prioritization based on the ones that have the most impact on the travel time leads to a reduced resilience loss, especially for seismic events with long return periods. Based on this preliminary study, future developments will pertain to the application of this approach to a real-world road network in a multi-risk context, thanks to the emergence of multi-hazard fragility models (Gehl and D'Ayala, 2016).

Keywords: bridges, Bayesian Networks, functional losses, restoration, fragility curves

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# **Immediate Resilience: Numerical Simulation and Implementation Issues**

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## **Introduction**

It is recognized the multidisciplinary relevance of resilience, focusing, in recent years, also the attention of the seismic engineering community, where resilience is often identified as an attribute of structures, with four main characteristic dimensions (Resourcefulness-Rapidity-Robustness-Redundancy) (Cimellaro et al., 2010), as the capacity of recovering functionality subsequently to a loss of performance. Within this context, structural control solutions, primarily recognized as effective measures for mitigating earthquake loading, may also allow resilience improvement in the structures where they are adopted.

Such feature is exploited by a special class of control systems that can adapt themselves to different conditions, such as local failures, compensating losses of performance and, therefore, offering a contribution to structural resilience: the semi-active adaptive control class (Casati and Domaneschi, 2007; Domaneschi, 2010). Such interesting performance can be exploited by changing the working parameters of the control system in real time when a local failure is detected and localized.

It is worth underlining the innovative aspect related to the very short time employed by the control devices (e.g. semi-active) for automatically compensating the occurred local failure. This property has been termed as immediate resilience and it has been recently presented in the existent literature (Domaneschi and Martinelli, 2016). A new measure index of resilience has been also presented as well where a penalty function allows for a zero value of resilience once an acceptable recovery time is fixed. Furthermore, the total resilience index is gradually linearly reduced with time passing through a suitable reduction factor. Within this approach, the crucial aspect of time with respect to the Rapidity dimension of resilience is essentially accounted.

Numerical simulations are invaluable tools for testing and evaluating seismic resilience on structures. In particular immediate resilience property of an existing bridge benchmark is studied within a multipurpose finite element code. The methodology for reproducing local failures and introducing automatic compensation by control elements is described. The discussion is then extended for underlining general features of the finite element implementation, allowing to extend the resilience analyses and simulation at different codes.

## **Discussion and Remarks**

The proposed approach for enhancing structural resilience through control systems, with reference to the seismic hazards, is tested on the benchmark model of the existent cable-stayed bridge Bill Emerson Memorial Bridge in US. The original adaptive solutions proved effective in (Domaneschi, 2010) for the original benchmark statement, have been exploited on the numerically improved model in (Domaneschi and Martinelli, 2016; Domaneschi and Martinelli, 2014) and within the resilience framework (Domaneschi and Martinelli, 2016). The control scheme consists in a Redundant distribution of devices along the bridge axis between the deck and the bents/piers. Such devices are able to perform in longitudinal and horizontal direction allowing a dissipative function in the horizontal plane, decoupling also the deck motion from the supporting elements.

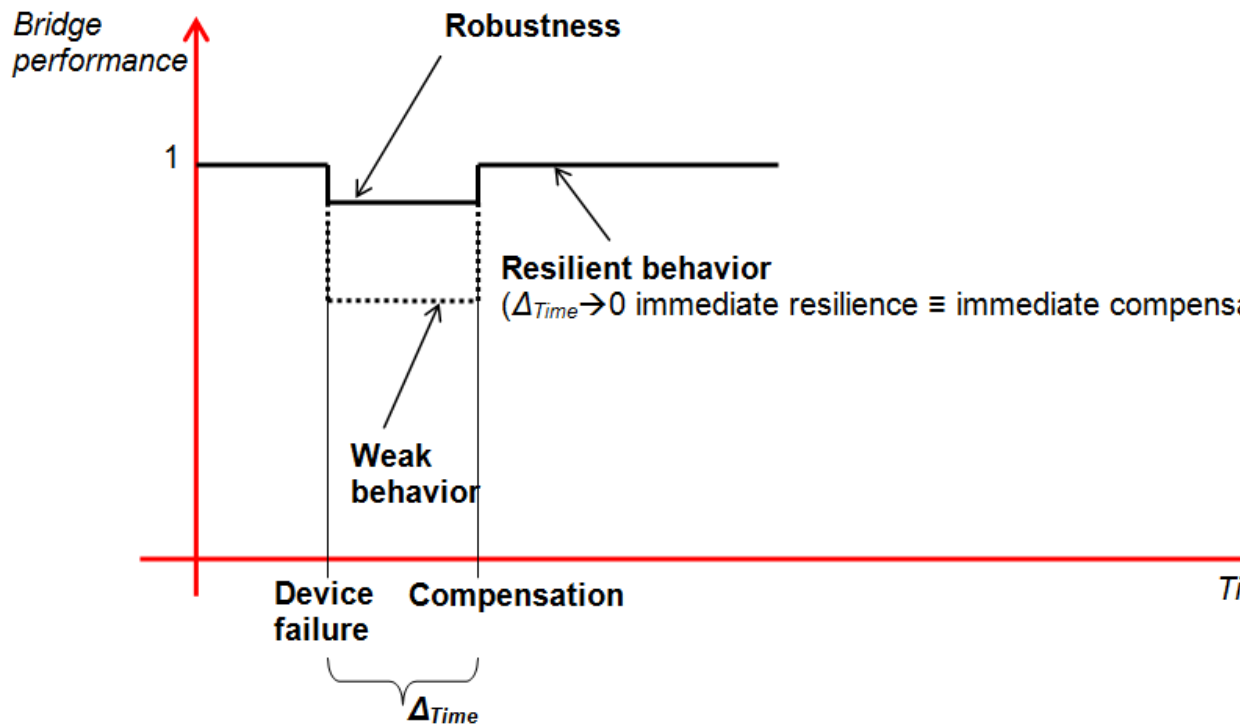
The semi-active model of hysteresis in (Domaneschi, 2012) is employed for managing the level of dissipation of each control device embedding a suitable control law. The

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whole control system is organized in a decentralized scheme, so that each subsystem (device) performs independently from the others with interesting benefits in terms of Robustness (Domaneschi, 2010). Through such adaptive arrangement, it is possible to compensate local device failures by changing in real time the working parameters of closer devices, which performs along the same degree of freedom. Thus, an automatic loss compensation action is performed.



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## **Advances in Risk and Resilience Assessment for the Built Environment**

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Some of the objectives and results of two EU funded projects, in which JRC has participated, are presented, especially as regards their resilience relevant activities.

### **The SYNER-G project: systemic seismic vulnerability and risk analysis for buildings, lifeline networks and infrastructures safety gain**

Past research on seismic risk analysis of assets and urban areas focused on the vulnerability assessment of individual elements and did not consider the systemic vulnerability and the consequent increase of the physical and socio-economic impact. It is therefore needed to develop a methodology for the evaluation of the seismic vulnerability of independent elements and systems, which accounts for the uncertainties in the models for damage and loss estimation, and considers the distinctive features of elements at risk in Europe together with the specific seismotectonic characteristics.

The SYNER-G project (Pitilakis et al. 2014a; 2014b) developed a methodological framework for the systemic assessment of physical and socio-economic vulnerability to earthquakes at urban and regional level. The built environment is modelled according to a detailed taxonomy of its component systems: buildings, transportation and utility networks, and critical facilities. The framework encompasses in an integrated way regional hazard, fragility assessment of components and socio-economic impacts of an earthquake. Furthermore, it accounts for uncertainties and interactions between systems. The project developed a prototype software that was used to apply and validate the methodology at urban and regional scale: the city and harbour of Thessaloniki (Greece), the city of Vienna (Austria), the gas system of L'Aquila (Italy), the electric power network in Sicily, a roadway network and a hospital in Italy.

### **The STREST project: harmonized approach to stress tests for critical infrastructures against natural hazards**

Critical infrastructures are the backbone of modern society and provide many essential goods and services, such as electrical power, water and telecommunications. Moreover, they are highly integrated and have growing mutual dependencies. Natural events that recently impacted critical infrastructures highlighted their vulnerability to natural and manmade hazards. They also revealed the risk of cascading failures with potentially widespread societal and economic consequences. To move towards a safer and more resilient society, it is required to develop and apply an improved framework and standardised tools for hazard and risk assessment that address events with low probability and high consequences.

The STREST project (Esposito et al., 2017; Mignan et al., 2017) developed a stress test framework to determine the risk and resilience of critical infrastructures systems, focusing on earthquakes, tsunamis, geotechnical effects and floods. The project developed a consistent modelling approach to hazard, vulnerability, risk and resilience assessment of low-probability and high-consequence events, considering relevant epistemic uncertainties and interdependencies of critical infrastructures. Moreover, STREST selected six key representative critical infrastructures in Europe for exploratory

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application of the stress test methodology: a petrochemical plant in Milazzo (Italy), large dams of the Valais region (Switzerland), hydrocarbon pipelines (Turkey), the Gasunie national gas storage and distribution network (Netherlands), the port infrastructure of Thessaloniki (Greece) and an industrial district in Emilia (Italy).

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SYNER-G Consortium: Aristotle University of Thessaloniki (coordinator – GR), Vienna Consulting Engineers (AT), Bureau de Recherches Géologiques et Minières (FR), Joint Research Centre (BE), Norwegian Geotechnical Institute (NO), University of Pavia (IT), University of Rome 'La Sapienza' (IT), Middle East Technical University (TR), Analisi e Monitoraggio del Rischio Ambientale (IT), Karlsruhe University of Technology (DE), University of Patras (GR), Willis Group Holdings (UK), Mid-America Earthquake Center, University of Illinois (USA), Kobe University (JP).

STREST Consortium: Eidgenössische Technische Hochschule Zurich (coordinator – CH), École Polytechnique Fédérale de Lausanne (CH), Basler & Hofmann (CH), European Centre for Training and Research in Earthquake Engineering (IT), Analisi e Monitoraggio del Rischio Ambientale (IT), Istituto Nazionale di Geofisica e Vulcanologia (IT), Netherlands Organisation for Applied Scientific Research (NL), Université Joseph Fourier (FR), Aristotle University of Thessaloniki (GR), Bogazici University (TR), Ljubljana University (SI), Joint Research Centre (BE).

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## **JRC's Geospatial Risk and Resilience Assessment Platform (GRRASP)**

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Communities and societies rely on a vast array of infrastructures and technological systems, whose efficiency is in many cases critical to the safety and security of citizens. Interconnections among these elements can substantially improve the attainable number and quality of services (e.g. ICT penetration in the electricity sector in the context of smart grids development). Nevertheless, interdependencies can also enable the propagation of domino effects in case of critical events, such as natural catastrophes or manmade hazards.

Over the years, the engineering community has developed a comprehensive toolbox of methods to assess the direct impact of hazards on specific assets and infrastructures. The study of interdependencies and cascading phenomena in multi-layer infrastructures hasn't yet reached the same level of maturity, despite its relevance. The research community is making a considerable effort in order to bridge this gap, and the Joint Research Centre (JRC) is collaborating with several partner institutions over the establishment of data models and analysis tools to support the assessment of resilience in complex systems.

Functional, geographical, cyber and logical interdependencies can be described by different types of datasets and methods, also involving multiple degrees of spatial granularity. Furthermore, the study of critical infrastructures can incorporate aspects of economic impact assessment, taking into account for instance business interruptions caused by the inoperability of technological systems.

These aspects led to the development of the Geospatial Risk and Resilience Assessment Platform (**GRRASP**). This is as a hybrid analysis environment that combines web-GIS technologies and mathematical models devoted to infrastructure analysis. It implements a server-client architecture, and a central installation can serve towards the administration of a community of users and their access to data and models.

Currently GRRASP incorporates several geospatial tools, allowing users to create, upload, and edit their own maps. Dataset sharing and access to public maps can also be granted depending on the user's identity and group/role membership. This enables the creation of user communities and can foster cooperation at regional, national or international scales.

The other core aspect of the architecture is related to analysis and simulation tools. These include a set of routines for the computation of graph metrics, which can be considered among the most widely applied mathematical methods for the analysis of complex networks. Additionally, GRRASP implements techniques for the representation

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and dynamic assessment of interdependencies among critical infrastructures. Based on a service-oriented approach, these techniques can be used to estimate the inoperability and disservice of interconnected infrastructures in a specified region. Examples include the impact of power outages on train lines, as well as the resulting shift in transportation demand to the road network and possible traffic congestion issues. Furthermore, input-output inoperability models are also implemented to allow the economic impact estimation based on some of the emerging techniques found in recent literature.

Scientific data presentation functionalities have been addressed extensively in the development of GRRASP, so that a rich yet expandable set of visualization capabilities has been developed for both geographical and non-geographical information.

In summary, three key characteristics distinguish GRRASP from other affine platforms:

- **it is not a single tool**; instead, it is a platform whose objective is to incorporate and combine several tools able to tackle different objectives within the framework of infrastructure risk and resilience assessment;
- **it is expandable**: new functionalities can be added in time by both JRC and third-party developers;
- **it enables the collaboration of groups of users**, who can share data and models as well as analysis results with their reference communities.

Public bodies such as EU member states and regional authorities can take advantage of GRRASP capabilities in order to analyse their infrastructure and set-up action plans, as well. An ideal process could include, for instance: a first step involving a structured data collection, oriented towards the use of models included in GRRASP; a second step wherein analyses are performed to identify cascade effects and the impacts on the economy due to disruptive events; finally, the use of the output of these analyses, for instance towards planning or training activities. In other words, GRRASP can enable a series of activities oriented to the improvement of infrastructure resilience at regional and national level, at reduced costs. It can also serve to connect more tightly the contribution of the research community with the action of authorities and operators involved in the management and protection of critical infrastructures.

GRRASP is available for download at <https://ec.europa.eu/jrc/en/grrasp>.





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