Structural health monitoring, a tool for improving critical infrastructure resilience

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Outline

- **Critical infrastructure**
- **Resilience**
- **SHM for improving CI Resilience**

Critical infrastructure (CI)

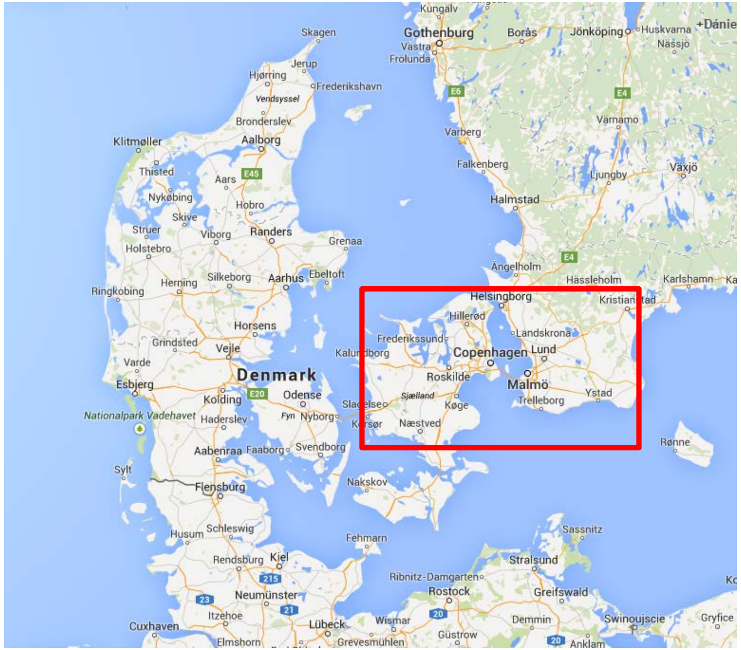
CI definition:

- Assets essential for the maintenance of ***vital societal functions*** (health, safety, security, economic or social well-being of people, etc.) and
- the disruption or destruction of which would have a ***significant impact*** as a result of the failure to maintain those functions.

CI characteristics:

- Complex (technical) systems,
- Exposure to several types of hazards,
- Serious consequences of failure,
- Interdependencies with other types of infrastructure.

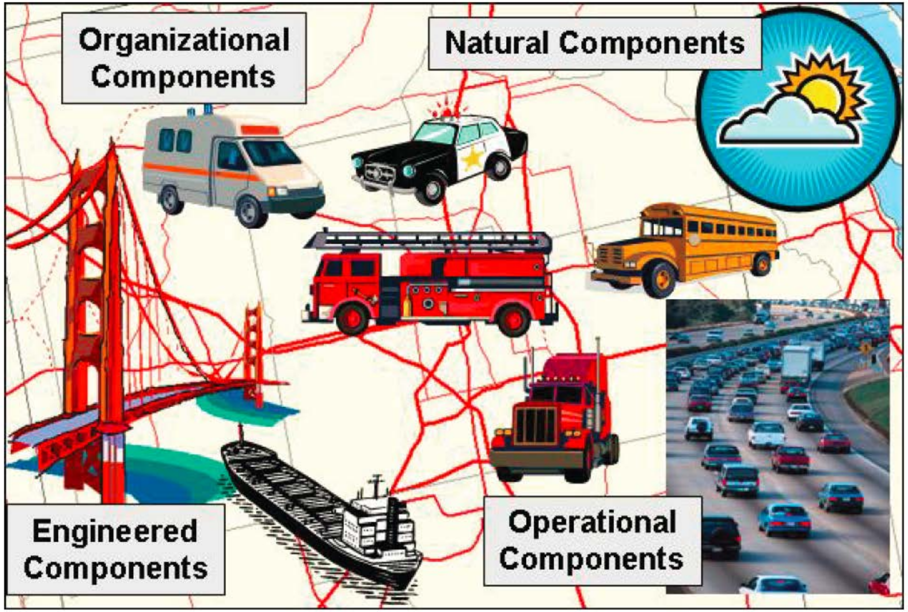
Critical infrastructure (CI)



Critical infrastructure (CI)

CI system (Catbas et al., 2006)
(Highway transportation infrastructure)

- Engineered components
- Natural components
- Organizational components
- Operational components



(Catbas et al., 2006)

Critical infrastructure (CI)

Shift from CI protection to building resilience

CI protection

- safety of assets cannot be ensured by all means.

New policies and research initiatives shift the focus on **resilience** rather than protection.

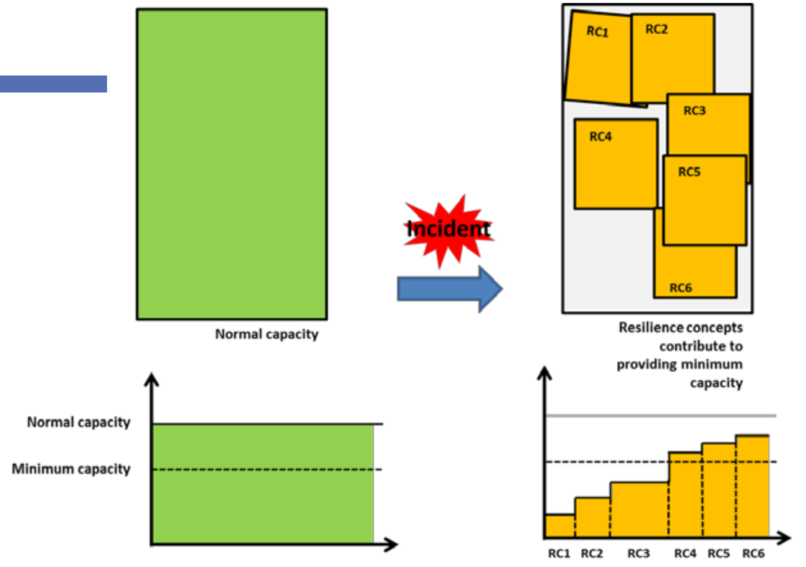
CI resilience

- The ability of CIs to ***mitigate*** hazards, ***contain*** the effects of disasters when they occur, and carry out ***recovery*** activities in ways that minimize disruption and mitigate the effect of future disasters (***reallocate*** resources).
- Further: reduce ***cascading effects*** (→ www.casceff.eu).

Resilience concepts

Improved risk evaluation and implementation of resilience concepts to critical infrastructure (IMPROVER)

- Community resilience as a ***baseline criteria*** for performance of the infrastructure in times of crises. (Baseline may readjust as society responds to the situation.)
- Different ***resilience concepts may overlap*** in the way in which they ensure overall resilience.
- ***Evaluation of resilience***: it is necessary not only to evaluate the overall resilience of infrastructure to threats but also to evaluate the performance and impact of the individual resilience concepts.
- The overall resilience of a system could be streamlined by ***removing any overlaps*** in resilience concepts whilst providing the same overall level of resilience.



System is fully functional, possibly capable of delivering services above the minimum level expected.

Normal functionality is not available and the resilience concepts 'patch' the system to ensure that it is capable of providing the minimum function required of it.

Resilience concepts

General concepts (Holling, 1996)

Engineering resilience

- The ability of the system to resist disturbances and quickly ***return to the equilibrium state***.
- Focus is on the ***stability*** of an equilibrium state.
- ***Efficiency***, ***constancy*** and ***predictability*** →
- Controlled, fail-safe design and optimized performance.

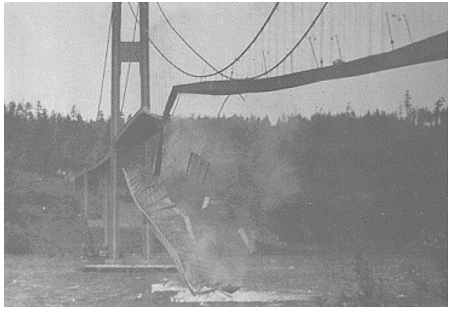
Ecological resilience

- The magnitude of disturbance that can be absorbed before the system ***changes state***.
- Focus is on conditions far from equilibrium, where large disturbances can ***flip*** the system ***to another equilibrium state***.
- ***Persistence***, ***change*** and ***unpredictability*** →
- Adaptation and survival in a changing environment.

Resilience concepts

The contrasting aspects of engineering and ecological resilience require ***different management actions:***

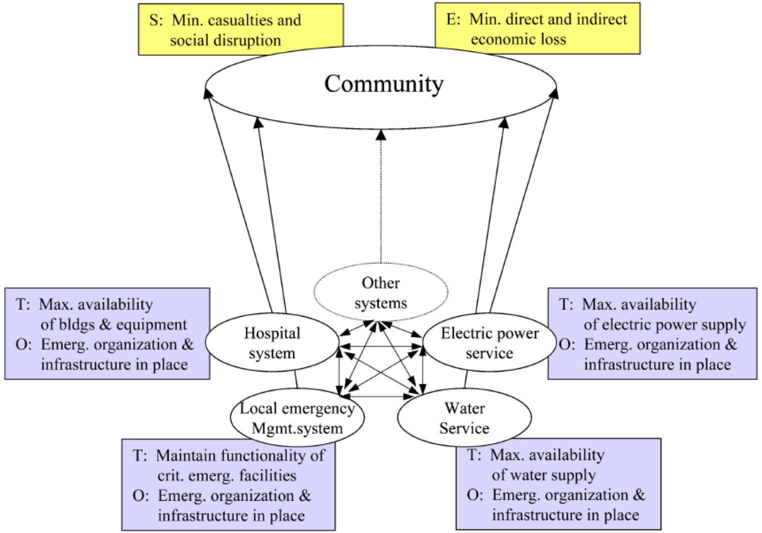
- Focusing on ***optimizing*** a system for a single (set of known) objective functions might ***increase the vulnerability*** of the system to unforeseen events.
- ***Effective control*** of internal variables at the edge of instability generates ***external options.***
- In design and management of CIs due to their complex nature and close relation to non-structural systems, and advised strategy might be to find a ***balance between the two concepts***.



Resilience dimensions

MCEER framework (Bruneau et al., 2003)

- **Technological dimension:** the physical properties of systems, including the ability to ***resist damage*** and loss of function and to fail in a safe way.
- **Organizational resilience:** organizations and institutions that ***manage*** the physical components of the systems characterized by: organizational capacity, planning, training, leadership, experience, information management etc.
- **Social dimension:** population and community characteristics that render ***social groups*** either more ***vulnerable*** or more adaptable to hazards and disasters e.g. poverty, low levels of education, linguistic isolation, and a lack of access to resources for protective action.
- **Economic resilience:** the capacity to reduce both ***direct and indirect economic losses*** resulting from disasters.



(Bruneau et al., 2003)

Extension: PEOPLES framework with 7 dimensions (Reinhorn and Cimellaro, 2014)

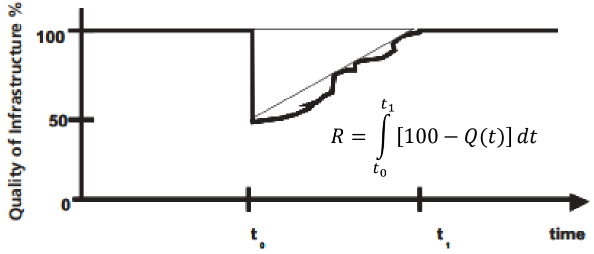
Resilience triangle

Community resilience (Bruneau et al., 2003)

- ***loss of functionality/performance*** from damage and disruption, as well as the pattern of ***restoration and recovery*** over time after a certain loss.
- measures for improving resilience aim *to **reduce the size of the*** resilience ***triangle***, i.e. maximize the area under the performance curve.

Inherent resilience: functioning well during ***non-crisis time.***

Adaptive resilience: flexibility ***during and after crisis.***

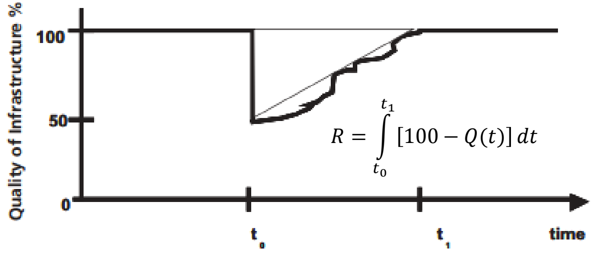


(Bruneau et al., 2003)

Resilience triangle

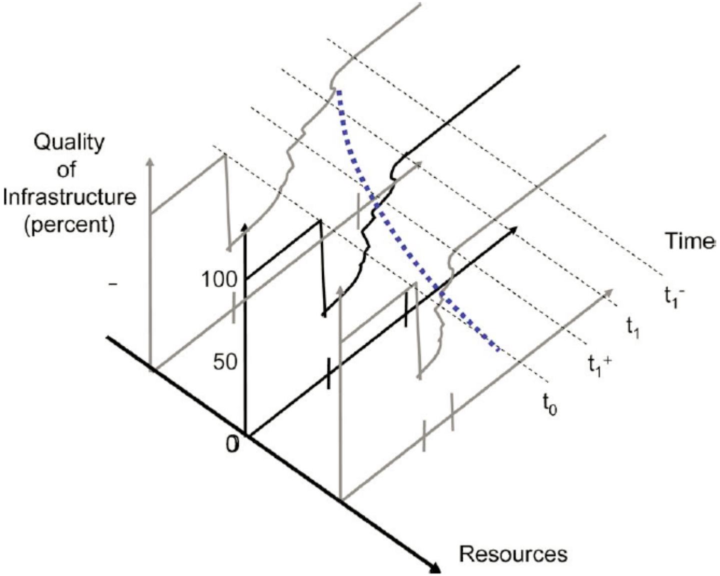
4 Rs of community resilience

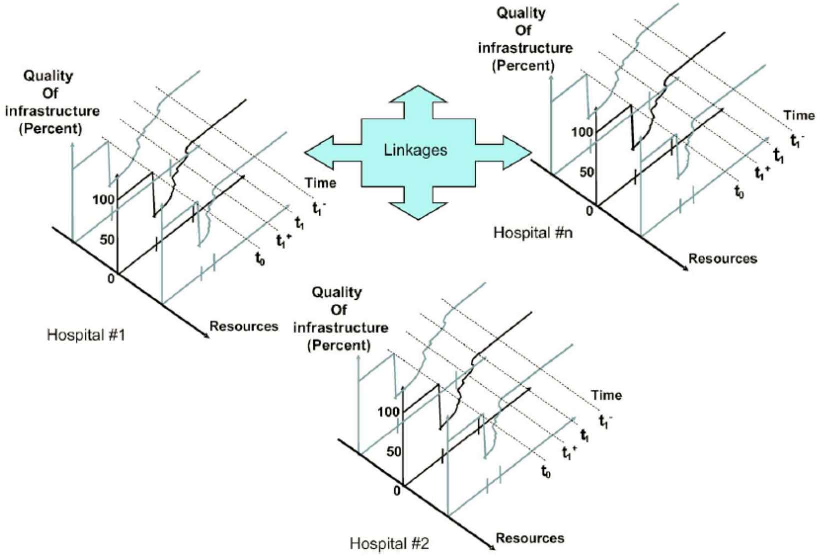
- ***Robustness:*** the inherent ability of the system to ***withstand external demands*** without suffering degradation or loss of function.
- ***Redundancy:*** the extent to which the system could be ***replaced by alternative solutions*** under stress.
- ***Resourcefulness:*** the capacity to ***identify problems***, ***establish priorities*** and ***mobilize resources*** in emergency situations.
- ***Rapidity:*** the ***speed*** to meet priorities and achieve goals in order to ***reduce*** losses, overcome disruption and ***restore*** services.



(Bruneau et al., 2003)

Resilience triangle



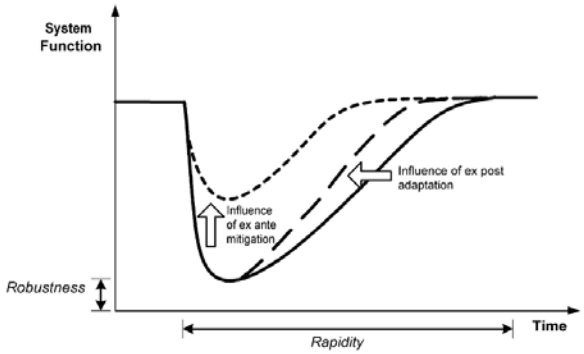


(Bruneau and Reinhorn, 2007)

Resilience triangle (extended)

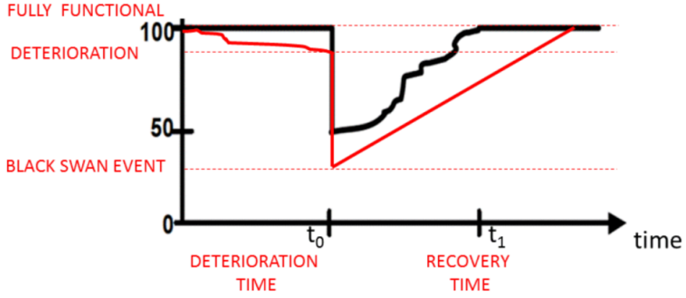
RISE framework (McDaniels et al., 2008)

- Effects of decision making on resilience
- ”Changing nature of external environment”



RISE framework (Ortenzi et al., 2013)

- Extension of the MCEER framework by including deterioration



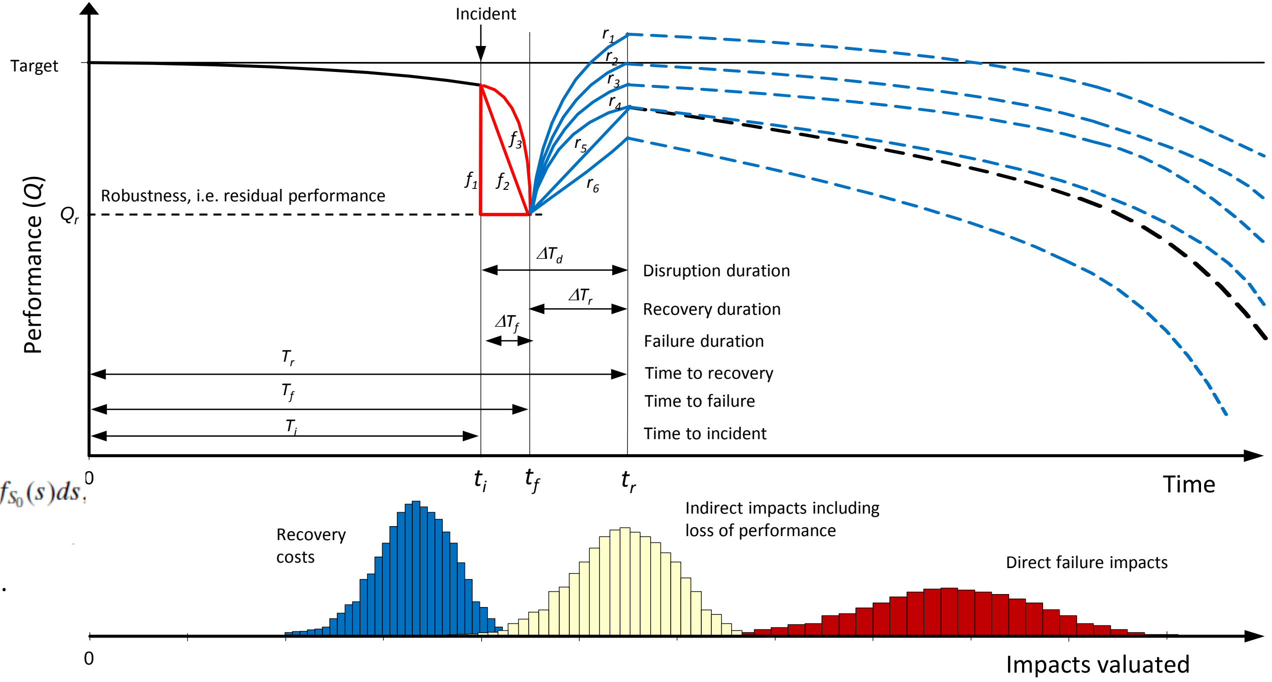
Resilience triangle (probabilistic)

(Ayyub., 2013)

$$R_e = \frac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r}$$

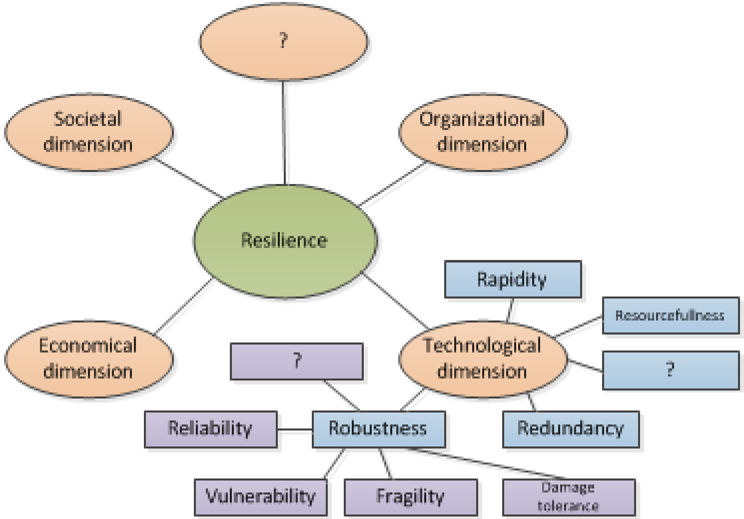
$$F = \frac{\int_{t_i}^{t_f} f dt}{\int_{t_i}^{t_f} Q dt} \qquad R = \frac{\int_{t_f}^{t_r} r dt}{\int_{t_f}^{t_r} Q dt}$$

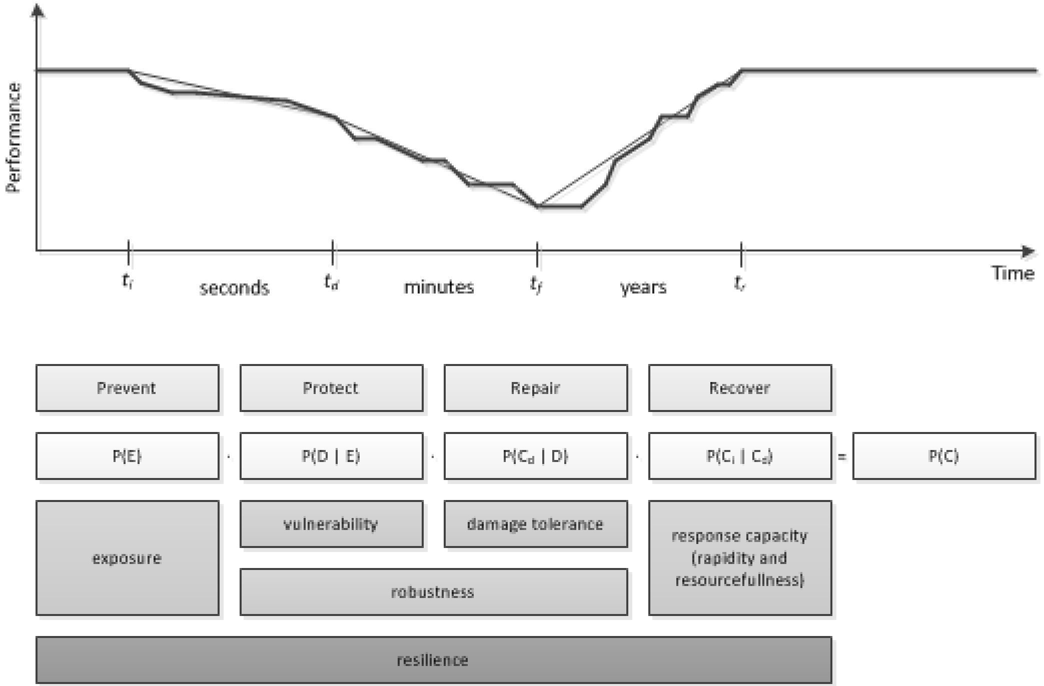
$$f_{T_f} = -\frac{d}{dt}\int_{s=0}^{\infty} \exp\left[-\lambda t\left(1-\frac{1}{t}\int_{\tau=0}^{t} F_L(\alpha(\tau)s)d\tau\right)\right] f_{S_0}(s)ds,$$



Other probabilistic descriptions also exist (e.g. Reinhor and Cimellaro, 2014).

Resilience concepts vs structural robustness





Based on (Starossek and Haberland, 2010; Sørensen, 2010)

SHM for improving resilience

Structural health monitoring (SHM)

- strategy of ***identifying***, ***locating*** and ***quantifying*** damage in infrastructure assets;

In order to identify these changes, SHM compares the ***current state*** of the system based on current or recent sensor output with ***previous*** (assumed undamaged) ***states*** of the system based on historical records of sensor output.

SHM allows to (Magalhães et al.):

- Check design assumptions,
- Verify SLS,
- Evaluate structural condition,
- Provide information after extreme events,
- Provide data for inspection/maintenance planning,
- Evaluate maintenance/repair efficiency,
- Gain better knowledge about structural behavior.

SHM for improving resilience

CIs often ***have to be functional*** during ***response*** and ***recovery*** after disasters (e.g. bridges, hospitals), therefore (Catbas et al. , 2006):

- Emergency teams should have ***access to time-sensitive data*** to determine the type and amount of damage to bridges.
- ***Rapid evaluation methods*** for emergency response operations specifically for critical vehicles (fire trucks, ambulances, and evacuation buses) are needed.
- ***Communication***, ***coordination***, and ***integration of information*** from different sources is needed to improve the capacity of first responders.

SHM can provide the tools and technologies for gathering the data that can be used for safety, security and emergency management.

SHM for improving resilience

SHM can significantly contribute to the different dimensions of resilience through:

- Developing condition-based maintenance strategies (***robustness***),
- Provide information on alternative possibilities (***redundancy***),
- Prioritizing maintenance and emergency actions for better use of resources (***resourcefulness***),
- Alerting first responders in case of emergency (***rapidity***).

If SHM is not designed and implemented properly:

- Resources might be wasted and the time to recovery might be prolonged causing ***unnecessary disruption*** to infrastructure network users or even
- ***Trigger cascading effects*** impacting other vital societal functions through interdependencies.

(Peng et al., 2011)

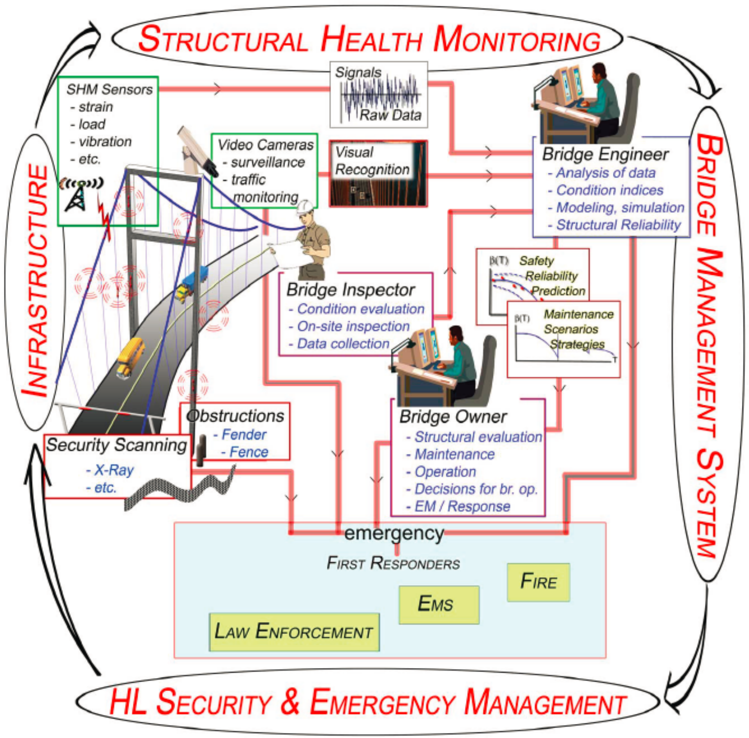
SHM for improving resilience

This could be achieved through the integration of SHM with:

- (Traffic) surveillance systems,
- Security control systems,
- Weather stations,
- Asset management systems,
- Decision support systems,
- etc.

Challenges for integrated SHM systems:

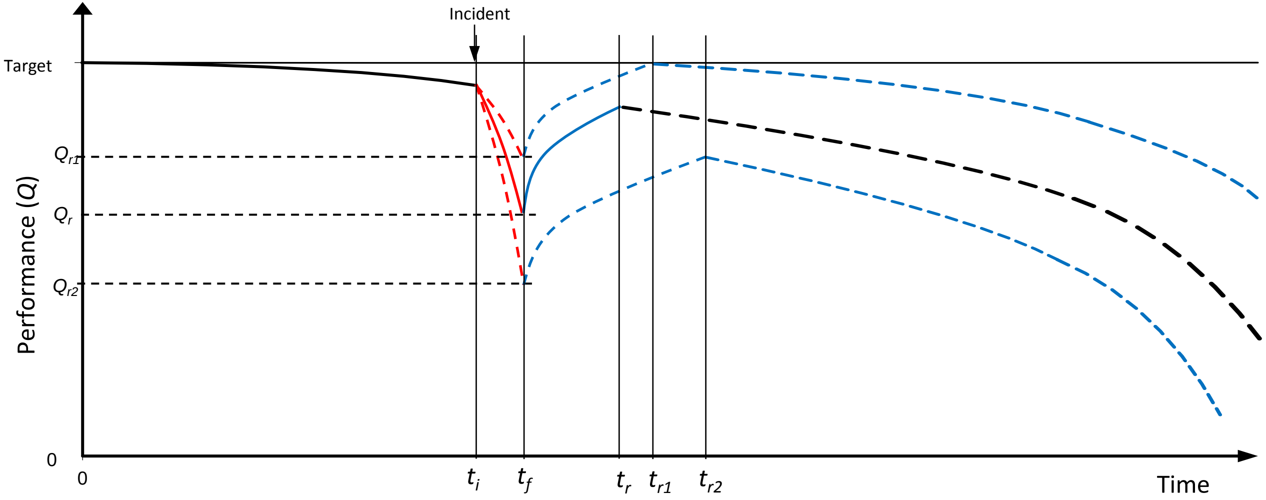
- Resilience of CI should be assessed for all types of hazards (natural and man-made disasters);
- To develop and maintain resilience, adaptable SHM is needed that can respond to changing requirements and possibilities;
- Protection of the system (and data) itself;
- Administrative issues.



(Catbas et al. , 2006)

SHM for improving resilience

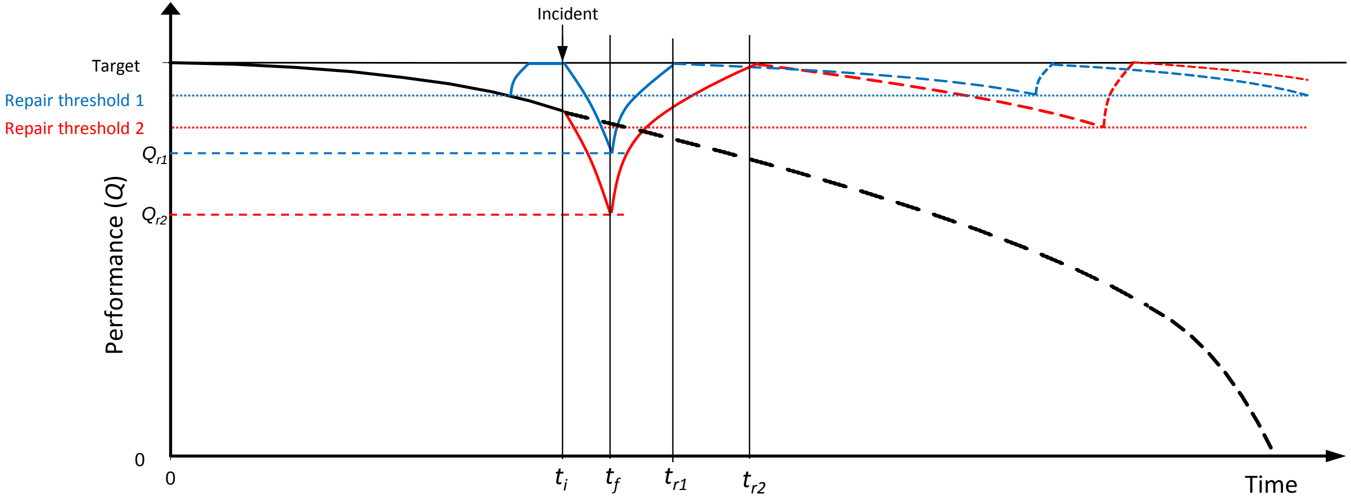
SHM contributing to adaptive resilience



(Ayyub and Zhang, 2014)

SHM for improving resilience

SHM contributing to inherent resilience



Conclusions

- SHM should focus on monitoring the performance of structures in a way that the ***available resources could be optimized*** and ***recovery*** actions after deterioration or damage could be ***effectively*** and ***rapidly*** undertaken, i.e. to ***improve resilience*** taking into account all 4 attributes (robustness, redundancy, resourcefulness and rapidity).
- ***Integrated SHM*** systems should not consider resilience in isolation, but together with external services and assets.
- Flexible for adaptation, thus ***adaptability*** should be incorporated in the quantification of the value of SHM.
- ***Protection*** of the data and the SHM system should be ensured. Furthermore the ***robustness*** (or even resilience) of the SHM system should assessed.

Thank you for your attention!