From resilience assessment to design for resilience: what is missing?

Paolo Franchin - 2022, July 14th
A lot
Community resilience

People

- Users
  - (also a complex system)

Social sciences

Infrastructure

System

Engineering

Obstacles to achieving resilience

- Political, economical, cultural

Research needs

Technical (methods, tools)
Advanced Mathematical and Physical Sciences for Advanced Materials and Technologies

Cosmology, Space Science and Space Technology

Modeling and Engineering Risk and Complexity
Approach

- **Top-down**
  - Input-output model
  - Complete (but generic?)

- **Bottom-up**
  - Process-based System of systems
  - Truncation (may be large)
Point of view

Engineering/Civil/Structural...

Low unit cost  
+  
Millions units sold  
=  
Design cost: a multiple of unit cost

High unit cost  
+  
One unit sold  
=  
Design cost: just a (small) fraction of unit cost

...in any case, patch release or recall...

...in any case, relax and go to jail...

...not just buildings but bridges, roads, dams… all the components of the Infrastructure we have built to respond to the demand for housing, mobility, transport, water and energy
Point of view

Engineering/Civil/Structural...

When cost of design is a multiple of the unit cost, you can build as many prototypes as you like.

Design by testing

Too bad that design by testing does not really work for us (not exactly controlled lab conditions + high consequences of failure)

We cannot afford to fail hence the need for safe-sided design
Evolution of design in civil engineering

**Conventional design**
A single asset, with uncontrolled notional safety margins and based on approximate models

**Performance-based design**
A single asset, with controlled safety margins based on more refined models of reality

**Resilience-based design**
Still a single asset, but with controlled safety margins specified to meet higher-level, systemic performance targets (resilience)

In other words: how safe is safe enough?

- Model ≠ reality
- Discrepancies
- Uncertainty
- Probability & statistics
- Codes
- Margins
- Safety/cost trade-off
Resilience

\[ R = \int_{t_0}^{t_r} Q(t) \, dt \]

(Bruneau et al. 2003)
Resilience is difficult to quantify because it is a systemic metric of a complex system.
What about the system state Q?

- **Immaterial level**
  - "Insurance boundary"
  - 3rd level of supplier

- **Material level**
  - B1
  - B2
  - B3
  - B4
  - B5

- **Supply-chain model of business loss**

- **Direct loss (cost of damage)**

- **Indirect loss**

Casting everything in economic terms is a convenient way.
Uncertainty

Immaterial level

Material level

Surface

Bedrock
Assessing resilience is a difficult task, building it into the system even more so. Two, non mutually exclusive strategies to invest resources:

- Prevention
- Cure

Robustness Redundancy Resourcefulness

State (e.g., GDP)

Time

(Bruneau et al 2003)
Uncertainty in time of occurrence of shocks

Prevention or cure?

Cure: reasons to wait

(Meadows et al 2004)
Prevention or cure?

In praise of prevention

Uncertainty for $t > t_{\text{shock}}$ much larger

What if the shock is TOO LARGE? Preventing the loss may be the only way

Huge prediction uncertainty even on the trend line

(Davis 2014)
Research needs

Using system sims to inform decision making (emergency management)

Validation
Sensitivity to plug-in models

Resilience

System | Consequences
Physical/Functional
As simple as possible, but not simpler (flow-based)

Component | Damage

Simulation at the base of risk analysis since the ’70s because:
• Rare events
• Complex system
• Experimentation economically unsustainable & physically infeasible

+ Unprecedented cheap computing power

Resilience-based design (RBD)

Improve surrogate models (fragilities)

P(\text{D}|I)

\text{Intensity } I

P_{\text{target}}
Resilience-based design

\[ R \rightarrow P \]

System \quad Single asset
An unexpected analogy and the important differences

Nuclear Power Plant

**System level**

Undesired outcome

- Core damage
- Radioactivity release

Vital plant functions

- Reactivity control
- Fuel cooling
- Confinement

Frontline systems

- Containment spray system

Support systems

- Water
- Electrical

Component or sub-system level

Community

**System level**

Undesired outcome

- Outmigration

Vital community functions

- Housing
- Employment
- Education
- Public services

Primary systems (bldgs)

- Residences
- Offices
- Factories
- Schools
- Hospitals

Secondary systems (lifelines)

- Water
- Waste
- Energy
- Communication
- Transport

Component or sub-system level

(Mieler et al 2013)
From a global measure to intermediate targets

1. Establish community undesired outcome
2. Establish acceptable probability of undesired outcome
3. Establish VCF event trees
4. Combine VCF trees into single community tree
5. Identify adverse event sequences causing undesired outcome and associated probabilities
6. Evaluate mean annual target for each VCF tracking variable

Expected annual disruption compatible with community resilience goal:

\[ E[R] = \sum_{j=1}^{3} R_j p_{ij} \]

\[ E[C] = \sum_{j=1}^{3} C_j p_{2j} \]

Primary and secondary systems
From the sub-systems to the components

Systemic analysis can fill this gap

Resilience-based performance target for a **new hospital**

Hospital ∈ Health-Care System ∈ Public Services VCF

Service importance matrix (1×n)

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<tr>
<th>Public services</th>
<th>Police</th>
<th>Health-care</th>
<th>Food</th>
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System importance matrix (n×m)

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<th>Systems</th>
<th>Primary</th>
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<td>Health-care</td>
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<tr>
<td>Food</td>
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New hospital tolerable disruption (unknown)

Disruption to existing Buildings and lifelines (from systemic analysis!)

$D_{VCF} = E[C] \rightarrow D_{system,1} \leq E[C] \frac{I_{service}I_{system,1}D_{system,1}}{I_{service}I_{system,1}} + E[C] \frac{I_{service}I_{system,2}D_{system,2}}{I_{service}I_{system,1}}$

What would then be the relation with

$P_C = 2 \times 10^{-4} \div 10^{-5}?$
2 System model
SYNERG modeling framework

Mieler et al: community as a NPP

System level

Undesired outcome

Permanent displacement

Outmigration

Vital community functions

Housing

Employment

Education

Public services

Primary systems (bldg)

Residential

Offices

Factories

Schools

Hospitals

Secondary systems (lifelines)

Water

Waste

Energy

Communication

Transport

SYNER-G

System level

Undesired outcome

Temporary displacement

Displaced population

Casualties & fatalities

Vital community functions

Housing

Employment

Health care

Primary systems (bldg)

Residential

Offices

Factories

Hospitals

Secondary systems (lifelines)

Water

Gas

Power

Transport

Component or sub-system level

Component or sub-system level
Object-oriented model

a) Physical system of systems

b) Digital model: collection of objects

c) Abstraction, first level: classes
Templates for objects

d) Abstraction, second level
Hierarchy of classes
Inheritance
Networks: connectivity modeling

- All networks are represented as graphs
  - Differences only in damageability: fragility models (component-specific)
  - Connectivity represented by either adjacency or incidence matrices
  - Adjacency can be symmetric (undirected graph) or non-sym. (directed)
  - Node end/or edge removal results in modification of these matrices

### Undirected (e.g. power, water)

![Undirected graph](image)

\[
A = \begin{bmatrix}
1 & 1 & 0 & 1 & 1 \\
0 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
\end{bmatrix}
\]

\[
I = \begin{bmatrix}
0 & 1 & 1 & 0 \\
0 & 1 & 0 & 1 \\
1 & 0 & 0 & 1 \\
1 & 0 & 1 & 0 \\
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\end{bmatrix}
\]

### Directed (e.g. roads)

![Directed graph](image)

\[
A = \begin{bmatrix}
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### Damage

![Damage graph](image)

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\end{bmatrix}
\]
Connectivity-based metrics

Grid disconnection

\( n_v = 4 = n_S + n_D = 2 + 2 \)

\[ SCL = 1 - \frac{1}{n_D} \sum_{i=n_S}^{n_S+1} \frac{N_{S,i}}{N_{S,i}} \]

Number of Sources connected to Demand node \( i \)

In undisturbed (zero) conditions

In disturbed (s=seismic) conditions

\[ N_{S3,0} = 2 \]
\[ N_{S4,0} = 2 \]

\[ Q_3 \geq 0 \]
\[ Q_4 \geq 0 \]

\[ N_{S3,s} = 2 \]
\[ N_{S4,s} = 2 \]

\[ SCL = 1 - \frac{1}{2} \left( \frac{2}{2} + \frac{2}{2} \right) = 0 \]

\[ E[SCL] = \frac{1}{3} \left( 0 + \frac{1}{2} + \frac{1}{2} \right) = \frac{1}{3} \]
Networks: alternative models

• Connectivity models with enhanced performance metrics
  • e.g. Hierarchical decomposition

• Flow models
  • Two types of equations
    • Balance equations (flow continuity at nodes)
    • Resistance equations (line loss)

• Utilities (undirected)

  • WSS
    \[ I_D^T q - Q = 0 \]
    \[ \Delta h - r(q) = (I_S h_S + I_D h_D) - r(q) = 0 \]
    \[ r(q) = Rq \Lambda \]

  • GAS
    \[ I_D^T q - Q = 0 \]
    \[ \Delta p - r(q) = (I_S p_S + I_D p_D) - r(q) = 0 \]
    \[ r(q) = \begin{cases} r_{ij}(q_{ij}) = p_i - p_j = K_L q_{ij}^2 & \text{low-pressure} \\ r_{ij}(q_{ij}) = p_i^2 - p_j^2 = K_M q_{ij}^2 & \text{medium-pressure} \end{cases} \]
Design vs Assessment

Flow models (utilities: WSS, GAS, EPN, etc)

Demand-driven vs Head-driven + additional demands

Undamaged network: design, demand must be satisfied

\[
\begin{align*}
\text{Water supply system:} \\
\begin{cases}
I_D^T \mathbf{q} - Q &= 0 \\
(I_s h_s + I_d h_D) - \mathbf{r} (\mathbf{q}) &= 0
\end{cases}
\end{align*}
\]

\[
\begin{align*}
\text{Gas distribution system:} \\
\begin{cases}
I_D^T \mathbf{q} - Q &= 0 \\
(I_s p_s + I_d p_D) - \mathbf{r} (\mathbf{q}) &= 0
\end{cases}
\end{align*}
\]

Damaged network: assessment, demand may not be satisfied

\[
\begin{align*}
\text{Head or pressure driven:} \\
\begin{cases}
I_D^T \tilde{\mathbf{q}} - \tilde{Q} (\tilde{h}_D) &= 0 \\
(I_s \tilde{h}_s + I_d \tilde{h}_D) - \tilde{\mathbf{r}} (\tilde{\mathbf{q}}) &= 0
\end{cases}
\end{align*}
\]

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\begin{align*}
\text{Additional demands:} \\
\begin{cases}
I_D^T \tilde{\mathbf{q}} - \tilde{Q} (\tilde{h}_D) - Q_{\text{seismic}} (\tilde{h}_D) &= 0 \\
(I_s \tilde{h}_s + I_d \tilde{h}_D) - \tilde{\mathbf{r}} (\tilde{\mathbf{q}}) &= 0
\end{cases}
\end{align*}
\]

Equations can be further improved:
- Source capacity is not modelled!
- Post-event demand model must be linked to systemic damage
- For EPN the model is not even demand-driven yet…
Power networks

• Flow analysis much more «complex»
  • AC optimal power flow (ACOPF) – tough nonlinear (nonconvex) constrained optimization problem
    *aka Security-constrained Economic Dispatch (SCED)*
    • Formulated in 1955, still no fast/robust solution technique
    • People use everything from pure connectivity, to DC (linearized), to AC (nonlinear)
    • We used AC, but that even this is incomplete (no line contraints)
    • We added internal sub-station modelling and short-circuit propagation
Power networks: connectivity vs flow

IEEE118 example network, fictitiously placed in a seismic environment, analyzed with 5 methods

- M1: connectivity
- M2: enhanced connectivity (hierarchical decomp.)
- M3: AC flow
- M4: M3+internal logic
- M5: M4+short-circuit propagation
Upgrade strategy

\[ SSI = \frac{\sum_{i=1}^{N_L} P_{i,0} \cdot (1 - R_i) \cdot w_i}{\sum_{i=1}^{N_L} P_{i,0}} \]

\[ UBI_i = \frac{E[SSI|\text{upgrade } i] - E[SSI]}{1 - E[SSI]} \]
3 Decision-support systems
Uncertainty

Immaterial level

Material level

Uncertainty layer

Surface

Bedrock
Uncertainty + evolving state of information = DSS

• Long term goal: use model to inform a real-time decision support system

• Treat the uncertainty network as a **Bayesian Network**

• Challenges:
  
  • Size of real infrastructure systems
  
  • BN modeling of system problems involving physical flows
    
    • Bensi, Der Kiureghian, Straub (2014) approach to systems modeling (*Minimum Link Set formulation*)
    
    • Alternative idea: derive approximate BN structure and CPTs from off-line simulation from our model (*Thrifty Naïve formulation*)
...and then by decreasing CPT size constraining number of parents (say, at most 2 or 3)
Efficient minimum link set formulation
Proposal: thrifty-Naïve formulation

Build system-related portion of BN-structure and estimate associated CPTs using raw component-system data

First application of this kind in Doguc & Ramirez-Marquez (RESS, 2009)

Proposed method has the same complexity $O(n^2)$ but does not depend on components ordering

Algorithm

1. Naïve formulation
2. Off-line simulation: correlation matrix of components’ and system states
   Can account for connectivity or flow-based state indicators
3. Set threshold $\rho_{\text{min}}$ and delete BN edges with $|\rho| < \rho_{\text{min}}$
   Can also set max # of parents $N$ (similarly to Doguc & Ramirez-Marquez) and leave edges for $n \leq N$ components with largest correlation $|\rho| > \rho_{\text{min}}$
   Sensitivity to threshold?
Step 1: Build Naïve Structure...
Step 2: State matrix from simulation

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Step 3: Elimination of low correlation edges

SCL components 1-2-7-9

SSI components 4-7-9-11
Final configuration vs «best alternative»

- Simpler to set up
- Handles flow-based system performance

- More complex to set up
- Cannot handle flow-based system performance
Fig. 10. Probability of failure of components according to: a) the prior distribution and b) to g) the posterior distributions for the considered successive inference scenarios. The evidenced components are shown with red squares. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Components’ models
Component damage model

Systemic analysis $\rightarrow$ 100s or 1000s of components $\rightarrow$ surrogate models

fragility $p(LS_{ij}|I_i) \rightarrow$ damage given intensity $p(C_i|I_i)$

$I_i$ is just one parameter of ground motion $I_i|I_i$ other GM parameters depend on site

Fragility is structure & site-dependent
Fragility from field damage $\rightarrow$ difficult to generalize $\rightarrow$ numerical simulation

Calibrated models
Component damage model

Fragility analysis via numerical simulation is a delicate business. Results depend on: ground motions, numerical model, analysis method, statistical method and modelled uncertainty.
Component damage model

A lot of effort has been devoted and is still being devoted to produce these models...

And then RINTC 2019-2023 with existing buildings and new bridges, and RINTC 2022-2023 with upgraded buildings and existing bridges....

And we have not even mentioned the effects of ageing: \( p(LS|I, t_0) < p(LS|I, t > t_0) \)
Conclusions
Conclusions

• Resilience can be improved by **reducing vulnerability** and improving response/recovery
  • The former seems the most reliable, given the uncertainty in $t > t_{\text{shock}}$

• Research needs
  • Systems’ behaviour: we need **more realistic representation**
    Flow! Or enhanced/smart connectivity...
  • Components’ damage: we need **better surrogate models**
    Fundamental research in structural and geotechnical engineering is still needed

• One day systemic analysis might be reliable enough to link performance of the components to global community resilience goals. This will provide:
  • A rational basis for performance targets in next generation codes
  • Support for building decision-support systems for emergency-management in real time

• Even if it never attains this level of reliability in predictions, systemic analysis of the built environment will allow better understanding of its dynamics

• I see huge scope for interdisciplinary research in the challenging task of managing the complexity of our **ageing** infrastructure to make it more resilient

• I hope some of the half-baked ideas and suggestions I presented have stimulated your imagination
References


- **Franchin, P., and F. Cavalieri. 2015.** “Probabilistic assessment of civil infrastructure resilience to earthquakes.” *Computer-Aided Civil And Infrastructure Engineering, 00*: 1–18. Wiley Online Library.


- The SYNERG model is implemented in an object-oriented Matlab code (OOFIMS https://sites.google.com/a/uniroma1.it/oofims/), all BN additions employ code from the Bayesian Network Toolbox by Kevin Murphy (https://code.google.com/p/bnt/)
Thank you!

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Contributors:

Francesco Cavalieri, Pierre Gehl
G. Weatherill, F. Noto, A. Lupoi, S. Tesfamariam, S. Giovinazzi, S. Esposito, I. Iervolino
Bonus track: multiple interacting hazards