Risk-based assessment of robustness: what can it do and what can't it do?

Jack Baker
Stanford University
Dept. of Civil & Environmental Engineering

Why consider robustness?

- Arguably, a guiding principle in the design of structures is to maximize the reliability of a structural system
- If we the structure and its environment perfectly (in a stochastic sense)
  - We could simply optimize the structure for maximum reliability
  - No need to worry about redundancy or robustness
- But experience shows us that this isn't the case
  - Analysis models are approximate
  - We omit human error
  - We fail to identify cascading failures
- Robustness criteria presumably try to compensate for these shortcomings

Why consider robustness?

- Robustness criteria presumably try to compensate for these shortcomings

- These criteria provide value if they minimize risk by ensuring acceptable performance under unanticipated circumstances

- A robustness definition: “The consequences of structural failure should not be disproportional to the effect causing the failure.”

So how do we balance robustness and reliability?

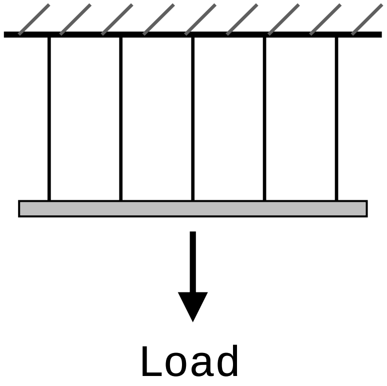
- If we are hoping to address unanticipated circumstances, can we assess robustness within a risk-based framework that requires the system and environment to be quantified?

- Perhaps not always, but …
  - We can use detailed risk assessments of testbed systems to identify properties of those systems that increase robustness
  - We can determine whether identified failures were caused by small initial perturbations of the system

A reliability-based assessment of robustness/vulnerability

Undamaged system

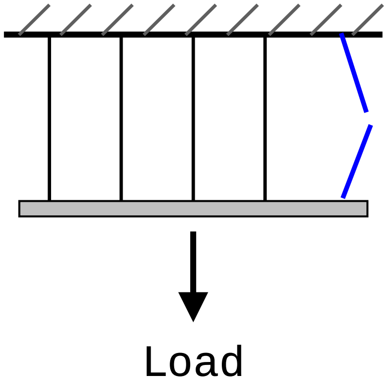
(resistance = r_0)



$$P(r_0, S)$$

Damaged system

(resistance = r_d)

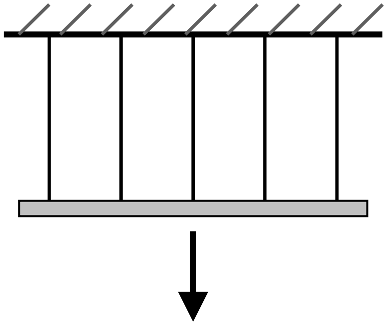


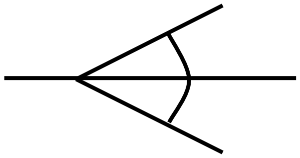
$$P(r_d, S)$$

$$V = \frac{P(r_d, S)}{P(r_0, S)}$$

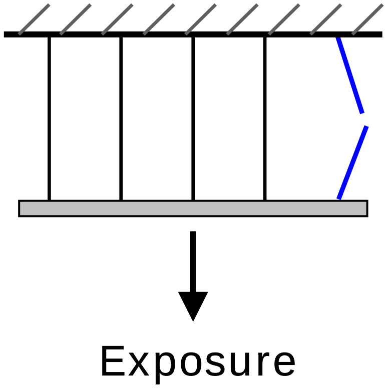
Index of vulnerability, from Lind (1995)

A risk-based assessment framework

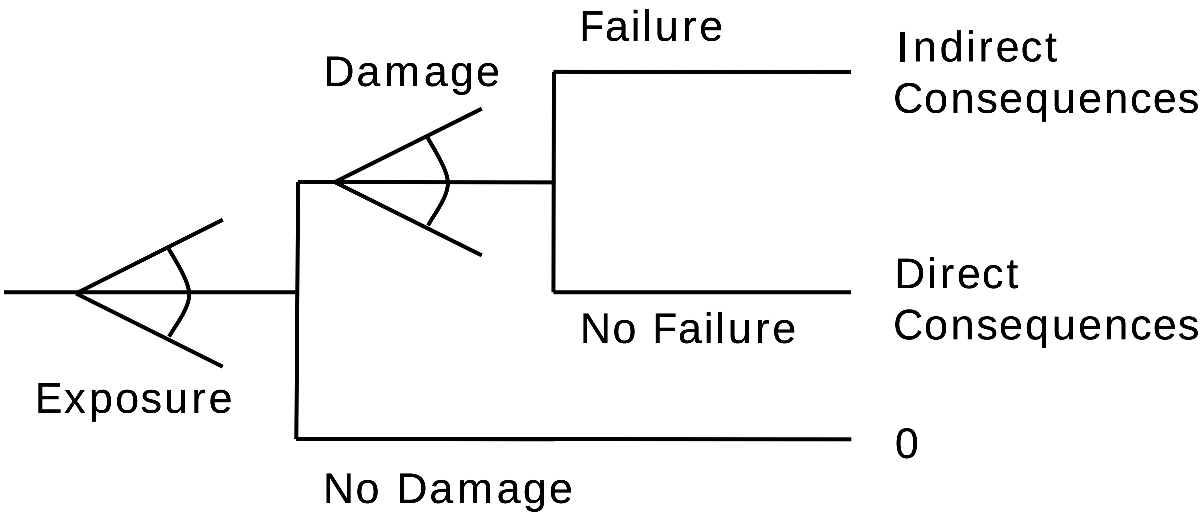




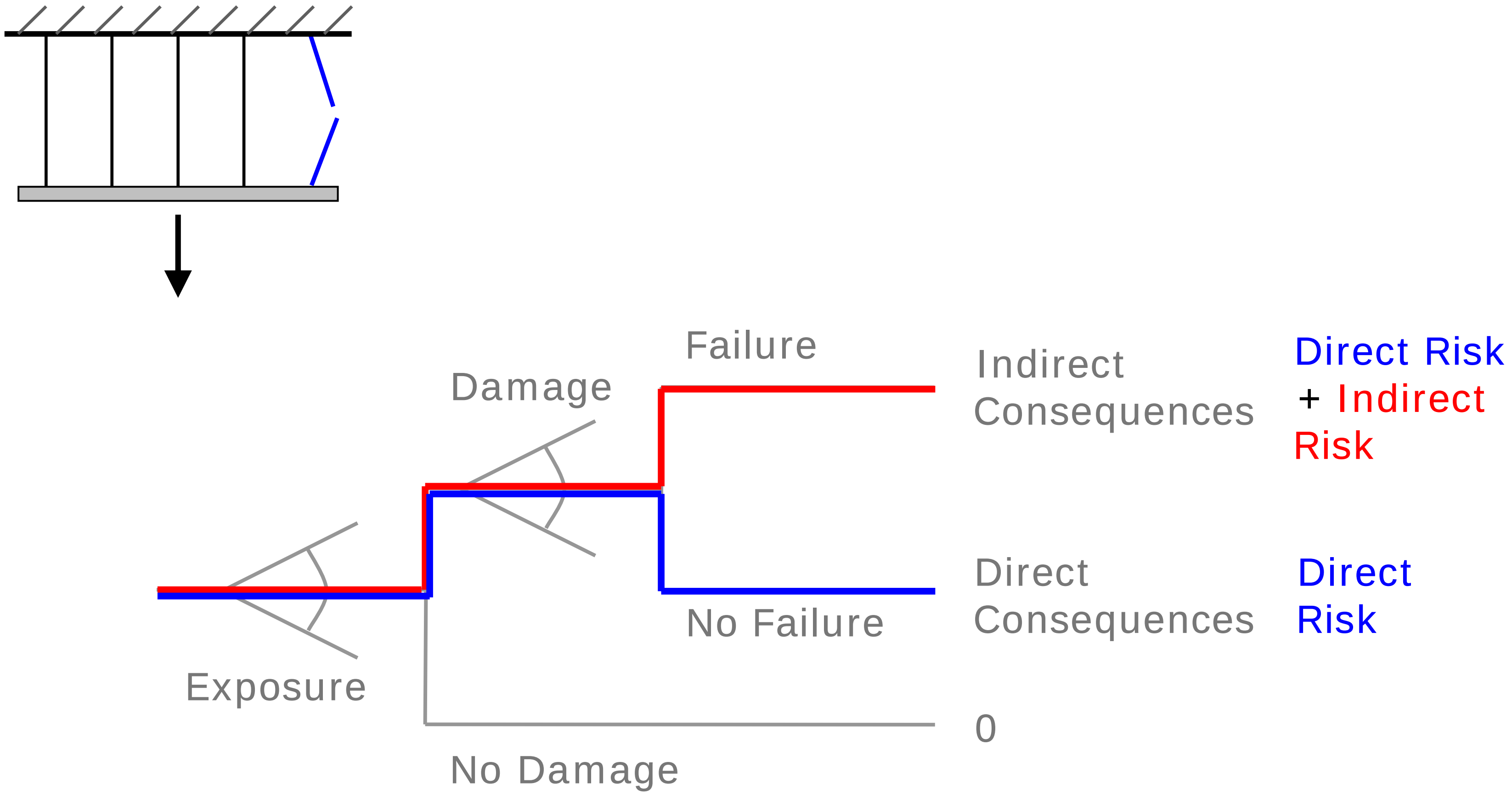
A risk-based assessment framework



An assessment framework



Calculation of risk



Damage

Failure

Indirect Consequences

Direct Risk + Indirect Risk

No Failure

Direct Consequences

Direct Risk

Exposure

No Damage

0

An index of robustness: $I_{Rob} = \dfrac{\text{Direct Risk}}{\text{Direct Risk} + \text{Indirect Risk}}$

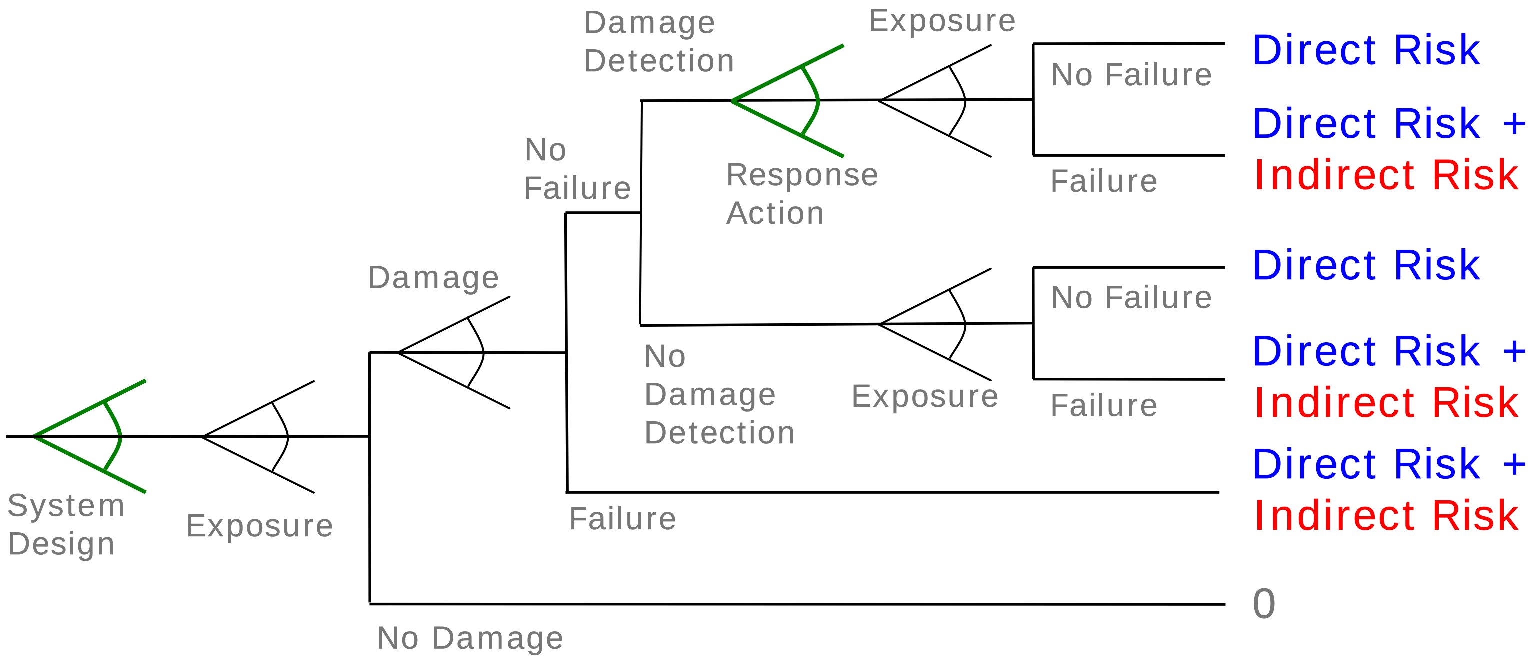
Features of this index

$$I_{Rob} = \frac{\text{Direct Risk}}{\text{Direct Risk} + \text{Indirect Risk}}$$

- Measures relative risk only
- Dependent upon reliability of the damaged system
- Dependent upon consequences

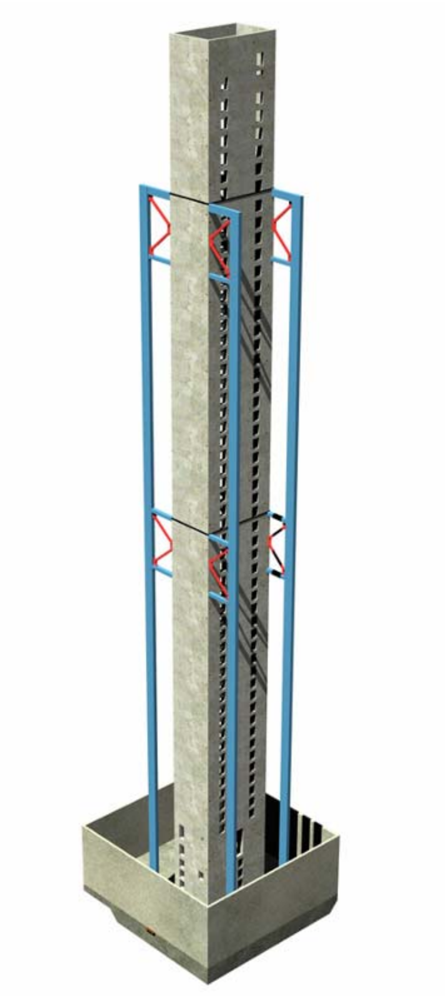
The framework facilitates decision analysis

- Choice of the physical system
- Choice of inspection and repair
- Choices to reduce consequences



An example: tall buildings in high seismic areas

One Rincon Hill – San Francisco



Lateral system

Height = 195 m

Tallest residential building in the western United States

“Efficient” lateral system

From: Pacific Earthquake Engineering Research Center

One Rincon Hill under construction

One Rincon Hill's efficient structural system

- Standard practice for tall buildings in high seismic zones
  - One primary lateral system (typically a braced frame or concrete shear wall core)
  - A secondary lateral system, designed for some fraction of the total lateral load (typically a perimeter moment frame)
- One Rincon Hill omits the perimeter moment frame
  - Allows for floor to ceiling windows
  - Reduces story heights
- But does this make the building less safe?
- Does the fact that it is a residential building make it different from the high-rise office buildings in the city?

Do redundancies make buildings more seismically safe?

- Wen and Song (2003) found that, among buildings with comparable lateral strength, reliability under earthquake loading was only moderately improved by using structural configurations with additional redundancy
  - Capacity of redundant elements is typically highly correlated
  - Uncertainty in seismic loading is large compared to uncertainty in capacity

- Primary lateral system was designed to high standards
- The building received a rigorous peer review
- High-rise residential buildings are being held to higher standards than other types of buildings
- New research is being conducted on this type of structural system

Do traditional redundant structural systems receive the same level of scrutiny?

These questions lead to Normal Accident Theory

- Normal Accident Theory (Perrow, 1984) says that accident often occur due to unforseen sequence of events

- Redundancy can contribute to these failures by increasing system complexity and encouraging risk-taking

Normal Accident Theory : an example

A Day in Your Life

- You have an important sales meeting downtown.
- Your coffee pot malfunctions, and you are delayed trying to get it working again.
- You are now late, and run out the door.
- You realize that you locked your keys inside the house.
- You usually have a spare key hidden outside, but you gave it to a friend last week *(failed redundant pathway).*
- You ask to borrow your neighbor's car, but it recently broke down *(failed backup system).*
- The bus drivers are on strike, so no busses are running *(unavailable work around).*
- You call a cab but none can be had because of the bus strike. *(tightly coupled events).*
- You give up and call in saying you can't make the meeting.
- You lose the sale.

Source: Charles Perrow, Normal Accidents: Living with High-Risk Technologies, 1984.

Normal Accident Theory: an example

What was the primary cause of this failure?

- Human error *(forgetting the keys)*
- Mechanical failure *(neighbor’s car)*
- The environment *(bus strike and taxi overload)*
- Design of the system (*a door that allows you to lock yourself out or lack of taxi surge capability)*
- Procedures used *(unreliable coffee maker, or not allowing extra time to leave the house)*
- Schedule expectations (*meeting at a fixed time and place)*

Source: Charles Perrow, Normal Accidents: Living with High-Risk Technologies, 1984.

Normal Accident Theory

Complex systems have:

- Unexpected interaction sequences that are not previously apparent
- Feedback loops
- Failures that can jump across subsystem boundaries

These can cause unexpected cascading failures

The interactions often can not be reasonably foreseen

Redundancy

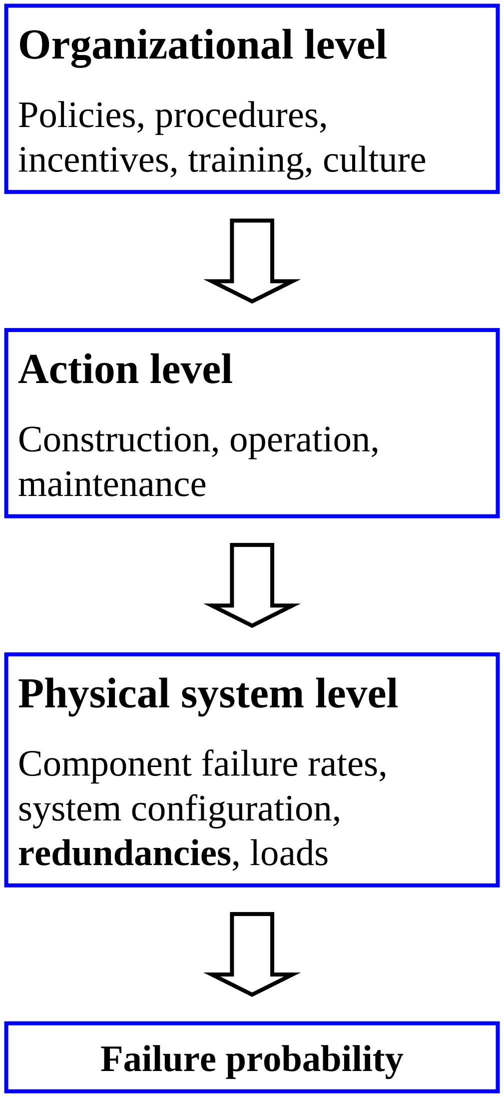
- Creates backups
- Can increase complexity and opaqueness
- Can encourage risk-taking

Source: Charles Perrow, Normal Accidents: Living with High-Risk Technologies, 1984.

Another concept: System-Action-Management risk assessment

Recognizes that more than just the physical system affects failures

Changes to the physical system can affect behaviors further up the model



Organizational level

Policies, procedures, incentives, training, culture

Action level

Construction, operation, maintenance

Physical system level

Component failure rates, system configuration, **redundancies**, loads

Failure probability

From Murphy and Pate-Cornell, 1996

Redundancy in data networks: a useful comparison?

Redundancy is also carefully quantified in other systems.

Data networks provide redundancy through

- **Duplicate components**. Physical hardware is duplicated.
- **Duplicate links/paths**. More than one route for data to move from point to point.
- **“Mirroring:” duplicate data sources**. The product (data) is provided in more than one physical location.

Parallels with civil structures?

- **Redundancy**
- **Multiple load paths**
- **?**

Redundancy in data networks: a useful comparison?

High-rise residential towers may be held to higher standards than high-rise office towers

“Mirroring” of facilities: it is harder to provide backup housing than it is to provide backup office space, if the building is damaged

Is this a redundancy/robustness issue, even thought it doesn’t relate to the physical system?

One possibility: robustness guidelines could differ for structures with backup facilities, in the same way that important structures have different requirements.

Conclusions

- Positive aspects of robustness assessment
  - Systems without disproportional failure consequences are clearly desirable
  - It appears that quantitative evaluations of robustness are feasible
  - Can be performed using risk/reliability-based methods

- But a word of caution
  - Consider the impact of potential unforseen interactions
  - Keep in mind that added redundancies can also produce negative side-effects
    - System complexity
    - Backups that aren’t independent from primary systems
    - Encouragement of risk-taking

- A balance between these two mindsets can be very effective in creating useful and safe structures

- A potential new concept: consider redundant facilities when deciding on the stringency of robustness requirements