Risk and Safety

in

Engineering

Dr. Jochen Köhler

Swiss Federal Institute of Technology

ETH Zurich, Switzerland

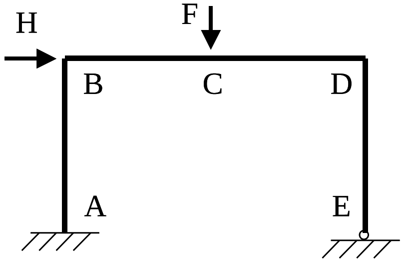
Contents of Today's Lecture

- Introduction to structural systems reliability
- General systems reliability analysis
- Mechanical modelling of systems
- Reliability analysis for structural systems
- Risk based assessment of structural robustness

Introduction to structural systems reliability

Until now we have focused on the reliability of individual failure modes

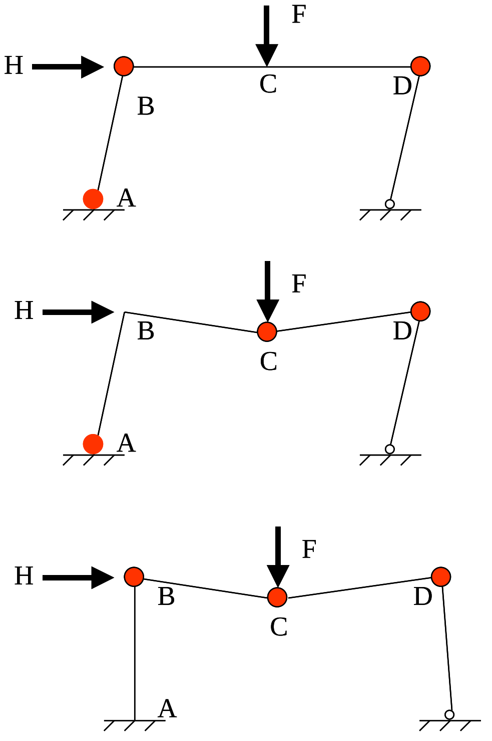
- Reliability analyses of components



However, generally structural systems only fail if two or more failure modes/components fail.

This problem complex is addressed by the theory of

- Structural systems reliability analysis



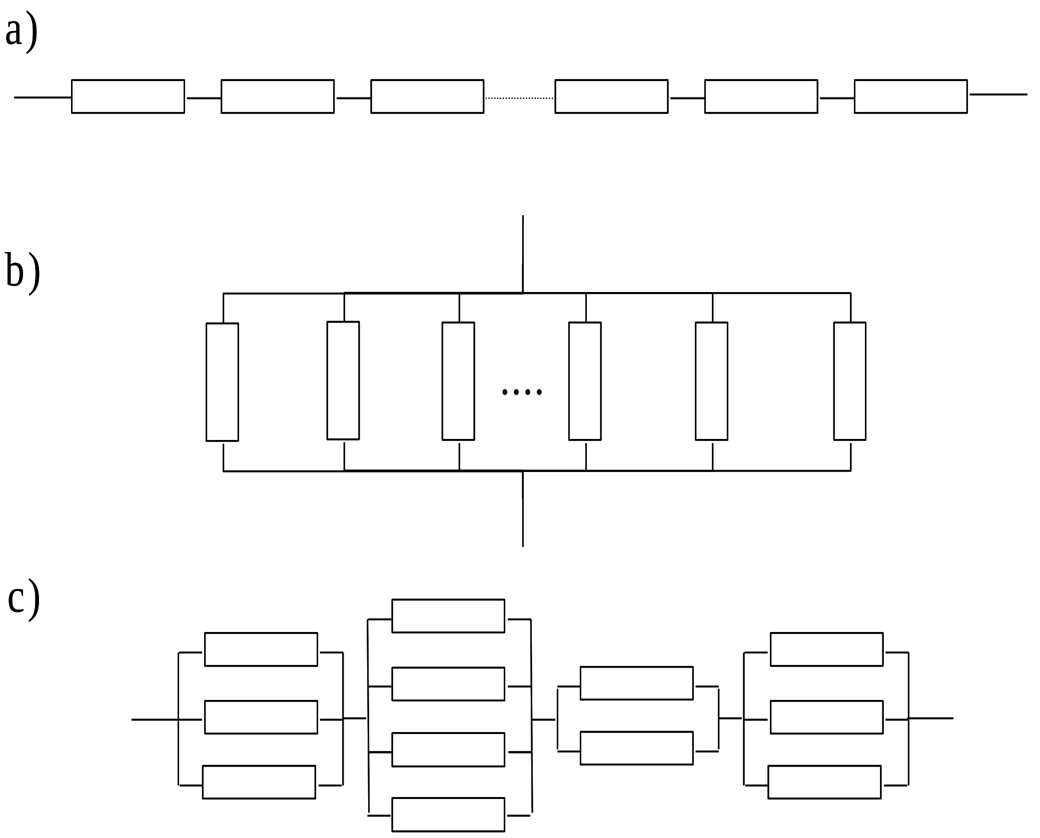
General systems reliability analysis

Probabilistic characteristics of systems

Block diagrams are normally used in the representation of systems in structural systems reliability analysis

Each component in the block diagrams represent one failure mode for the structure

a) series system
b) parallel system
c) mixed system



General systems reliability analysis

Uncorrelated components

The failure probability of a **series system** may be determined by

$$P_F = 1 - P_S = 1 - \prod_{i=1}^{n} (1 - P(F_i))$$

The failure probability of a **parallel system** may be determined by

$$P_F = \prod_{i=1}^{n} P(F_i)$$

General systems reliability analysis

Correlated components

If the individual components of the system have linear and Normal distributed safety margins

The failure probability of a series system may be determined by

$$P_F = 1 - P_S = 1 - \Phi_n(\boldsymbol{\beta}, \boldsymbol{\rho})$$

The failure probability of a parallel system may be determined by

$$P_F = \Phi_n(-\boldsymbol{\beta}, \boldsymbol{\rho})$$

General systems reliability analysis

Simple bounds on systems reliability

The failure probability of a **series system** may be bounded by

$$\max_{i=1}^{n}\left\{P(F_i)\right\} \leq P_F \leq 1-\prod_{i=1}^{n}(1-P(F_i))$$

Full correlation — Uncorrelated

The failure probability of a **parallel system** may be bounded by

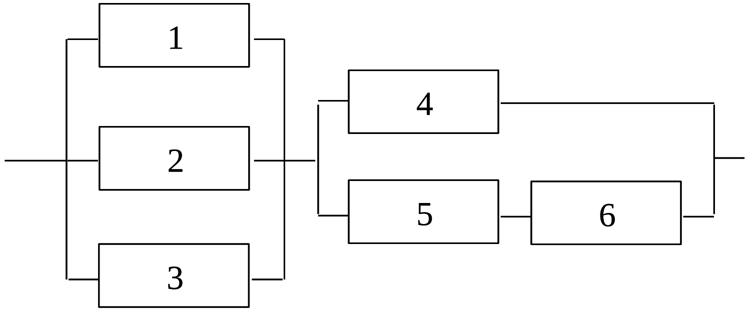
$$\prod_{i=1}^{n} P(F_i) \leq P_F \leq \min_{i=1}^{n}\left\{P(F_i)\right\}$$

Uncorrelated — Full correlation

General systems reliability analysis

Example

We consider a structural system for which failure is represented by the following block diagram



The components have the following failure probabilities

$$P(F_1) = P(F_2) = P(F_4) = 1 \cdot 10^{-2}$$

$$P(F_3) = P(F_5) = P(F_6) = 1 \cdot 10^{-5}$$

The components may be correlated

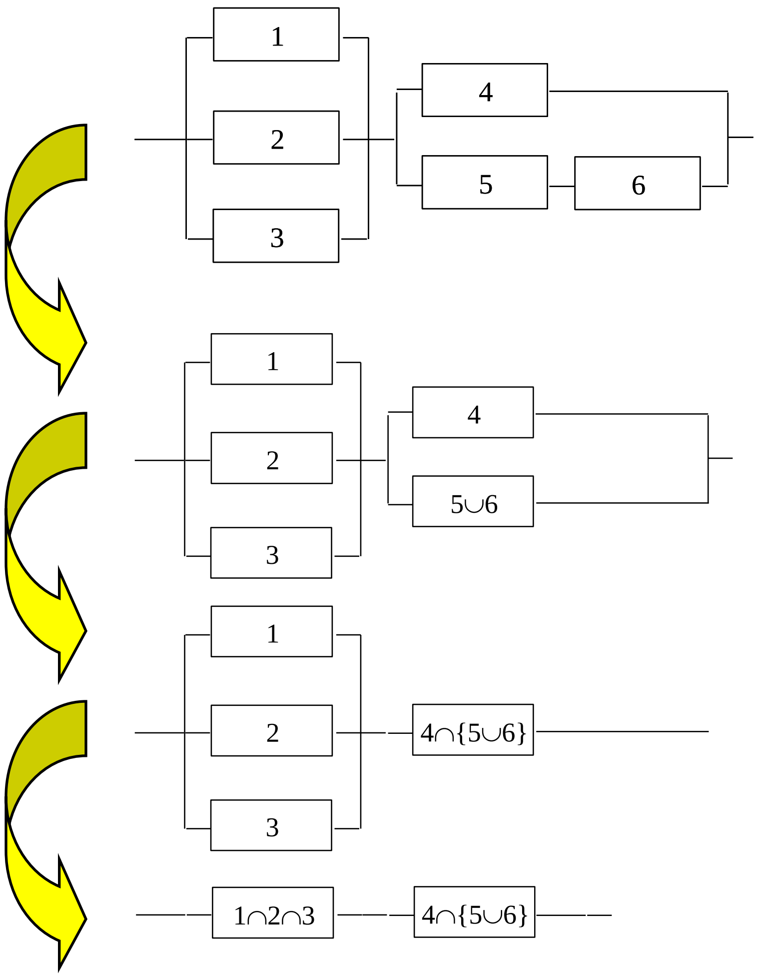
General systems reliability analysis

Example

How can we in a simplified manner analyse such a mixed system of series and parallel systems in combination

We can reduce it into sub-systems sequentially:

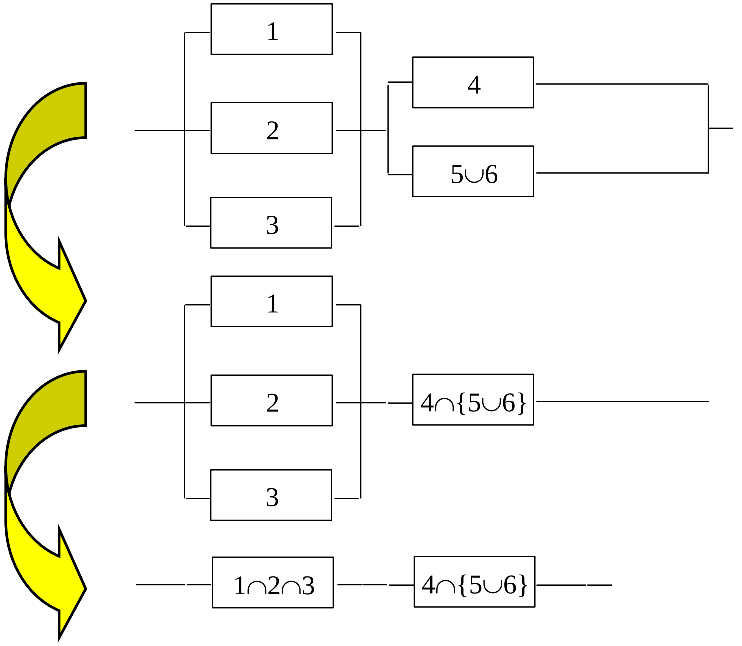
either into series systems or parallel systems



Systems reliability analysis

Example

If we assume uncorrelated components we have



$$P(5 \bigcup 6) = 1 - (1 - 1 \cdot 10^{-5})^2 = 2 \cdot 10^{-5}$$

$$P(4 \bigcap \{5 \bigcup 6\}) = 1 \cdot 10^{-2} \times 2 \cdot 10^{-5} = 2 \cdot 10^{-7}$$

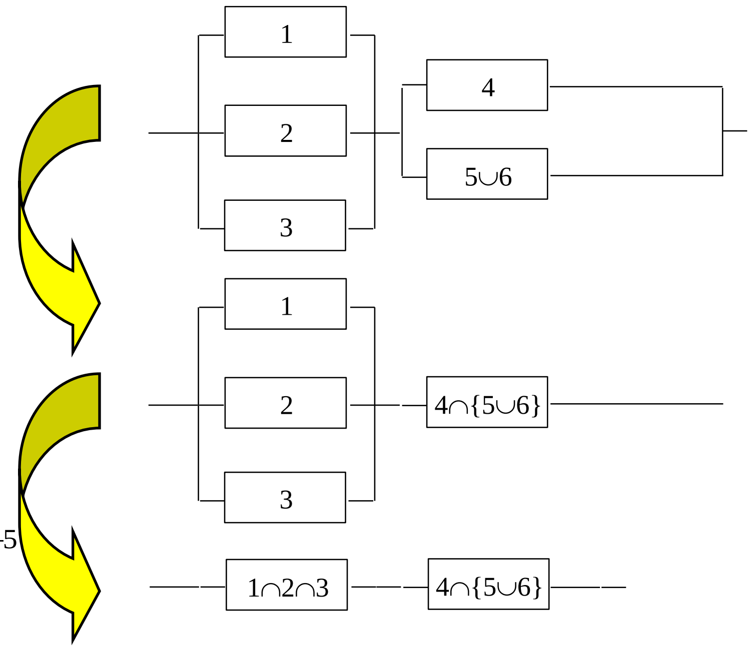
$$P(1 \bigcap 2 \bigcap 3) = (1 \cdot 10^{-2})^2 (1 \cdot 10^{-5}) = 1 \cdot 10^{-9}$$

$$P_{S,\rho=0} = P(\{1 \bigcap 2 \bigcap 3\} \bigcup \{4 \bigcap \{5 \bigcup 6\}\}) = 1 - (1 - 2 \cdot 10^{-7})(1 - 1 \cdot 10^{-9}) = 2.01 \cdot 10^{-7}$$

Systems reliability analysis

Example

If we assume correlated components we have



$$P(5 \bigcup 6) = \max(1 \cdot 10^{-5}, 1 \cdot 10^{-5}) = 1 \cdot 10^{-5}$$

$$P(4 \bigcap \{5 \bigcup 6\}) = \min(1 \cdot 10^{-2}, 1 \cdot 10^{-5}) = 1 \cdot 10^{-5}$$

$$P(1 \bigcap 2 \bigcap 3) = \min(1 \cdot 10^{-2}, 1 \cdot 10^{-2}, 1 \cdot 10^{-5}) = 1 \cdot 10^{-5}$$

$$P_{S,\rho=1} = P(\{1 \bigcap 2 \bigcap 3\} \bigcup \{4 \bigcap \{5 \bigcup 6\}\}) = \max(1 \cdot 10^{-5}, 1 \cdot 10^{-5})$$

$$P_{S,\rho=1} = 1 \cdot 10^{-5}$$

The simple bounds are

$$2.01 \cdot 10^{-7} \leq P_S \leq 1 \cdot 10^{-5}$$

General systems reliability analysis

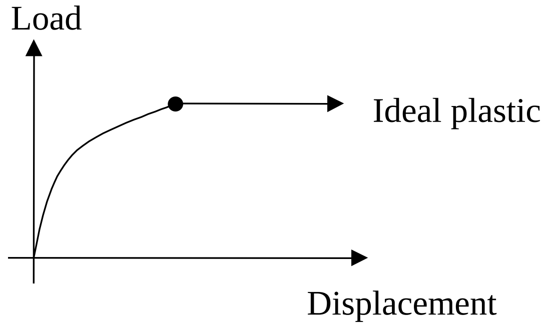
Mechanical modelling of structural systems

The behaviour of structural failure modes after failure is important for the safety of the system

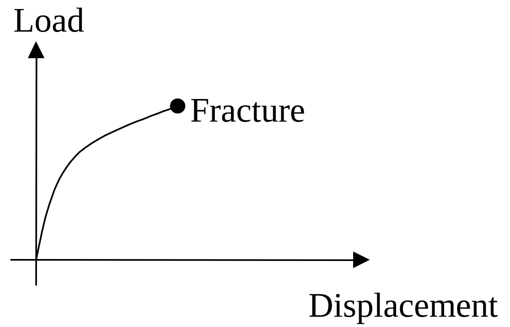
Two extreme cases are

- ductile components

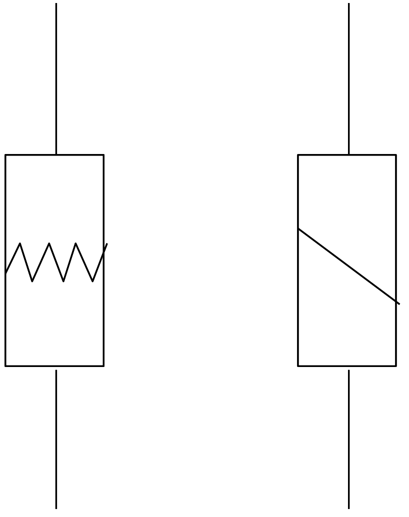
- brittle components



Ductile behaviour



Brittle behaviour



Brittle

Ductile

General systems reliability analysis

Parallel systems with ductile components

Assume a parallel system with n ductile components

The second order statistics of the strength are then given by

$$\mu_{R_S} = \sum_{i=1}^{n} \mu_{R_i} \qquad \sigma_{R_S}^2 = \sum_{i=1}^{n} \sigma_{R_i}^2$$

Furthermore we have that the strength is Normal distributed using the central limit theorem

If $\mu_{R_1} = \mu_{R_2} = \ldots = \mu_{R_n} = \mu$ **and** $\sigma_{R_1} = \sigma_{R_2} = \ldots = \sigma_{R_n} = \sigma$ **then we have:**

$$COV = \frac{\sigma}{\sqrt{n} \cdot \mu}$$

Why is robustness an issue?

- Despite modernization of design codes the engineering profession is still facing problems in terms of

  - collapsing structures and building

  - steady increase of insured damages

Why is robustness an issue?

- **Examples of collapses**

Bad Reichenhall
Germany, 2006

Why is robustness an issue?

- **Examples of collapses**

Siemens arena
Denmark, 2003

Why is robustness an issue?

- **Examples of collapses**

  Oklahoma City bombing
  USA, 1995

Why is robustness an issue?

- **Examples of collapses**

World Trade Center
USA, 2001

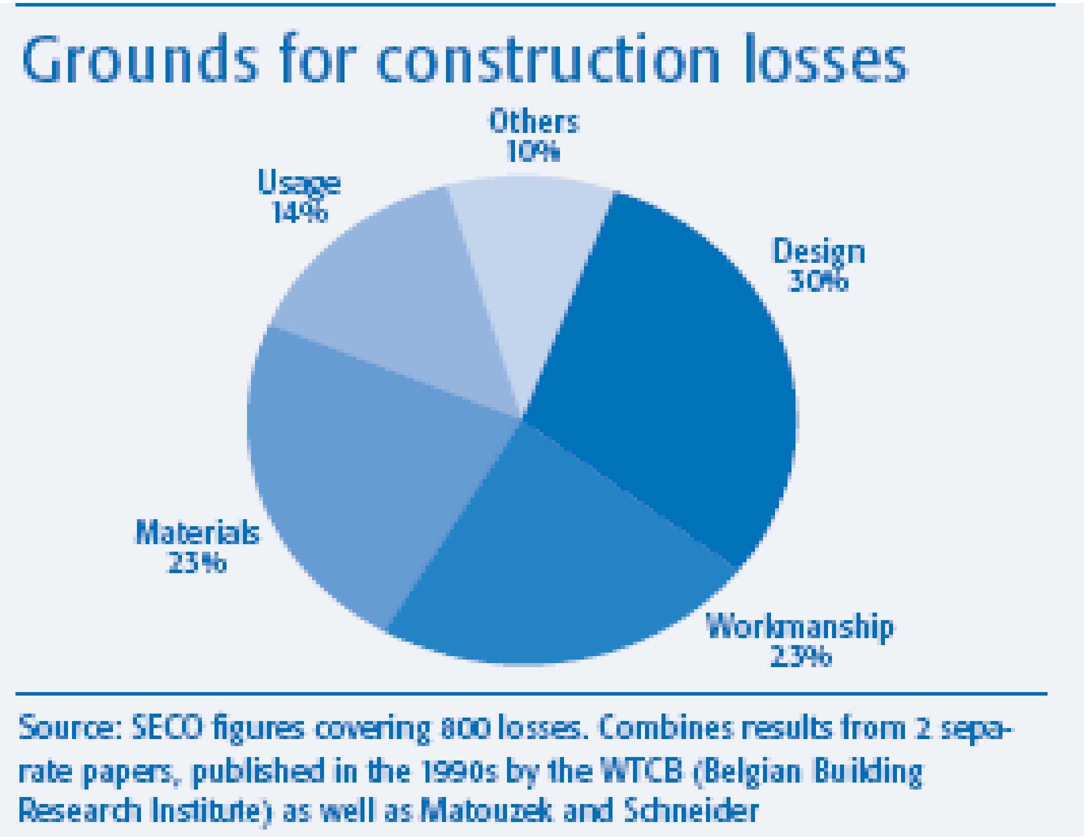
Why is robustness an issue?

- **Examples of collapses**

Charles de Gaulle
France, 2004

Why is robustness an issue?

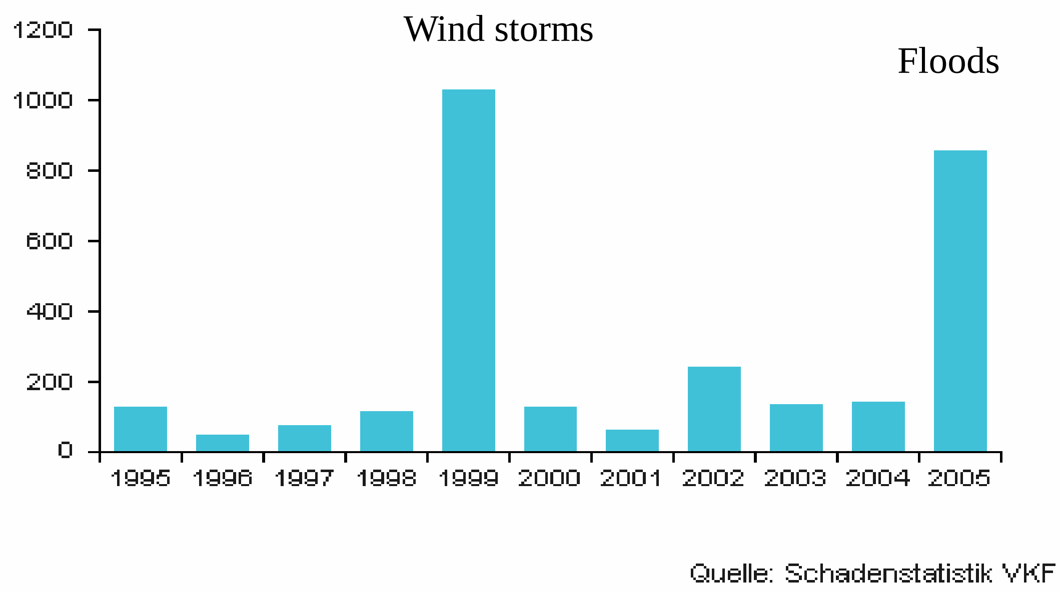
- **Losses due to building failures**



Why is robustness an issue?

- **Insured losses due to building failures**

  IRV Interkantonaler Rückversicherungs-verband, Switzerland



What is understood as robustness?

Structural Standards	The consequences of structural failure are not disproportional to the effect causing the failure [2].
Software Engineering	The ability…to react appropriately to abnormal circumstances (i.e., circumstances "outside of specifications"). A system may be correct without being robust [17].
Product Development and QC	The measure of the capacity of a production process to remain unaffected by small but deliberate variations of internal parameters so as to provide an indication of the reliability during normal use.
Ecosystems	The ability of a system to maintain function even with changes in internal structure or external environment [18].
Control Theory	The degree to which a system is insensitive to effects that are not considered in the design [19].
Statistics	A robust statistical technique is insensitive against small deviations in the assumptions [20].
Design Optimization	A robust solution in an optimization problem is one that has the best performance under its worst case (max-min rule) [21].
Bayesian Decision Making	By introducing a wide class of priors and loss functions, the elements of subjectivity and sensitivity to a narrow class of choices, are both reduced [22]
Language	The robustness of language…is a measure of the ability of human speakers to communicate despite incomplete information, ambiguity, and the constant element of surprise [23].

What are the attributes of robustness?

- Design codes have so far focused on inherent properties of the structures (components)

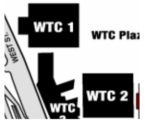
  - redundancy
  - ductility

- More recently focus has been directed to:

  - system performance (removal of members)
  - structural ties

What are the attributes of robustness?

The material loss cost consequences due to the collapse of the two WTC towers only comprised ¼ of the total costs due to damaged or lost material



It seems relevant to include consequences in the robustness equation !

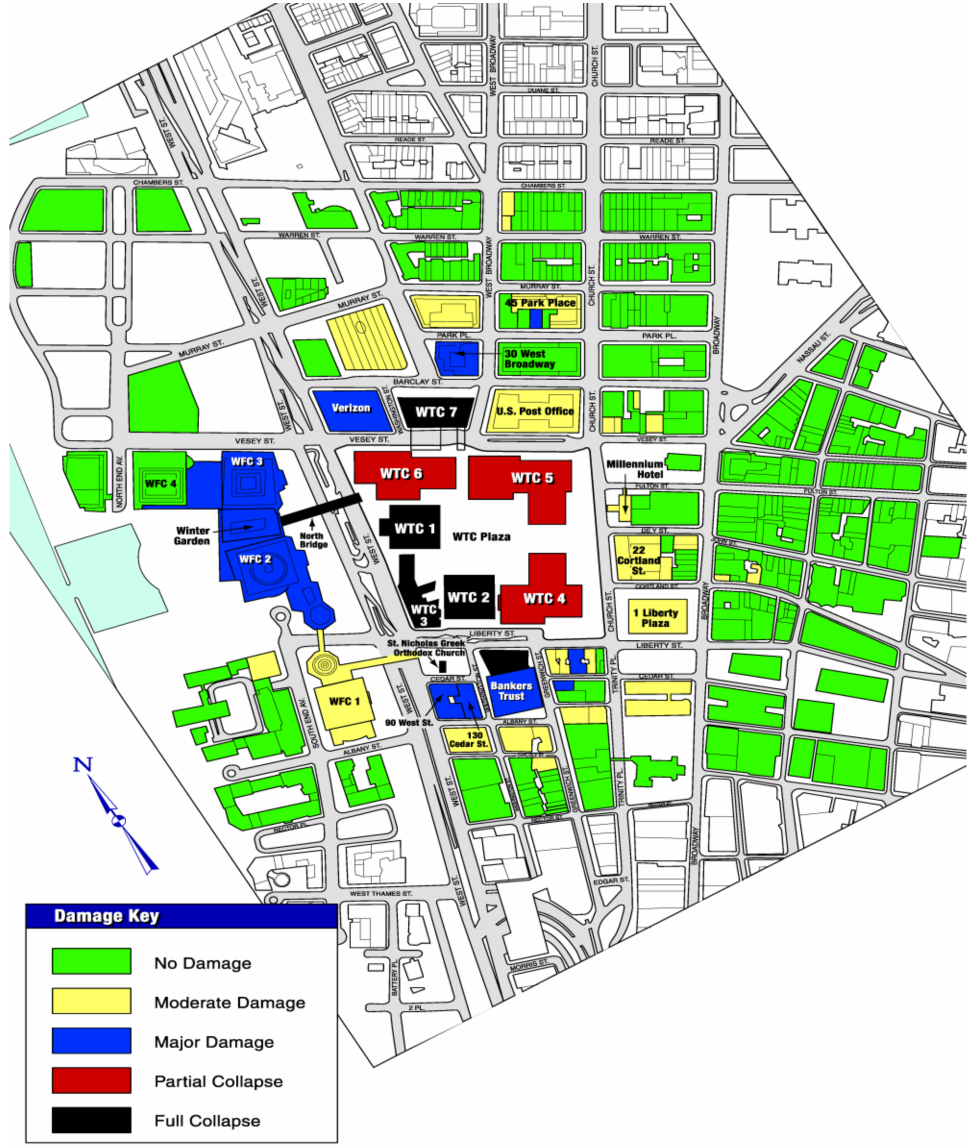
and these are scenario dependent !

What are the attributes of robustness?

The material loss cost consequences due to the collapse of the two WTC towers only comprised ¼ of the total costs due to damaged or lost material

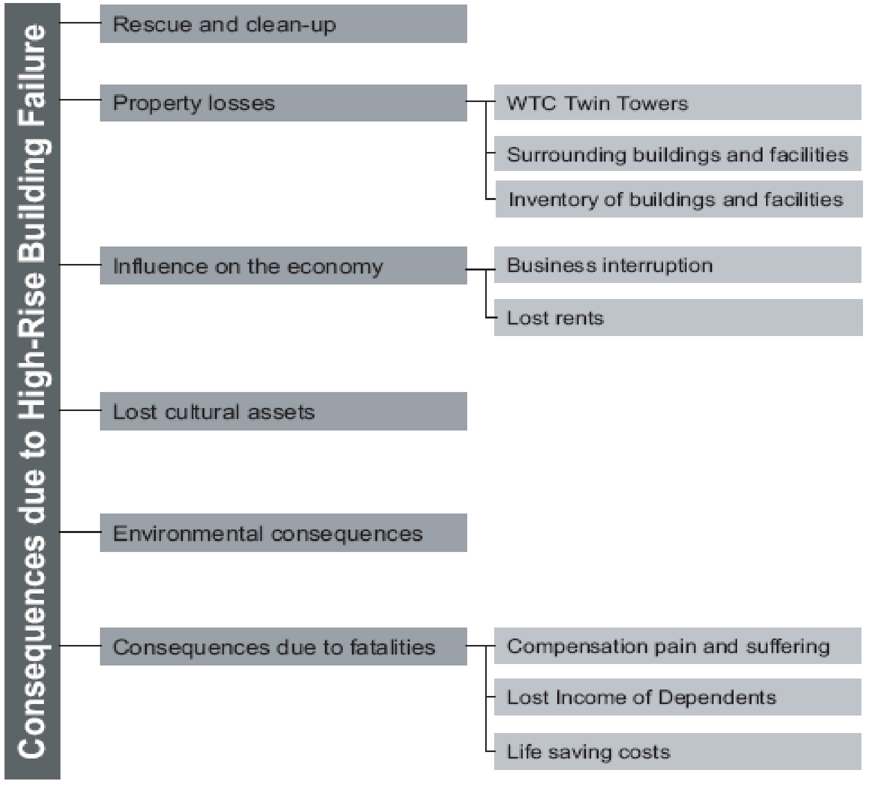
It seems relevant to include consequences in the robustness equation !

and these are scenario dependent !



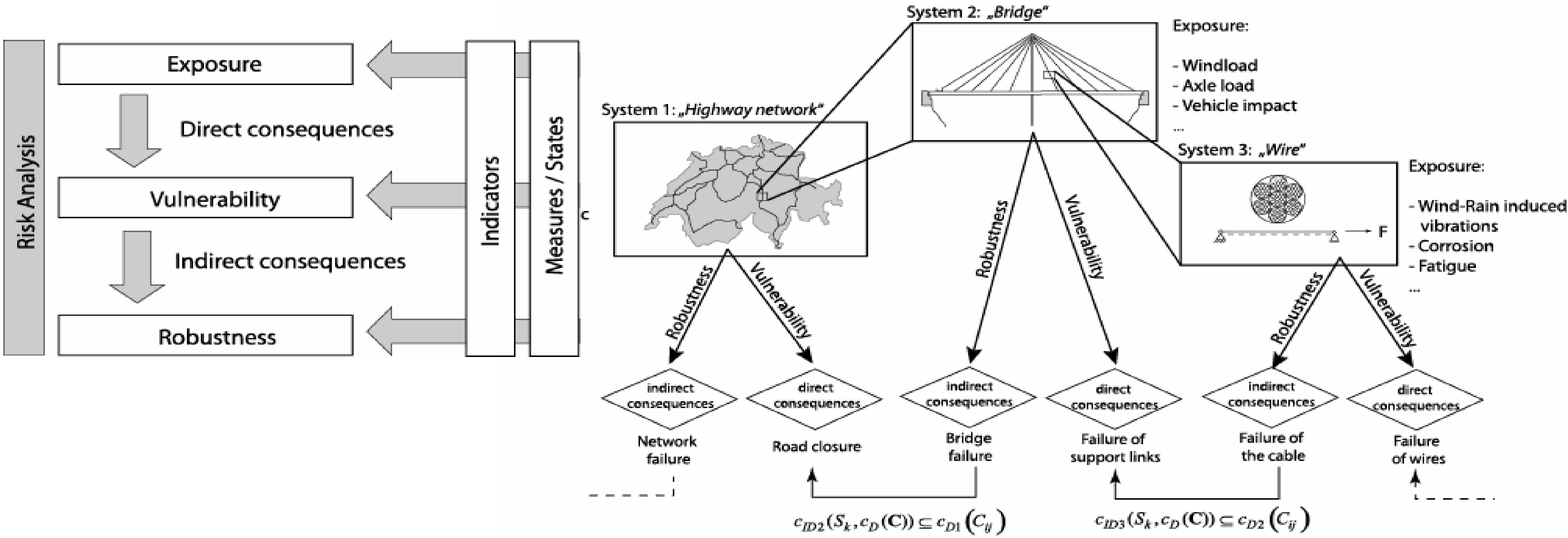
Which are the attributes of robustness?

- **The system definition is important because it defines the consequences following structural failures**



How to frame robustness?

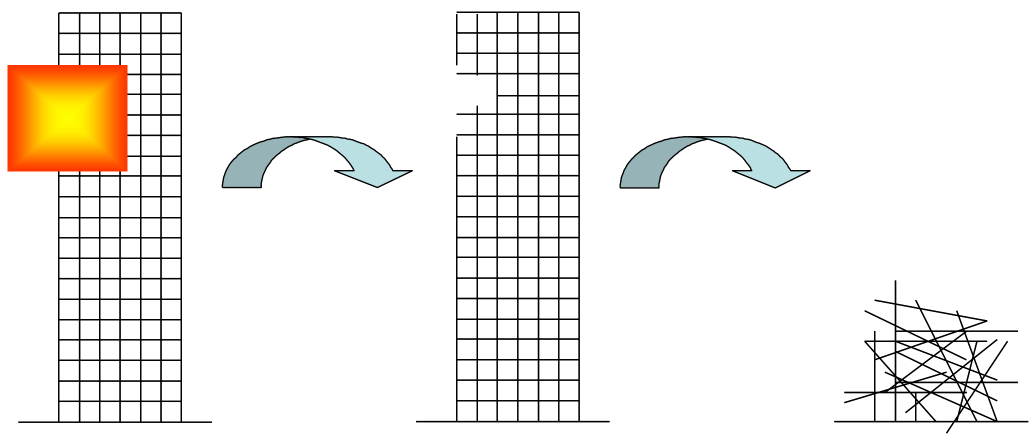
- Engineered systems have certain characteristics of generic nature – concept developed in the JCSS



How to frame robustness?

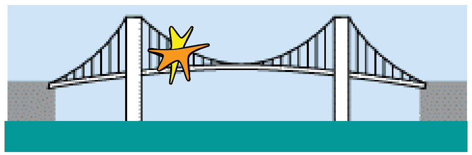
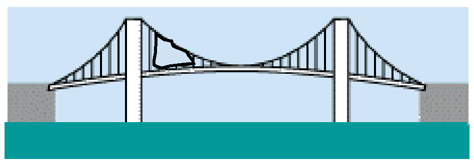
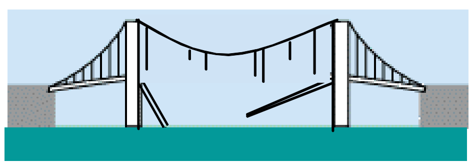
- This concept is also the idea behind the Eurocodes

Step 1	Step 2	Step 3
Identifical and modelling of relevant accidental hazards	Assessment of damage states to structure from different hazards	Assessment of the performance of the damaged structure



Assessment of the probability of occurence of different hazards with different intensities	Assessment of the probability of different states of damage and corresponding consequences for given hazards	Assessment of the probability of inadequate performance(s) of the damaged structure together with the corresponding consequence(s)

How to frame robustness?

Scenario representation	Physical characteristics	Indicators	Potential consequences
Exposure 	Flood Ship impact Explosion/Fire Earthquake Vehicle impact Wind loads Traffic loads Deicing salt Water Carbon dioxide	Use/functionality Location Environment Design life Societal importance	
Vulnerability 	Yielding Rupture Cracking Fatigue Wear Spalling Erosion Corrosion	Design codes Design target reliability Age Materials Quality of workmanship Condition Protective measures	**Direct consequences** Repair costs Temporary loss or reduced functionality Small number of injuries/fatalities Minor socio-economic losses Minor damages to environment
Robustness 	Loss of functionality partial collapse full collapse	Ductility Joint characteristics Redundancy Segmentation Condition control/monitoring Emergency preparedness	**Indirect consequences** Repair costs Temporary loss or reduced functionality Mid to large number of injuries/fatalities Moderate to major socio-economic losses Moderate to major damages to environment

Assessing robustness – a risk based framework

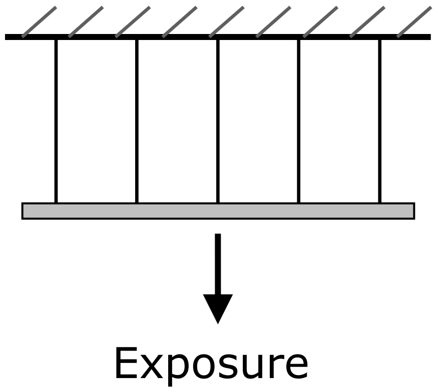
- Desirable properties of a robustness measure

  - Applicable to general systems

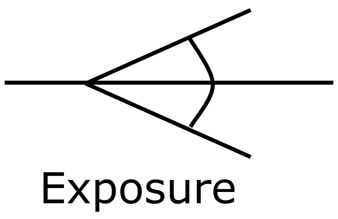
  - Allows for ranking of alternative systems

  - Provides a criterion for identifying acceptable robustness

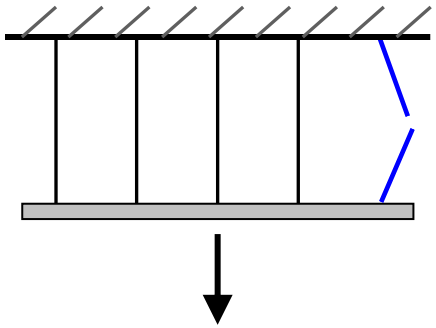
Assessing robustness – a risk based framework



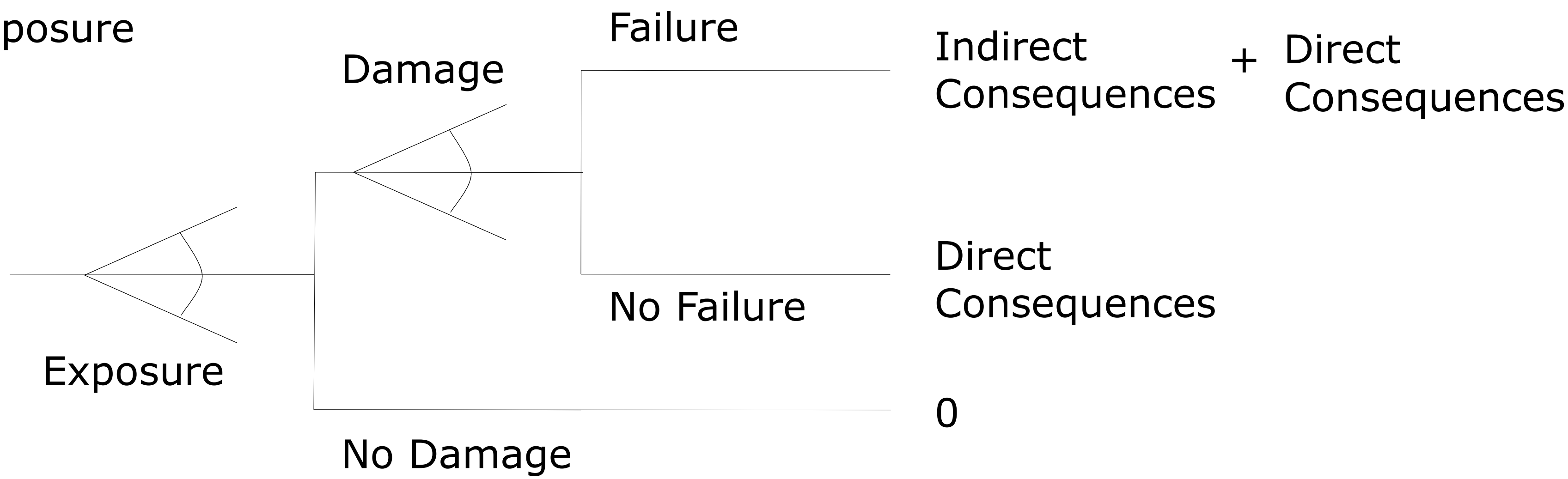
An assessment framework



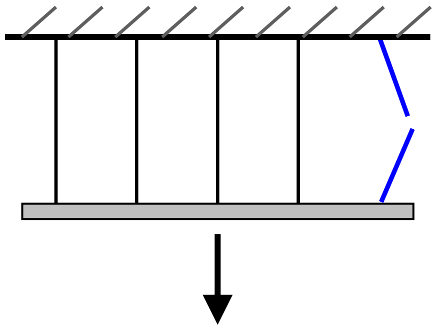
Assessing robustness – a risk based framework



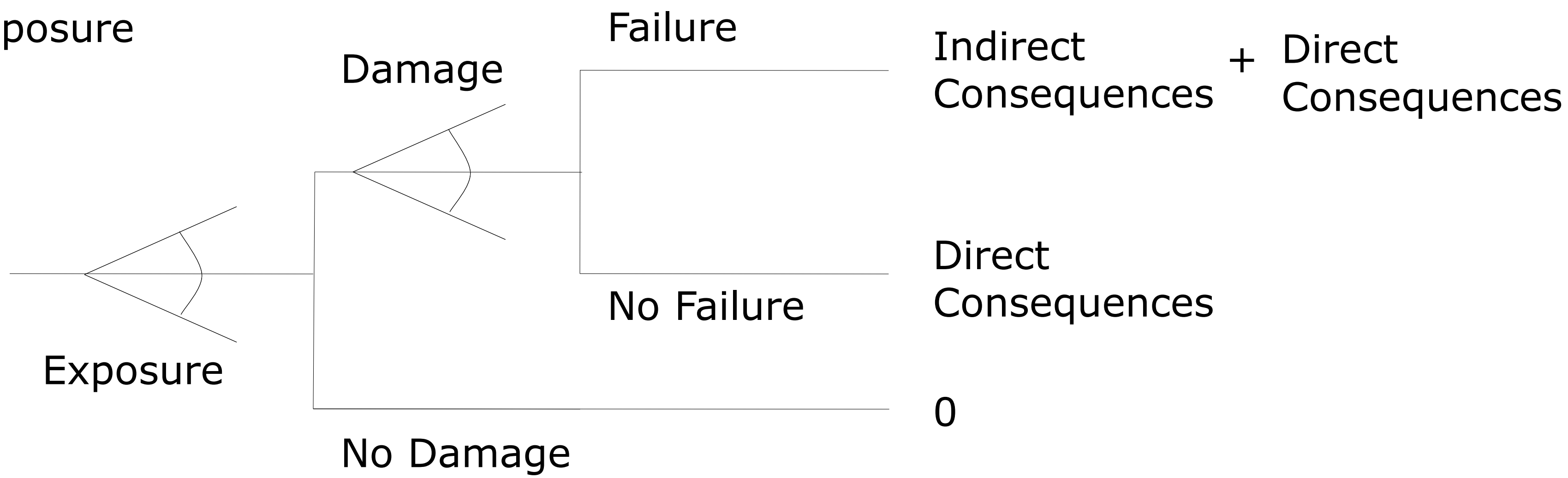
An assessment framework



Assessing robustness – a risk based framework



An assessment framework



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

Assessing robustness – a risk based framework

Features of the proposed index

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

- Assumes values between zero and one

- Measures relative risk only

- Dependent upon the probability of damage occurrence

- Dependent upon consequences