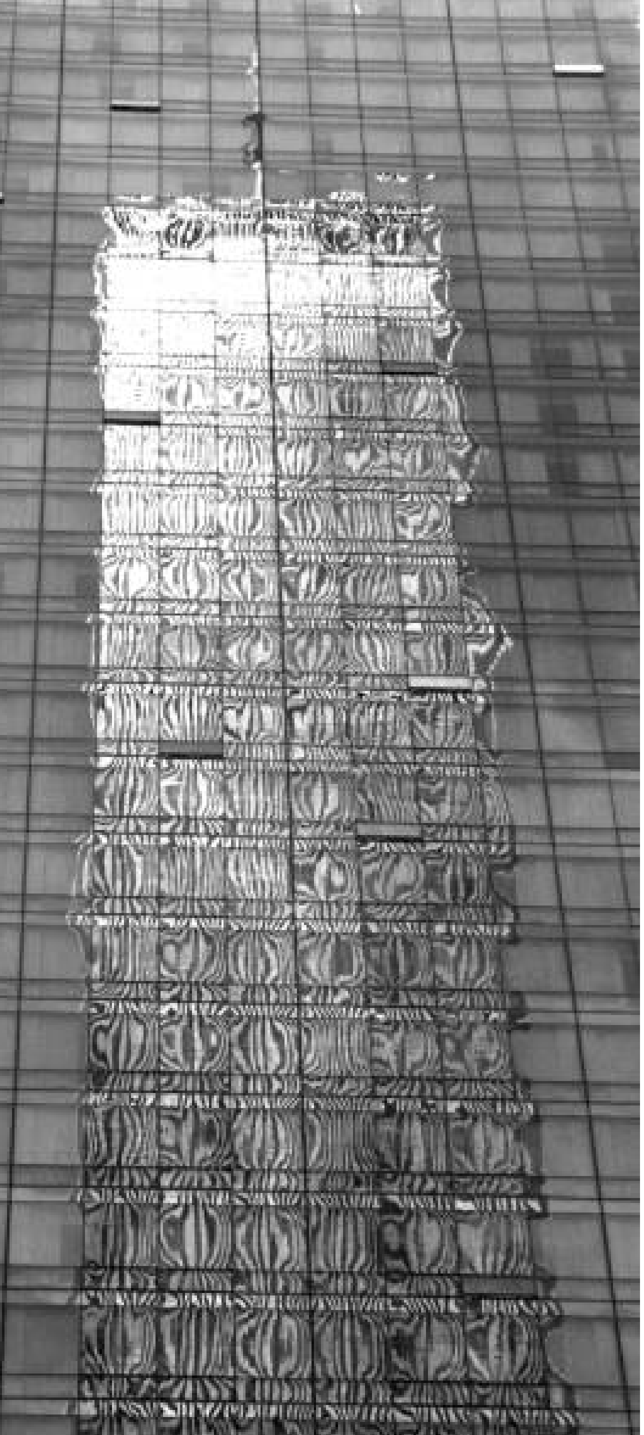

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A Swiss Study on the WTC Collapse for Improving Design and Safety of Extraordinary Building Structures

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- Principal studies
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  - robustness against progressive collapse
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- Structural robustness – new approaches
- Conclusions

Motivation

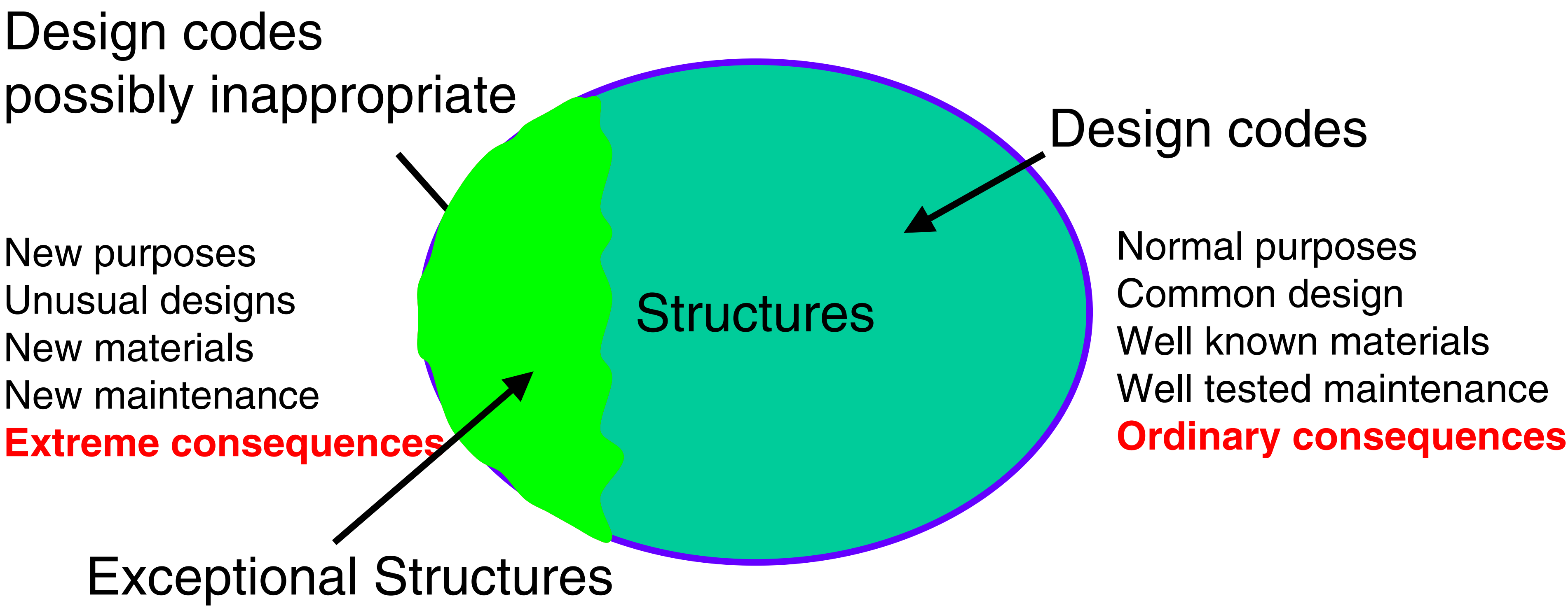
- Most modern design codes implicitly or explicitly set requirements to structural reliability

1	2	3	4
Relative cost of safety measure	Minor consequences of failure	Moderate consequences of failure	Large consequences of failure
Large (A)	$\beta=3.1$ ($p_F \approx 10^{-3}$)	$\beta=3.3$ ($p_F \approx 5\ 10^{-4}$)	$\beta=3.7$ ($p_F \approx 10^{-4}$)
Normal (B)	$\beta=3.7$ ($p_F \approx 10^{-4}$)	$\beta=4.2$ ($p_F \approx 10^{-5}$)	$\beta=4.4$ ($p_F \approx 5\ 10^{-6}$)
Small (C)	$\beta=4.2$ ($p_F \approx 10^{-5}$)	$\beta=4.4$ ($p_F \approx 5\ 10^{-6}$)	$\beta=4.7$ ($p_F \approx 10^{-6}$)

Joint Committee on Structural Safety Probabilistic Model Code

Motivation

- „Normal structures“ are designed according to structural design codes

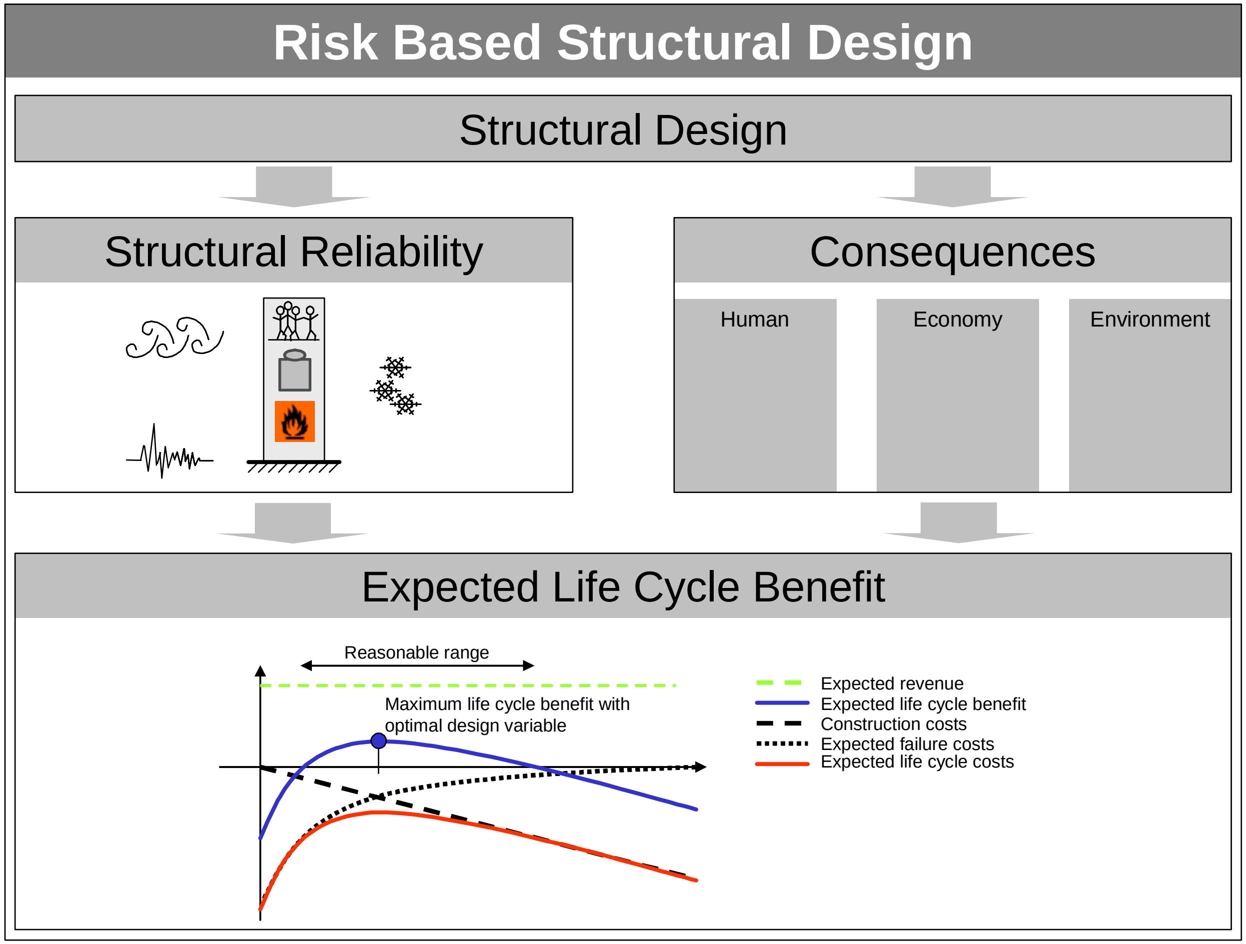


Motivation

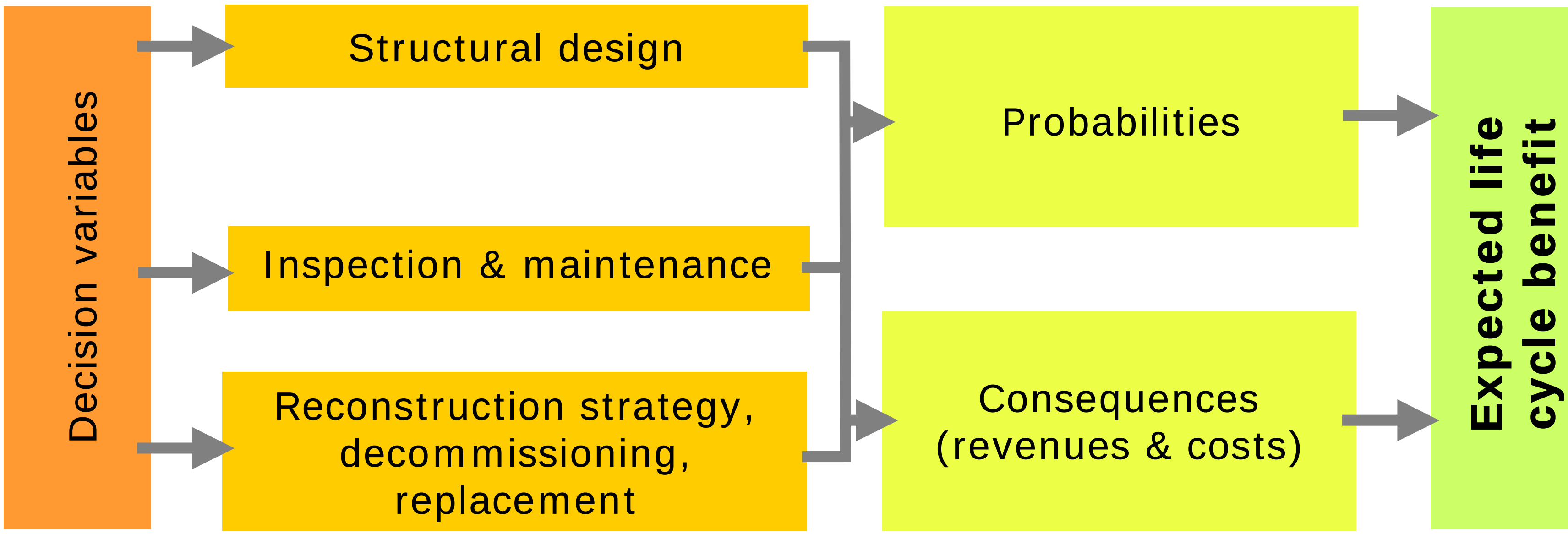
- Very little or no experience was available on the consequences of failures of extraordinary structures prior to the collapse of the WTC

- Despite the tragic circumstances involved in the collapse of the WTC the “event” should be studied in more detail to:
  - enhance design of extraordinary structures in the future
  - help reduce the risk associated with similar events in the future

Framework for risk based design



Framework for risk based design



$$
\begin{aligned}
E\left[LCC(P_F)\right] = B(P_F) \\
&= E\left[C_C(P_F)\right] + E\left[C_O(P_F)\right] + E\left[C_M(P_F)\right] + E\left[C_I(P_F)\right] \\
&+ E\left[C_{Rep}(P_F)\right] + \qquad + E\left[C_D(P_F)\right] + E\left[C_{Rev}(P_F)\right]
\end{aligned}
$$

Framework for risk based design

Step 1

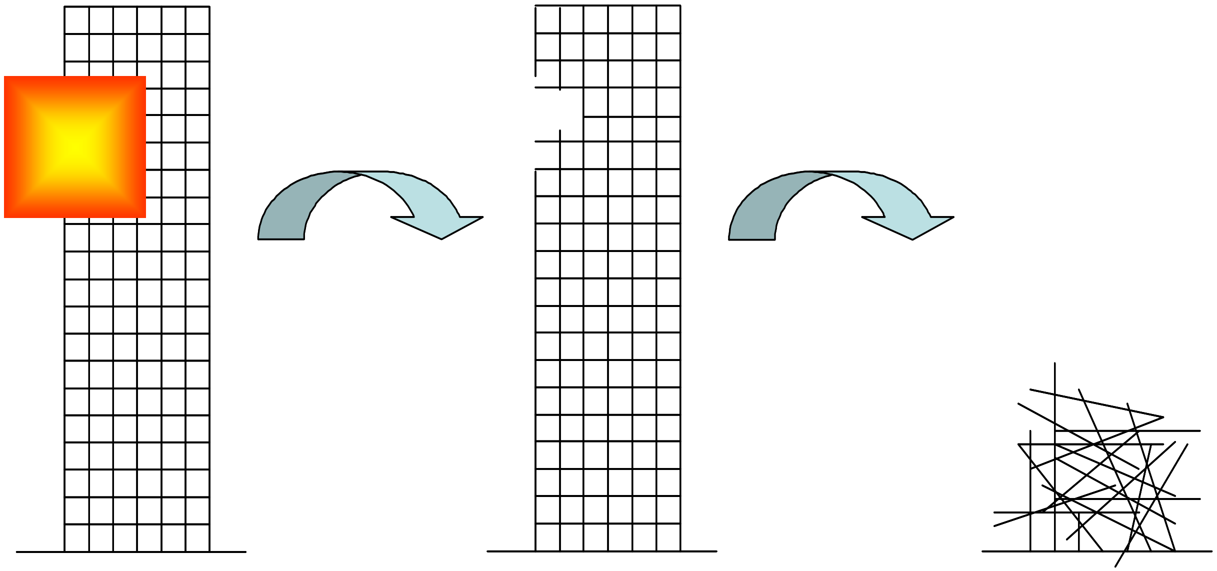
Identifical and modelling of relevant accidental hazards

Step 2

Assessment of damage states to structure from different hazards

Step 3

Assessment of the performance of the damaged structure



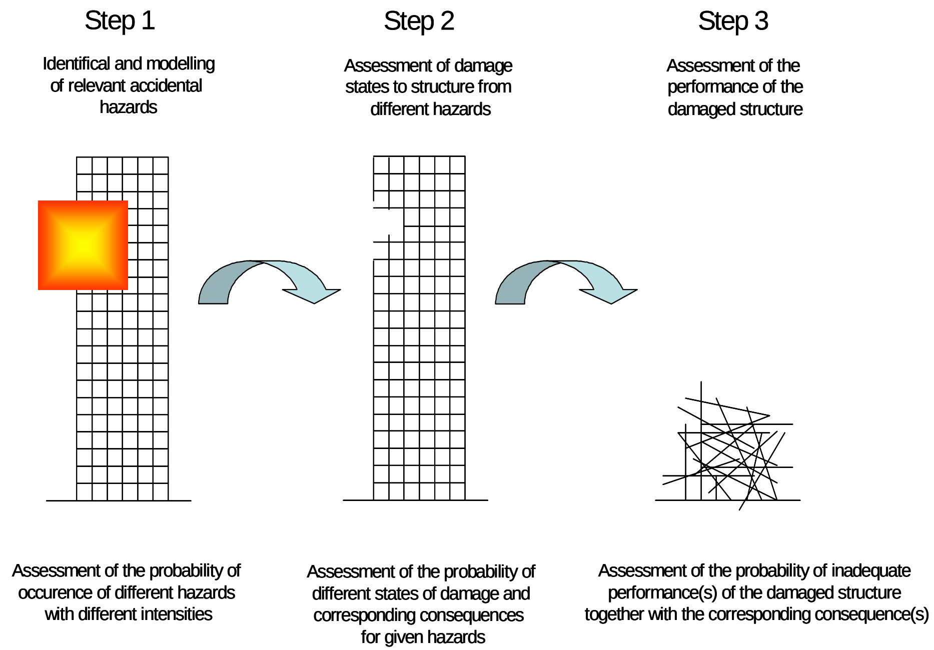
Assessment of the probability of occurence of different hazards with different intensities

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)

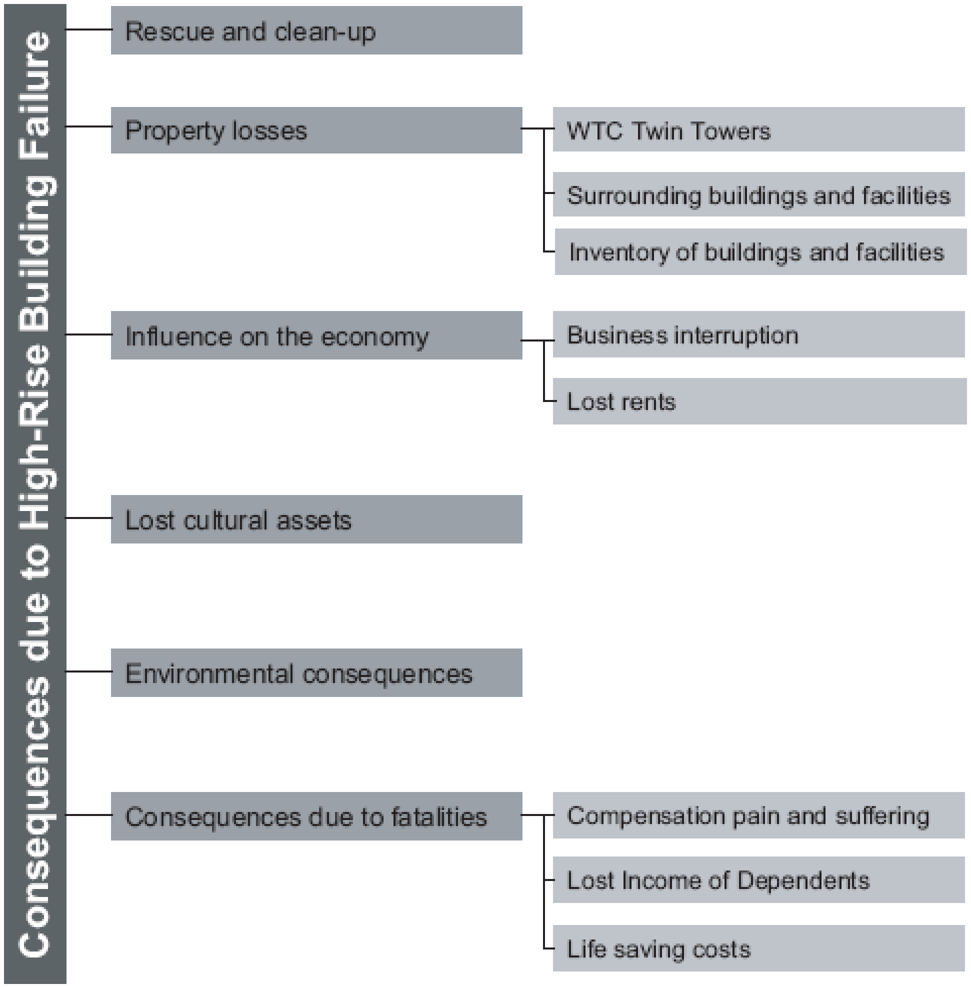
Framework for risk based design

Eurocode on accidental loads



$$E\left[C_F(A)\right] = \sum_{i=1}^{N_H}\sum_{j}^{N_D}\sum_{k=1}^{N_P} C(P_k)\; P(P_k \mid D_j)\; P(D_j \mid H_i)\; P(H_i)$$

Mapping of socio-economical consequences



Mapping of socio-economical consequences

Consequence Type			Scenario Low	Scenario High
Rescue & Clean-Up			1.7	1.7
Property			19.0	19.0
WTC Towers	4.7			
Other Destroyed Buildings	2.0			
Damaged Buildings	4.3			
Inventory	5.2			
Infrastructure	2.8			
Fatalities			5.0	5.0
Environment & Cultural Assets			0.1	0.1
Impact to economy				
Businesses				
Infrastructure	0.7	0.7		
Rents	1.2	1.2		
Total				

(in billion USD)

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Impact to economy			9.1	66.2
Businesses	7.2	64.3		
Infrastructure	0.7	0.7		
Rents	1.2	1.2		
Total			**34.9**	**92.0**

(in billion USD)

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(in billion USD)

	Comptroller NYC Oct. 4, 2001		Comptroller NYC Sept. 4, 2002		New York City Partnership		Federal Reserve Bank of New York	
	low	high	low	high	low	high	low	high
Income losses							3.6	6.4
Economic losses	28.0	43.0	52.3	64.3	38.8	38.8	7.2	12.8

(in billion USD)

Principal studies

- Vulnerability of fire protection

  Investigations were made to assess the vulnerability of passive fire protection of steel columns

  The analysis – based on nonlinear analysis – showed that the effect of even small damages to fire protection is significant – and relative insensitive to the location of the damage

  The integrity of passive fire protection is thus a major issue

Principal studies

- Robustness against progressive collapse

  Studies were carried out to assess the efficiency of two approaches to reduce the risk of progressive collapse due to airplane impact damage and subsequent fire load:

  1 reduce vulnerability - avoid story failure by ensuring small damage

  2 improve robustness to avoid progressive collapse due to falling stories

  Approach 1 (steel) seems superior but is expensive – in the order of 1-10% of total costs

Optimal target reliability levels

$$g(\mathbf{X}) = z\, f_y\ \xi - \left(\alpha_G\ G + \left[1-\alpha_G\right] L\right)$$

$$g_{fi}(\mathbf{X}) = z\, f_y\ k_y\ \xi_{fi} - \left(\alpha_G\ G + \left[1-\alpha_G\right] L_{fi}\right)$$

$$j = A / A_0 - 1$$

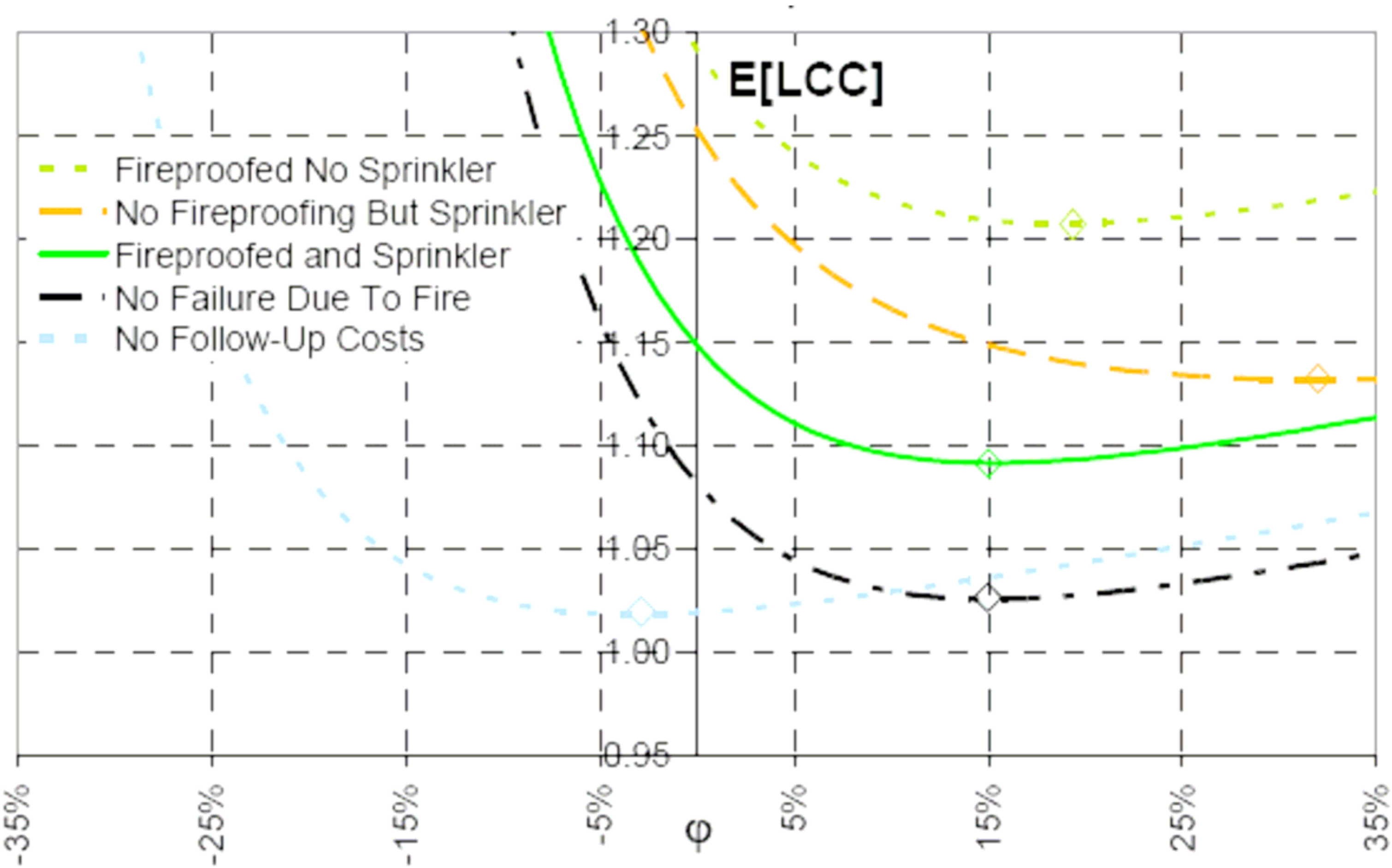
X	Dist. Type	E[X]	V_X
f_y	LN	1.00	5%
ξ	LN	1.00	10%
G	N	1.00	10%
L	G	1.00	40%
ξ_{fi}	LN	1.00	15%
L_{fi}	G	0.57	59%
q	G	400 MJ/m^2	25%

[1] JCSS 2001, *Probabilistic Model Code*, Joint Committee on Structural Safety, online, available at: www.jcss.ethz.ch

Optimal design without and with fire risks ($10^{-4}/m^2$)

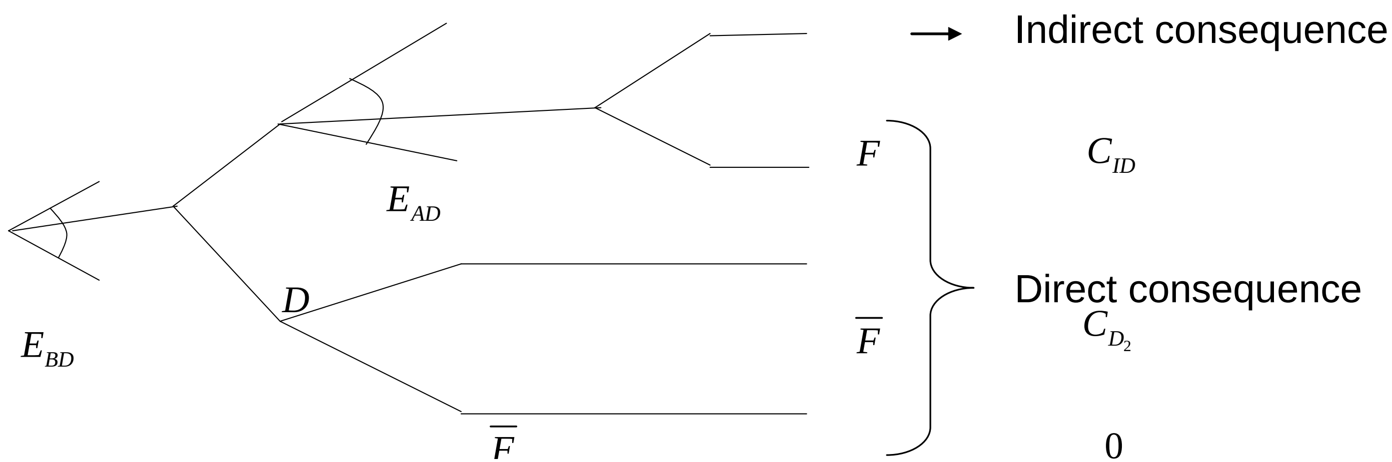
A_0: required cross section to ensure annual probability of failure of 10^{-4} - no fire

Optimal target reliability levels



Structural robustness – new approaches

- Robustness against progressive collapse

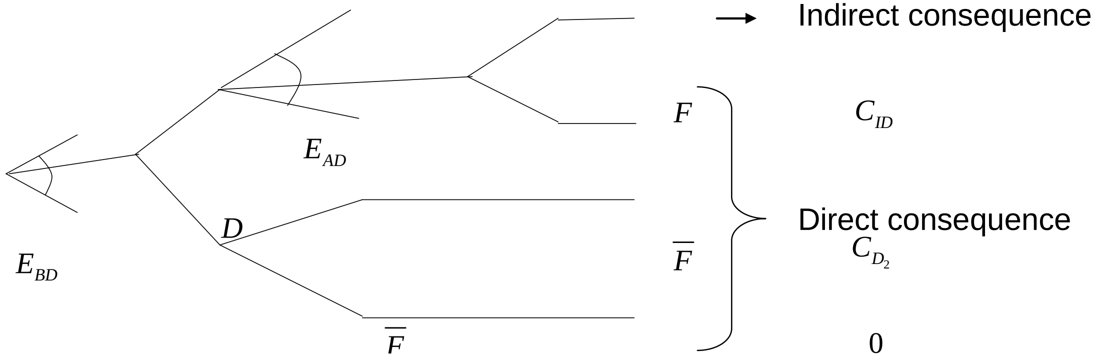


$$R_D = P(E_{BD})P(D|E_{BD})P(E_{AD}|D,E_{BD})P(\overline{F}|D,E_{AD})C_{D_2} + P(E_{BD})P(\overline{D}|E_{BD})P(F|E_{BD},\overline{D})C_{D_1}$$

$$R_{ID} = P(E_{BD})P(D|E_{BD})P(E_{AD}|D,E_{BD})P(F|D,E_{AD})C_{ID}$$

Structural robustness – new approaches

- Robustness against progressive collapse



Index of robustness

$$I_R = \frac{R_D}{R_D + R_{ID}} = \frac{R_{D_1} + R_{D_2}}{R_{D_1} + R_{D_2} + R_{ID}}$$

Requirement to robustness

$$\frac{\partial C_R(a)}{\partial a} = -\frac{\partial R_{ID}(a)}{\partial a}$$

Conclusions

- Extraordinary building structures justify extraordinary reliability acceptance criteria
- There seems to be a need for scenario based requirements to structural design – robustness
- Robustness should be quantified and requirements to robustness should be provided for most usual load scenarios
- International consensus and homogeneity on codification is necessary
- Collaboration on further developments should be aimed for

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