Robustness of buildings in structural codes

- Introduction
- Methodology
- Experience with other structures
- European approach
- U.S. code ASCE/PBD
- Risk analysis in practice
- Conclusions

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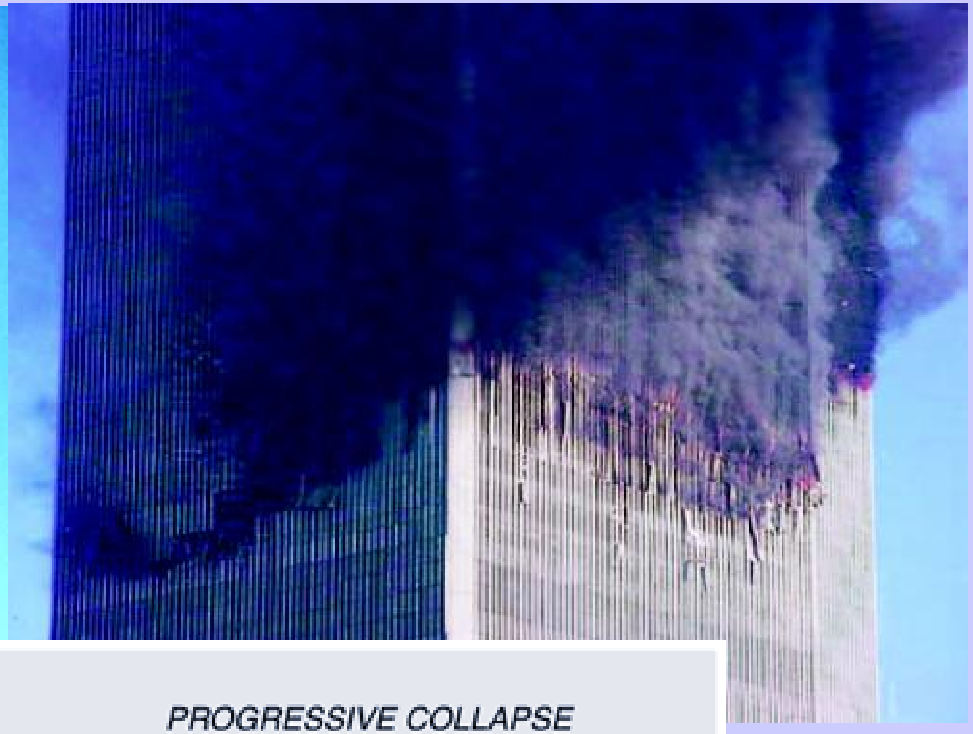
Definitions

- **Robustness is a performance characteristic of the structure representing its insensitivity to local failure**
- **Resistance is usually considered only on a local level (cross section, structural elements)**
- **Progressive collapse can be defined as collapse of all or a large part of the structure precipitated by local failure or damage**
- **Risk acceptability here is associated to global (system) failure (and not to member failure as specified in the codes)**

Progressive collapse



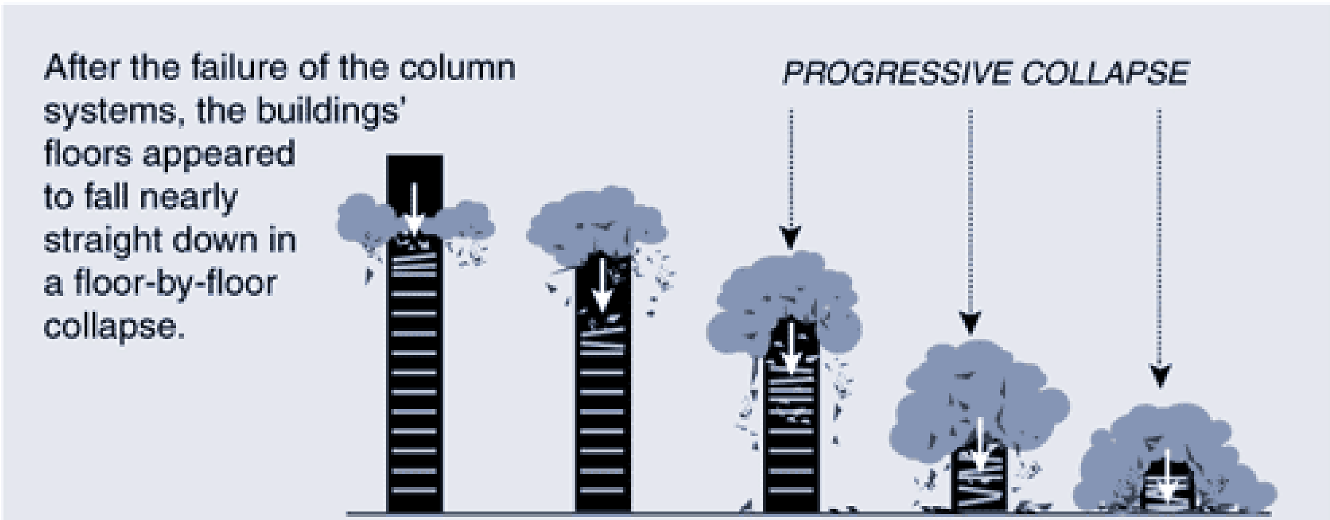
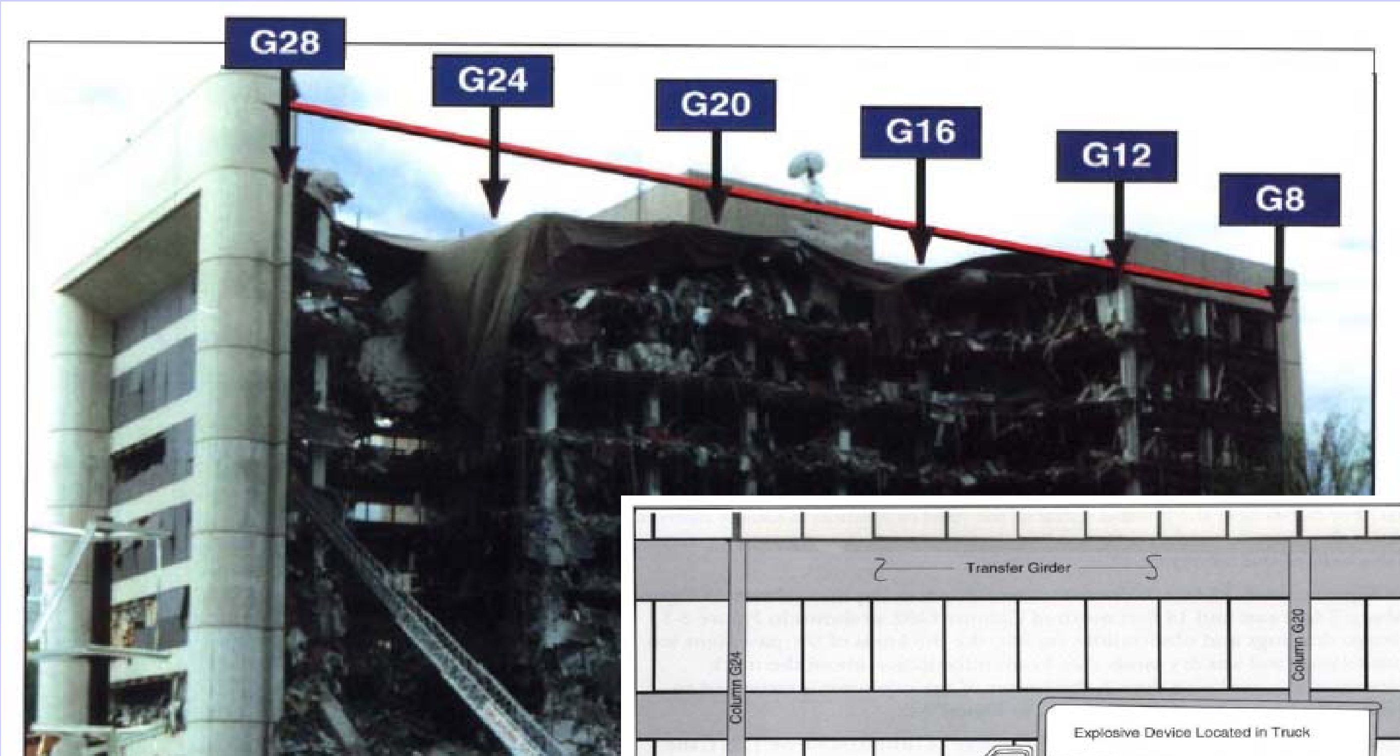
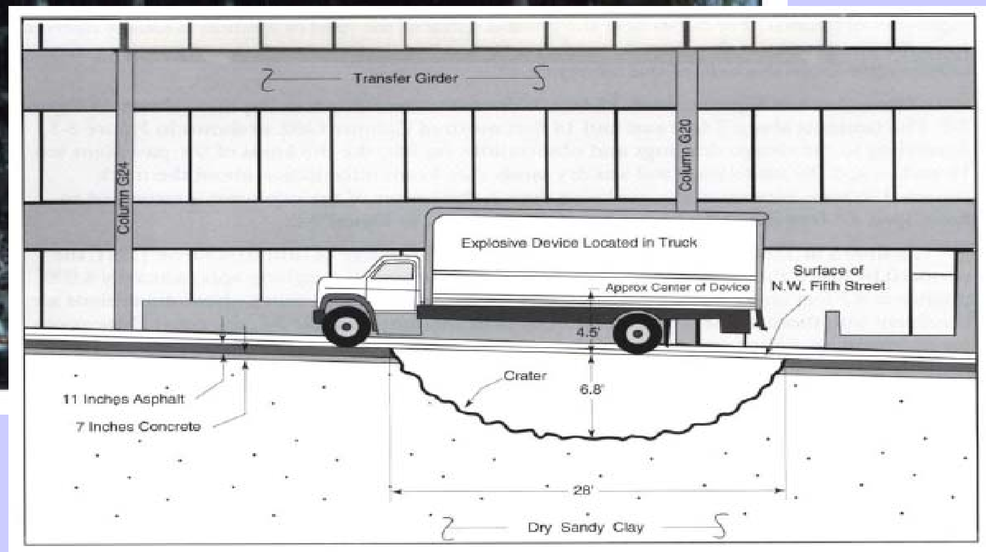


Illustration in the September 12, 2001 edition of the *New York Times*

Explosion





Murrah Building, 1995

Federal Building, Oklahoma
Progressive collapse design aspects

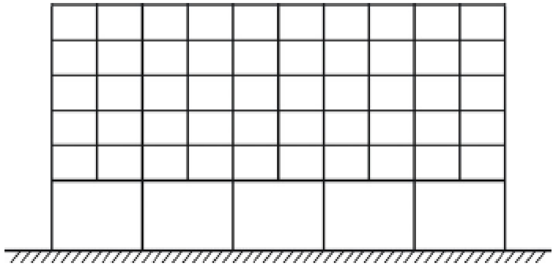


Fig. 1. Structural design concept

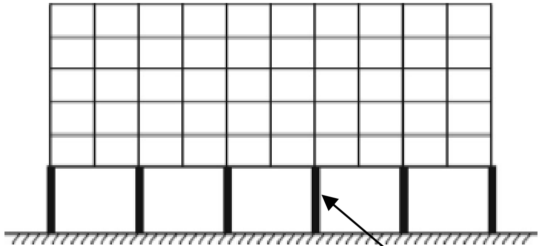


Fig. 2. Specific local resistance

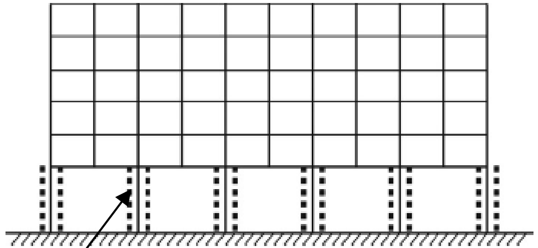


Fig. 3. Protective barriers

Local resistance

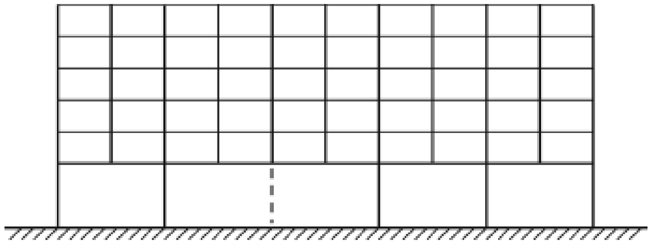


Fig. 4. Column failure introduced as load case "local failure"

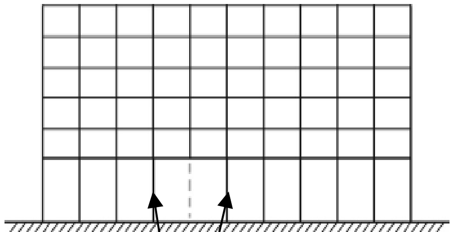


Fig. 5. Modification of structural system

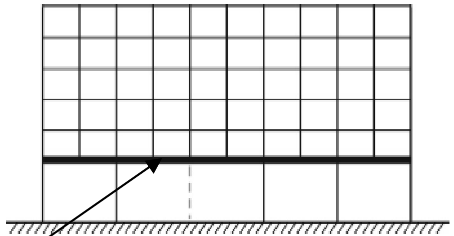
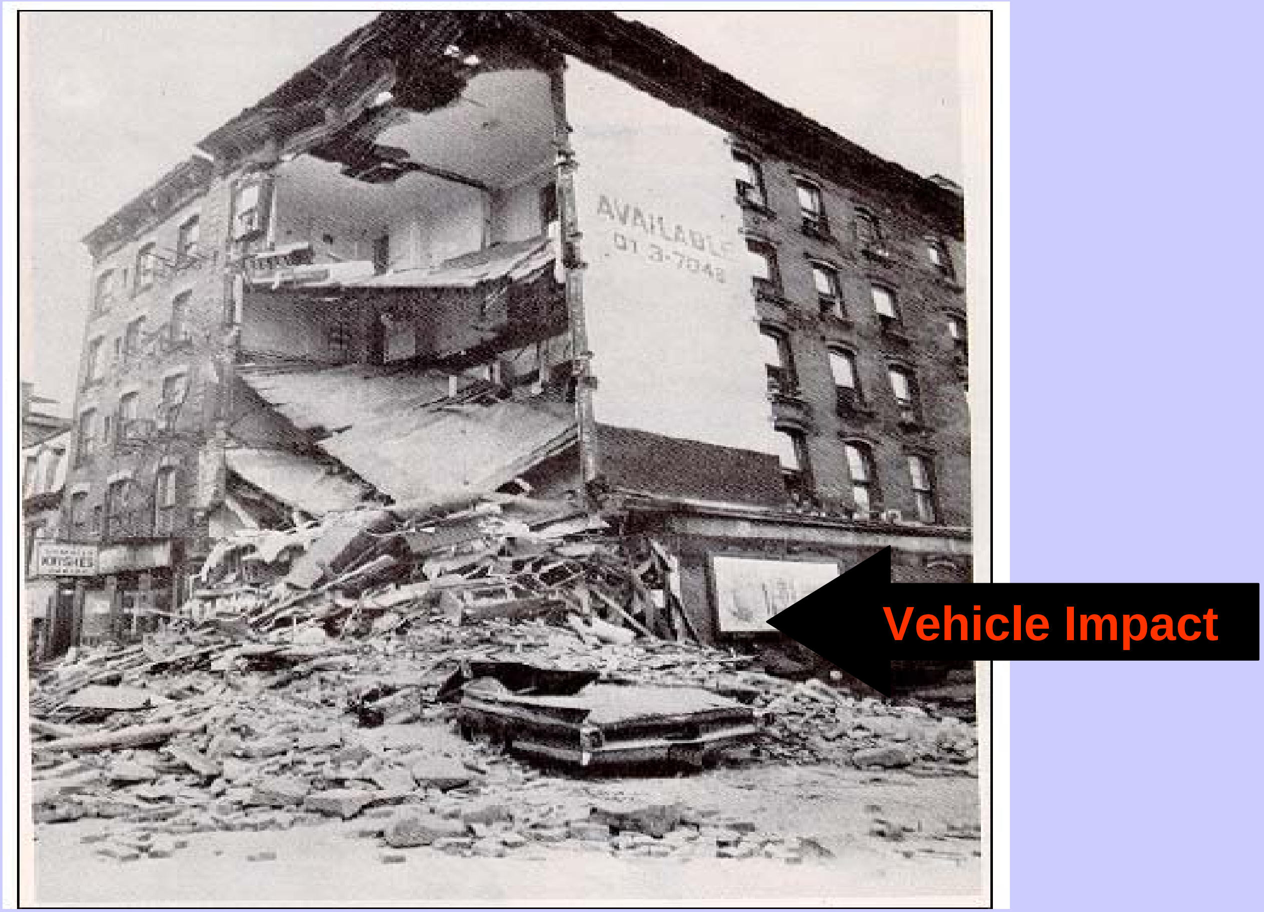


Fig. 6. Strengthening of transfer girder

Alternate load paths

Impact



Collapse of the corner of a building in New York, due to a vehicle impact. (Allen and Schiever 1972)

Accidental Impact on buildings

- **local damages**

Impact

Explosion

Probabilistic Formulation

$$P(C) = P(C|LE)P(L|E)P(E) < P_A$$

P(E) : probability of occurrence of E

P(L|E) : probability of local failure, L, given the occurrence of E

P(C|LE): probability of collapse given the occurrence of L due to E

P_A : acceptable probability of global failure

RISK R:

$$R = P(C) \times C < R_A \text{ (acceptable Risk)}$$

Probability of collapse

Consequences of collapse

Step 1

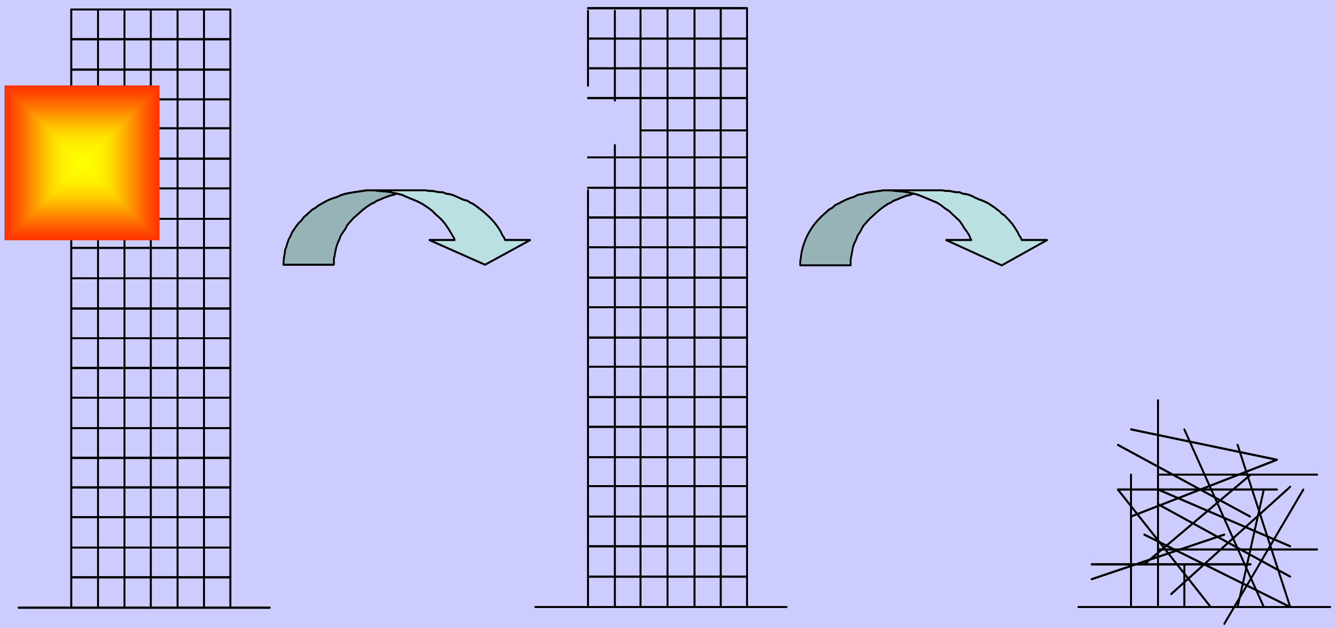
Identifical and modelling of relevant accidental hazards

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)

Input

Accidental rates

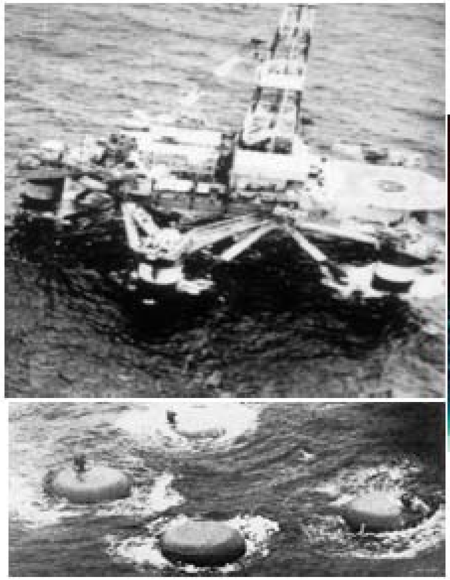
Ellingwood and Dusenberry (2005)

- **Gas explosions (per dwelling): $2x10^{-5}$ per year**
- **Bomb explosions (per dwelling): $2x10^{-6}$ per year**
- **Vehicular collisions (per building): $6x10^{-4}$ per year**
- **Fully developed fires (per building): $5x10^{-8}$ per m^2 per year**

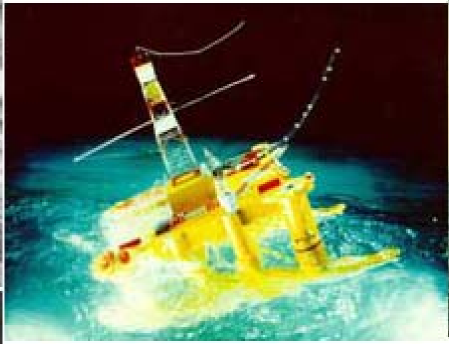
Consequences depend on type of structure

(safety class differentiation)

Offshore structures: Accidents which resulted in total collapse



a) Alexander L. Kielland before and after capsizing in 1980



b) Model of Ocean Ranger, which capsized in 1982, during survival testing

c) Piper Alpha fire and explosion in 1988

d) P - 36 accident in 2001

Progressive Collapse in codes (NORSOK, 2004)

resistance to accidental actions

the structure should be checked to maintain the prescribed load carrying function for the defined accidental loads

resistance in damaged condition

following local damage the structure shall continue to resist defined (reduced) load conditions for a specified time period

Condeep Platform

Accidental Load Design

Flooding of the utility shaft (2000 years event)

Verification in a damaged state for a period of 3 months

$G = R – P – L – D – E < 0 \mid$ Flooding event

R: resistance

P:permanent load effect

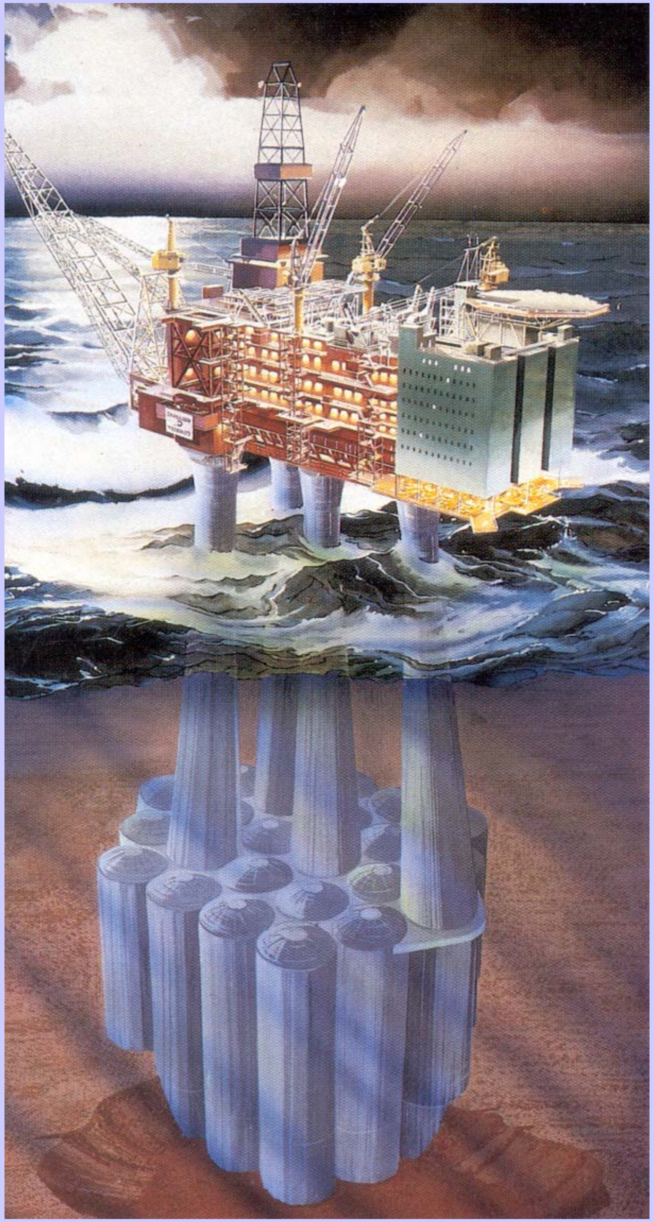
L: live load effect

D: deformation load effect

E: environmental load effect

Result:

$P[G < 0] = 0.002 - 0.016$ (depending upon load case)



Offshore structures: Limit State Design

Limit states	Physical appearance of failure mode	Remarks
Ultimate (ULS) -Overall "rigid body" stability - Ultimate strength of structure, mooring or possible foundation		Different for bottom – supported, or buoyant structures. Component design check
Fatigue (FLS) - Failure of welded joints due to repetitive loads		Component design check depending on residual system strength and access for inspection
Accidental collapse (ALS) - Ultimate capacity[1)] of damaged structure with "credible" damage		System design check

Robustness of tunnels

Mont Blanc tunnel fire 1999

New long tunnels (road tunnels up to 25km, railway tunnels up to 57km with heavy and mixed traffic)

=> New European Guidelines for tunnels

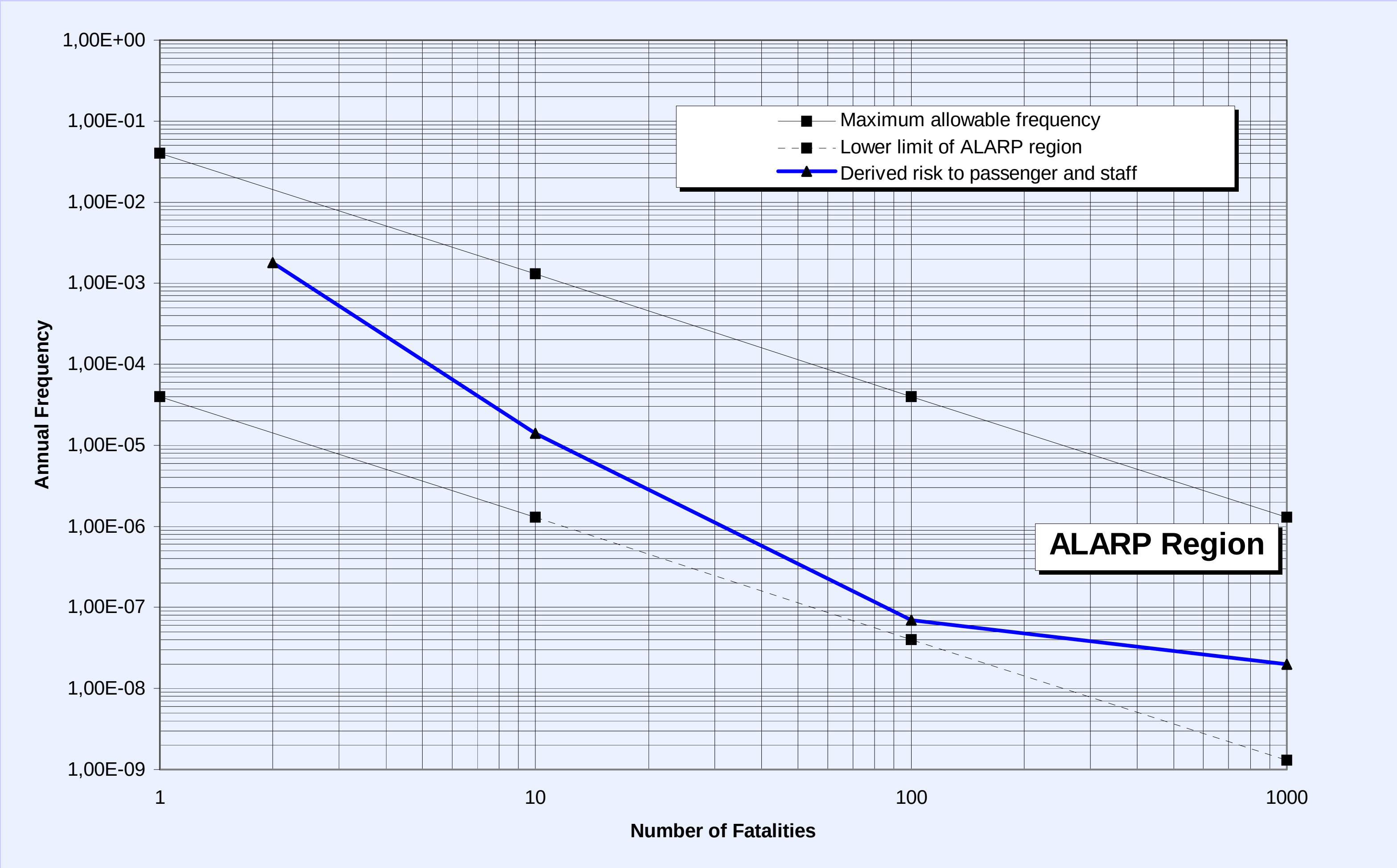
A) TUNNEL CLASSIFICATION (length, traffic, system)

B) SAFETY SYSTEMS

- **Prevention measures**
- **Mitigation Measures**
- **Self-Rescue Measures**
- **Rescue by third-measures**

C) RISK STUDY ASPECTS

Risk Analysis of subway tunnel



Hazard probability levels

Class	Frequency	Events per year
A	frequent	>10
B	occasional	1-10
C	remote	0.1-1
D	improbable	0.01-0.1
E	incredible	0.001-0.01

Hazard severity levels

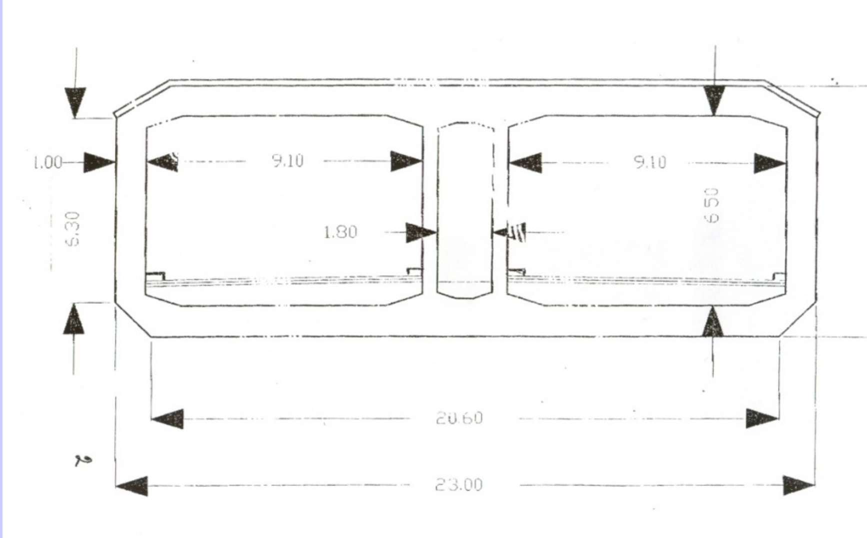
Class	Severity Category	Human losses
1	insignificant	---
2	marginal	injuries
3	critical	1
4	severe	5
5	catastrophic	50

Risk Acceptability Matrix

Frequency class	CONSEQUENCE CLASS 1	2	3	4	5
A	ALARP	NAL	NAL	NAL	NAL
B	ALARP	ALARP	NAL	NAL	NAL
C	AL	ALARP	ALARP	NAL	NAL
D	AL	AL	ALARP	ALARP	NAL
E	AL	AL	AL	ALARP	ALARP

AL: ACCEPTABLE NAL: NOT ACCEPTABLE

Tunnel under the Maliakos gulf, Greece
Feasibility Study



immersed tunnel, l =3200m

Accidental loads:

- **sunken ship impact**
- **fire**
- **explosion**
- **falling anchors impact**

Bridges

Confederation (Canada)

Rion – Antirion (Greece)

Component failures and consequences

Constructional arrangements

Buildings: Example Greek Embassy, Berlin, design/construction phase

Robustness aspects

r.c. structure with extra capacity

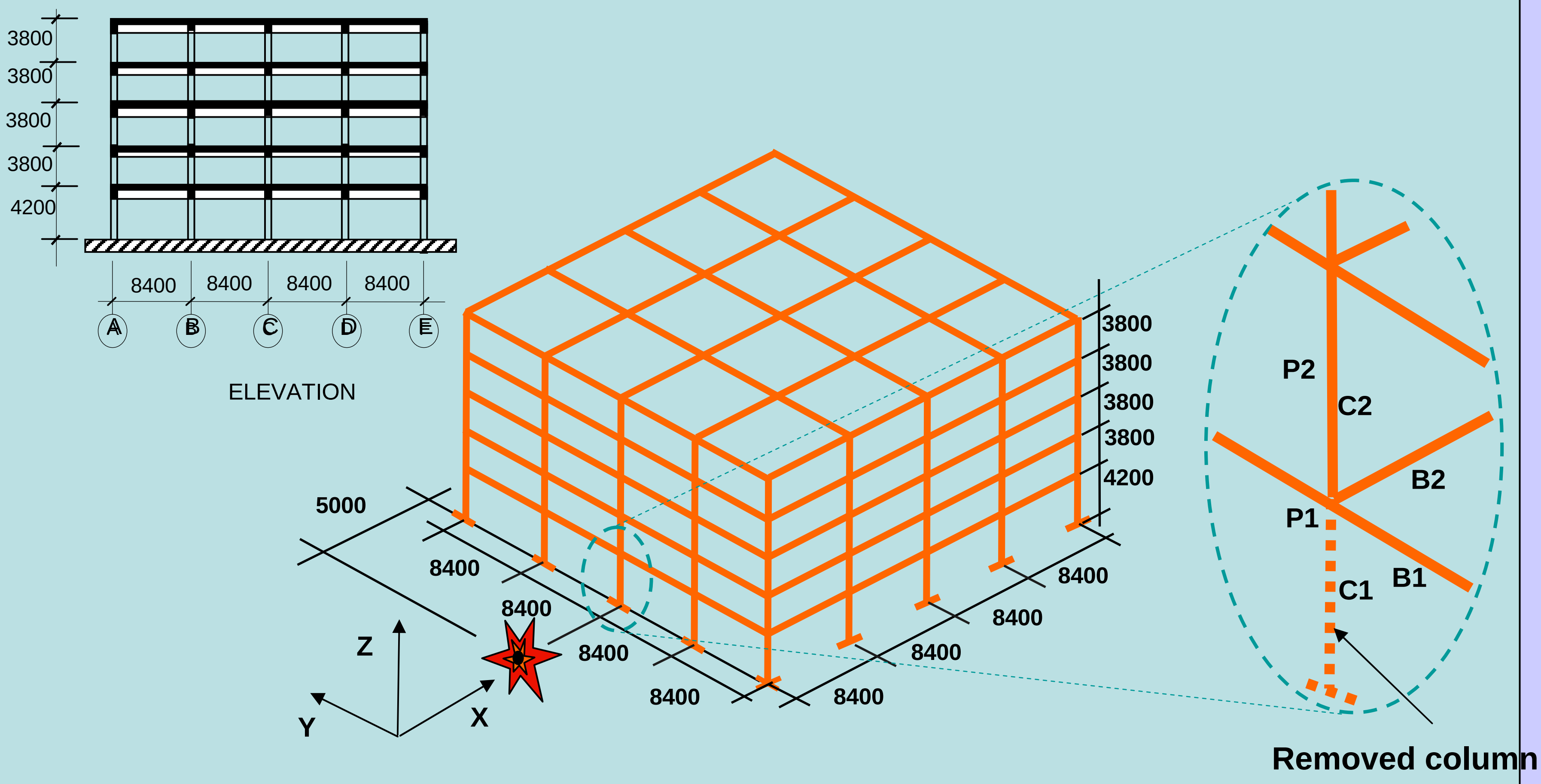
concrete roof

Fire resistance of bearing elements

Fire safety and evacuation concept

Protective and mitigation measures

Example 2: Concrete Frame Building (University of Melbourne)



Building codes

- Eurocode EN 1991-1-7
- ASCE 7-02 and 05
- BS steel 2000/Concrete 97
- Swedish, Danish codes
- Canadian 1990
- Other

  (material specific)

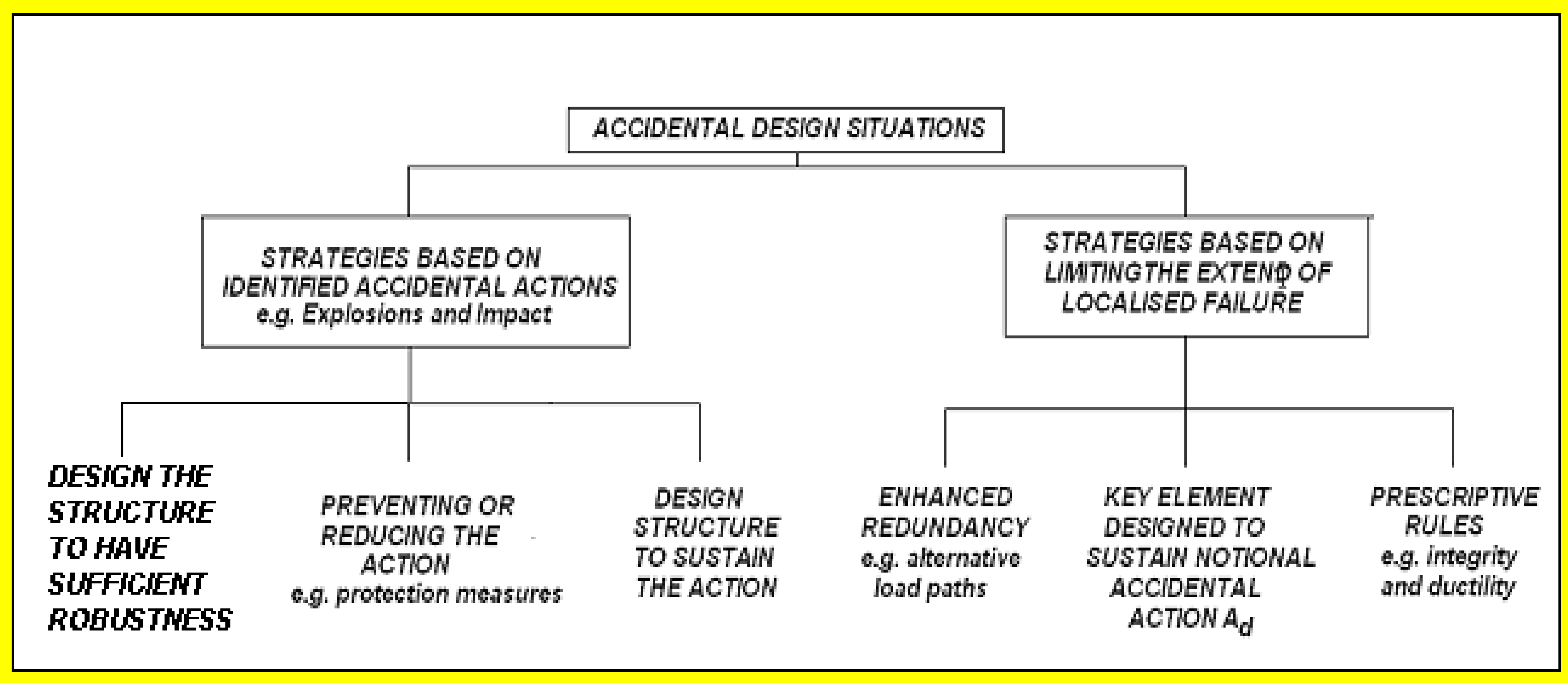
EN 1991-1-7 Annex A: Classification of buildings

Consequences class	Example structures
class 1	low rise buildings where only few people are present
class 2, lower group	most buildings up to 4 stories
class 2, upper group	most buildings up to 15 stories
class 3	high rise building, grand stands etc.

EN 1991-1-7 Annex A: What to do

Class 1	No special considerations
Class 2, Lower Group Frames	Horizontal ties in floors
Class 2, Lower group Wall structures	Full cellular shapes Floor to wall anchoring.
Class 2, Upper Group	Horizontal ties and effective vertical ties OR limited damage on notional removal OR special design of key elements
Class 3	Risk analysis and/or advanced mechanical analysis recommended

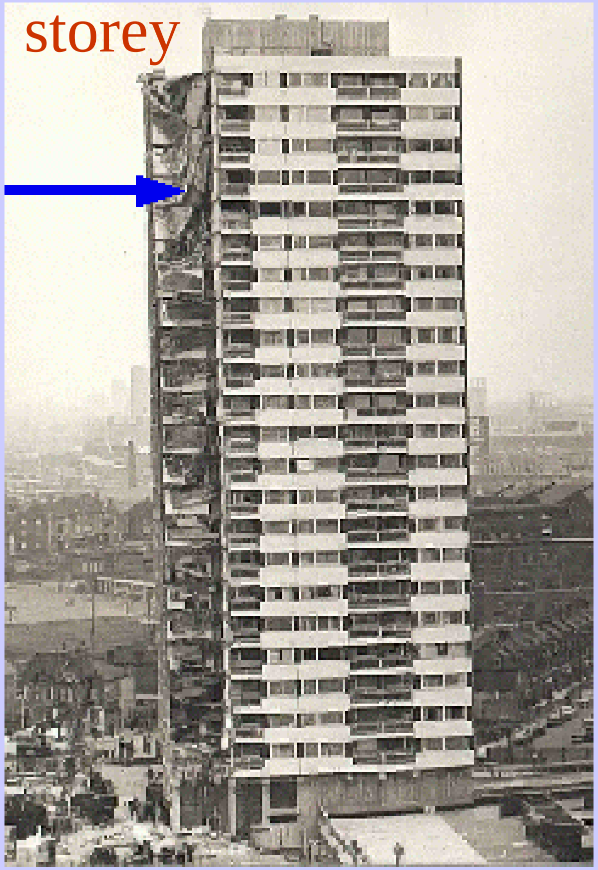
EN 1991-1-7 Design Strategies



Robustness – structural integrity

Structures should be designed in such a way that they exhibit robustness to the effect of impact or explosion.

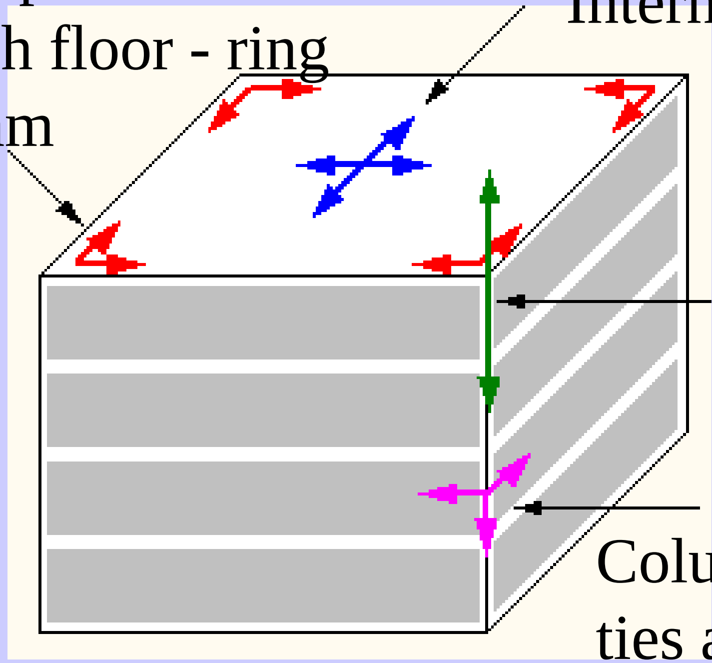
Ronan point 1960 – explosen on the 20th storey



The measures – bonds, ties

Peripheral ties at each floor - ring beam

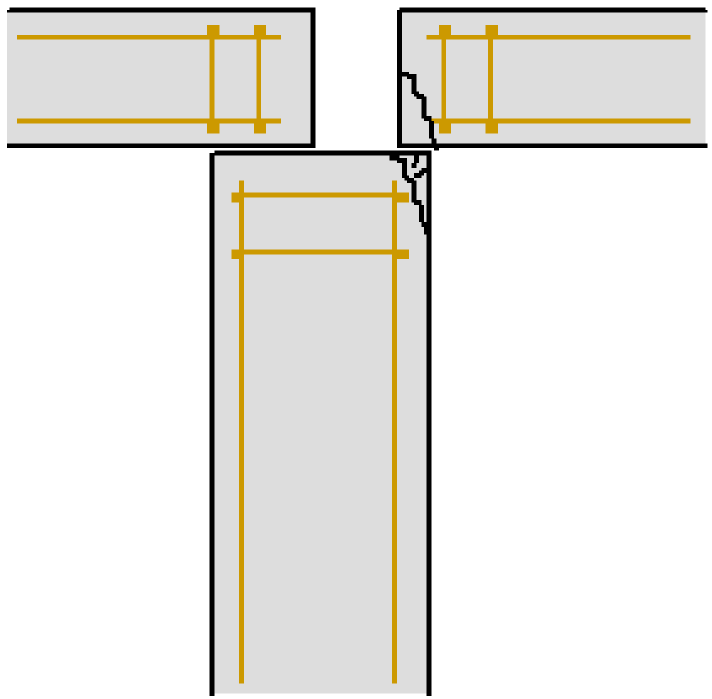
Internal ties

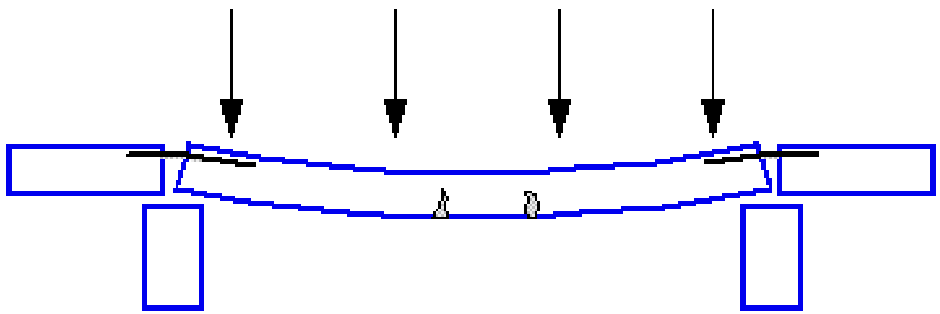


Continuous vertical ties In columns and walls

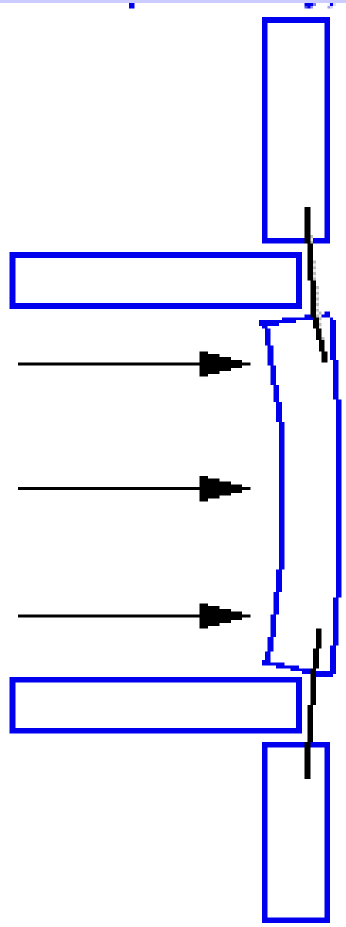
Columns and wall ties anchored into structure at each floor

Robustness measures





Horizontal ties



Vertical ties

American Approach ASCE 7

Design for extraordinary events (10^{-6} to 10^{-4} per year)

Direct method:

specific resistance objectives to progressive collapse

Indirect method:

- **minimum levels of strength,**
- **ductility,**
- **continuity**

American Approach ASCE 7

Direct method:

- **alternate load path method**
- **specific local resistance method**

Indirect method:

- **Redundancy**
- **Ductility (connections)**
- **Static system**
- **Returns on walls**
- **Ties**
- **other**

Performance-based Design in the U.S.A.

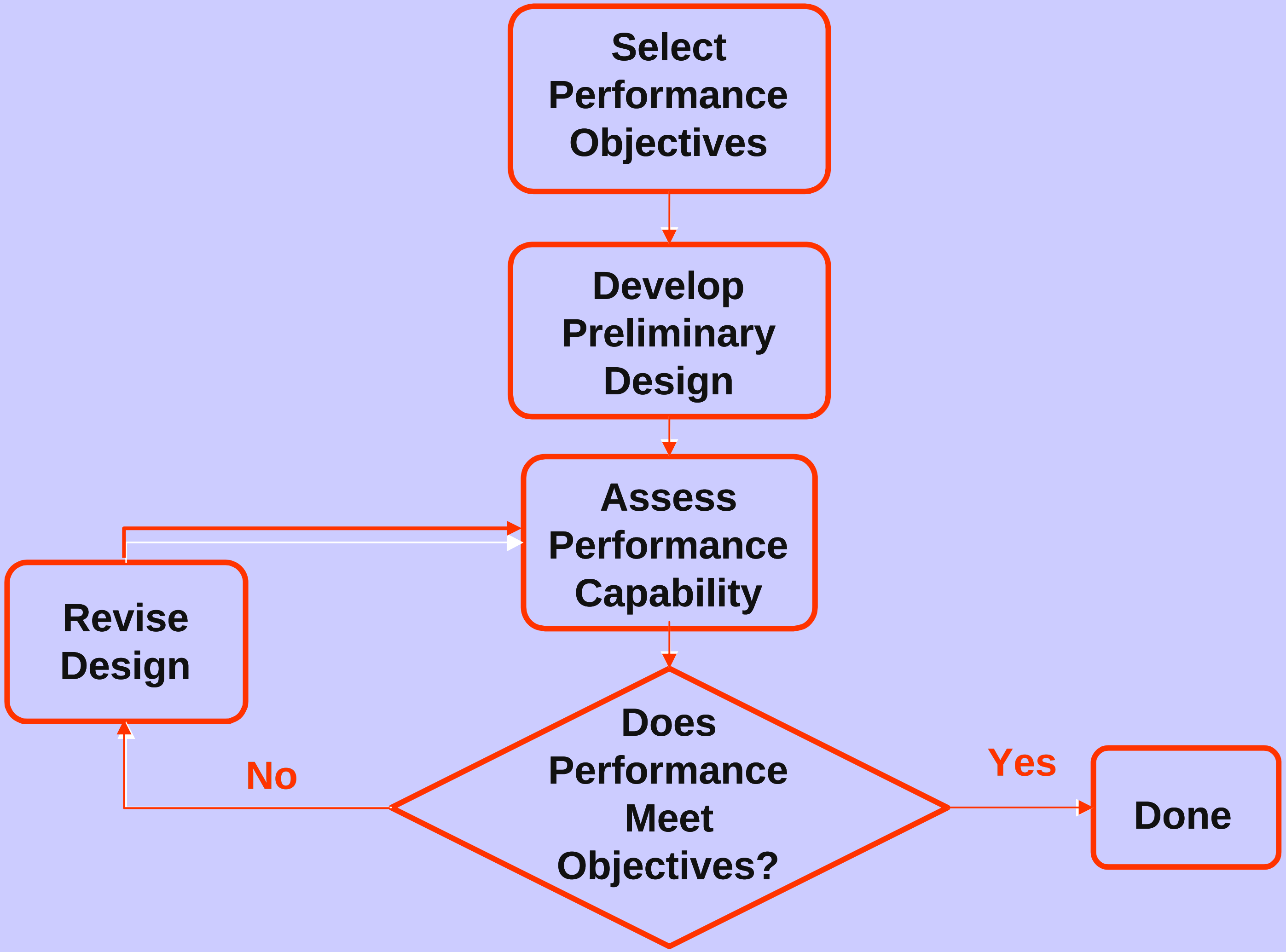
1 Rincon Hill
San Francisco, CA

Public Library
Seattle, WA

Los Angeles City Hall
Los Angles, CA

- Seismic, fire and blast-resistant design of new buildings
- Seismic upgrade of existing buildings (Hamburger, 2007)

The Process



Select Performance Objectives
Develop Preliminary Design
Assess Performance Capability
Revise Design
Does Performance Meet Objectives?
No
Yes
Done

Performance Based Design (PBD) for earthquake

Hazard Levels **Performance Levels**

Hazard Level for EQ	Operatio-nal	Occupiable Damaged	Life Safe, Major Damage	Near Collapse
Frequent (50%/ 50yrs)	a	b	c	d
Occasional (20%/50yrs)	e	f	g	h
Rare (10%/50yrs)	i	j	k	l
Max considered (2%/50yrs)	m	n	o	p

PBD Is used also for accidental loads!

Commonly selected performance objectives

Risk Acceptability Matrix

Frequency class	Consequence class 1	2	3	4	5
A	ALARP	NAL	NAL	NAL	NAL
B	ALARP	ALARP	NAL	NAL	NAL
C	AL	ALARP	ALARP	NAL	NAL
D	AL	AL	ALARP	ALARP	NAL
E	AL	AL	AL	ALARP	ALARP

Example: stadium roof (class 3)

- Performance objective: no structural collapse of stadia roof

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- Accidental Event: Floodlighting mast collapse onto stadia roof
- Likelihood: improbable
- Consequences: catastrophic (e.g. >20% collapse)

- Risk Matrix: =>Acceptable/Unacceptable

Conclusions

1. Some differences in the codes regarding load level of accidental loads and design provisions
2. Robustness is implemented by appropriate design and use of resistant materials
3. Detailed provisions for accidental loads in various other codes (tunnels, offshore structures)
4. Performance objectives for <u>global</u> failure are important (differentiation of classes)

⇒ Risk based rules are needed for important structures (risk acceptability matrix)

Current and Future Work within WG3 and TG

1. Discussion of current robustness criteria
2. Improvement through implementation of modern methodology (including risk acceptance)
3. Development of guidelines for practicing engineers (including choice of safety measures)
4. Risk based model code for robustness (for important structures)
5. Case studies