Risk-informed approaches for mitigating disproportionate collapse of buildings

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Disproportionate (progressive) collapse

A collapse that is triggered by localized damage that cannot be contained and leads to a chain reaction of failures resulting in a partial or total structural collapse, where the final damage is disproportionate to the local damage from the initiating event.

Events outside the design envelope

- Extreme environmental events
- Abnormal/accidental loads
- Design/construction error
- Occupant misuse

Ronan Point, UK (1968)

Bailey’s Crossroads, VA (1973)

L’Ambiance Plaza, CT (1987)

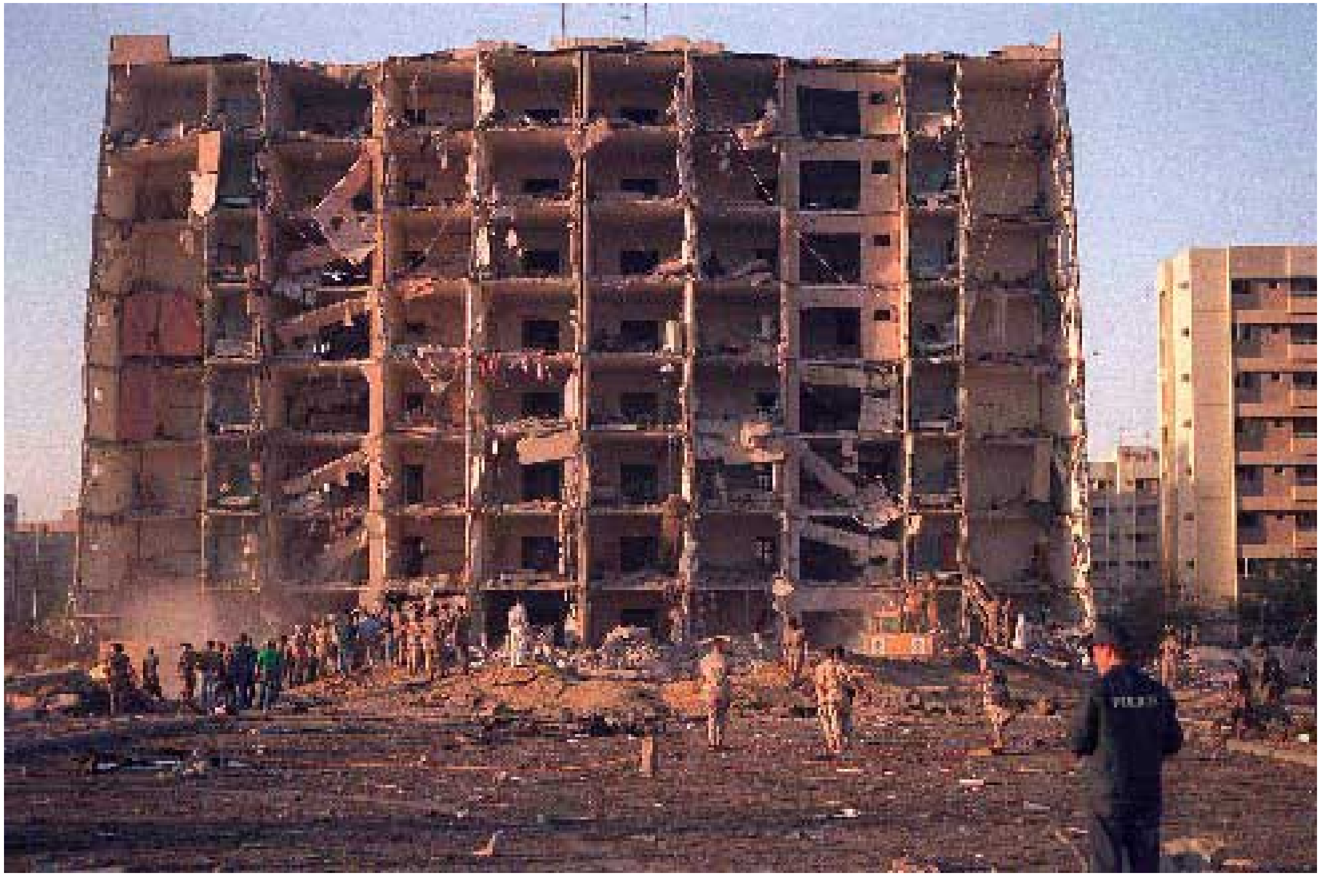
L’Ambiance Plaza, CT (1987)

Murrah Federal Building - Oklahoma City (1995)

Murrah Federal Building
Damage Statistics

- **Total Building Floor Area: ~ 137,800 ft ^{2}**
- **4% (~ 5,850 ft ^{2}) destroyed by blast**
- **42% (~ 58,100 ft ^{2}) destroyed by blast *plus* progressive collapse**

KHOBAR TOWER
(Saudi Arabia, 1996)



Significant collapse incidents

- Ronan Point, London, UK -1968
- Bailey's Crossroads, VA - 1973
- US Marine Barracks, Beirut, Lebanon – 1983
- L'Ambiance Plaza Apartments, CT - 1987
- Murrah Federal Building, Oklahoma – 1995
- Khobar Towers, Dhahran, Saudi Arabia - 1996
- US Embassies - Nairobi, Kenya and Dar es Salaam, Tanzania – 1998
- WTC 2001

Research motivation
Is there a need for improved design practices?

- New efficient building systems
- Demands for performance beyond what is provided by building code minimums
- Increasing media coverage and public awareness of building performance and demands for safety
- Perception of increasing risk for certain facilities

Overview of presentation

- Current provisions in building standards and codes
- Risk-informed decision-making for natural and man-made hazards
- Low-probability hazards
- Strategies for reducing risk of progressive collapse

Current code provisions addressing disproportionate collapse

- Performance requirement
- Minimum requirements for connectivity
- Damage tolerance - notional element removal
- Normative abnormal load (pressure or force)

ASCE STANDARD 7-05

General structural integrity

1. **General: §1.4** "Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage…"

2. **Combinations of Loads: § 2.5** "…strength and stability shall be checked to ensure that structures are capable of withstanding the effects of extraordinary (i.e., low-probability) events…"

NB: Recently issued ASCE 7-10 contains specific provisions

ACI Standard 318-05, Building code requirements for structural concrete

Prescriptive requirements for general structural integrity

- Chapter 7 - Details of reinforcement
  - **7.13 Requirements for structural integrity**
  - 7.13.1 Members shall be effectively tied together
  - 7.13.2 Cast-in-place: continuity reinforcement in joists and perimeter beams
  - 7.13.3 Precast: tension ties in transverse, longitudinal and vertical directions and around perimeter
- Chapter 13 – Two way slab systems
  - 13.3.8.5 Bottom reinforcement continuous through column core
  - 13.3.8.6 Bottom reinforcement continuous through shear heads and lifting collars
- Chapter 16 - Precast concrete (§16.5)
  - Minimum tie forces for bearing wall panels
- Chapter 18 – Prestressed concrete (§18.12.6)
  - Minimum tie forces for slab systems

Progressive collapse resistance of federal buildings

- ***DOD Unified Facilities Criteria*** **(UFC 4-023-03 Jul 2009)**
  - Classification of buildings by level of protection (VL,L,M,H)
  - Tie forces (VL,L); alternative path (notional element removal), specific local resistance
  - Net upward load on floor system: 1.0D + 0.5L
  - Alternative path analysis: [(0.9D or 1.2D) + 0.5L]* + 0.2W
  - Material-specific strength, deformation limits
- ***General Services Administration*** **(June 2003)**
  - Alternative path (notional element removal)
  - Alternative path analysis: [D + 0.25L]*
  - Demand/Capacity Ratio (DCR) (elastic); Rotation, ductility (inelastic)

*For static analysis, the gravity portion of the load adjacent to and above removed element is multiplied by 2.

BUILDING REGULATIONS – UK

- "…in the event of an accident, the building shall not suffer collapse to an extent disproportionate to cause…"
- Scope: by occupancy class - generally, buildings 5 stories and higher
- Tiered approach
  - Minimum tie forces [e.g., principal structural elements in steel frames shall be capable of resisting tensile forces of 75 kN (17 k)]
  - Damage from notional removal of element limited to 15% of story area or 100 m^2
  - Key elements designed for 34 kPa (5 psi) (*BS 6399 on Loads*)

EUROCODE 1991-1-7:2006
General design and structural load requirements

"A structure shall be designed in such a way that it will not be damaged by events like fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause"

Performance-based engineering
Concept

An engineering approach that is based on

- Specific performance objectives and safety goals
- Probabilistic or deterministic evaluation of hazards
- Quantitative evaluation of design alternatives against performance objectives

but does not prescribe a specific technical solution

Performance-based engineering
ICC Performance Code (2006)

Objective: To provide a desired level of structural performance….

Requirements: Structures shall

…remain stable and not collapse…

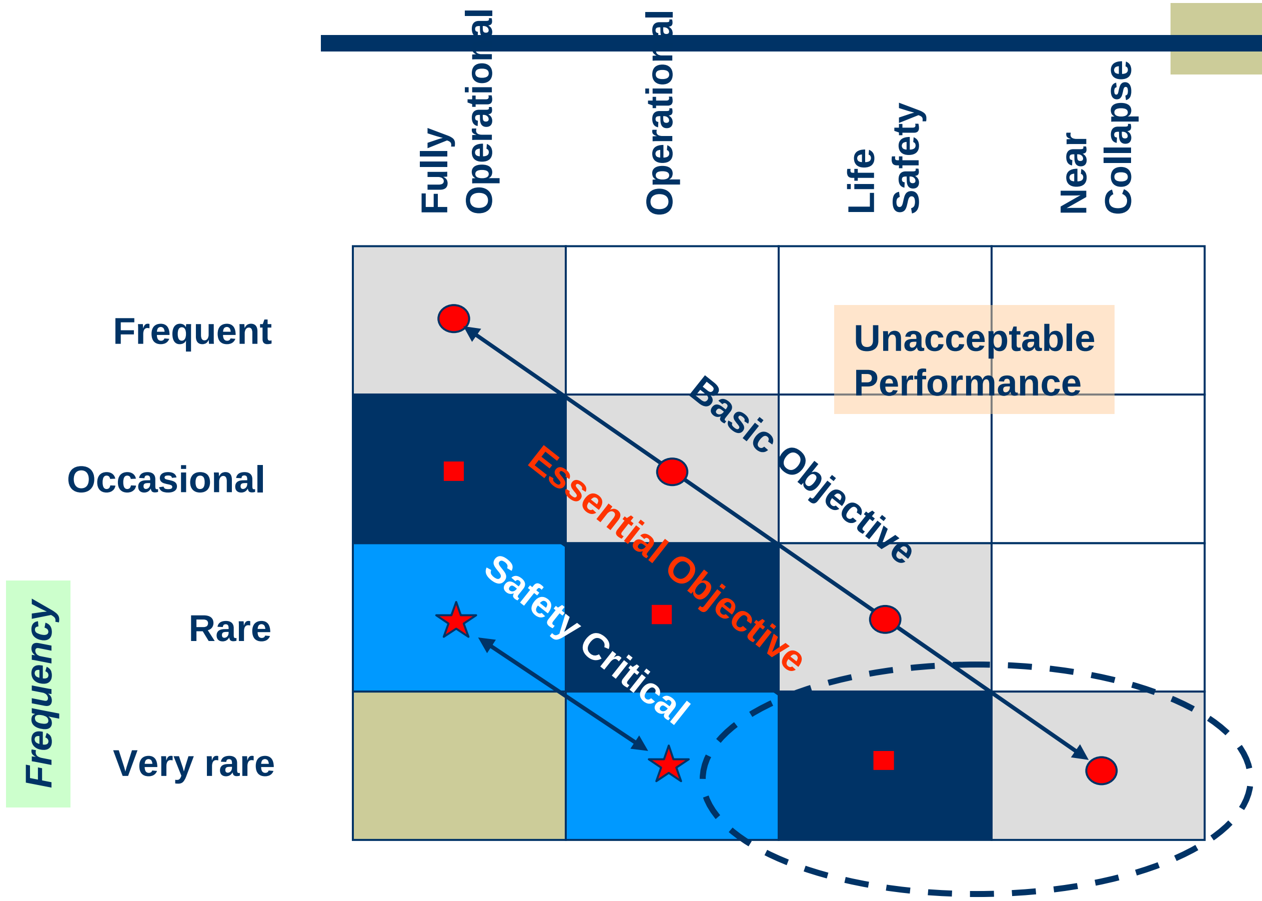
…be designed to sustain local damage…

…shall have low probability of causing loss of amenity…

Design shall consider…effects of **uncertainties**…

Performance objectives

SEAOC Vision 2000



DOE-STD-1020-02

Natural phenomena hazards design and evaluation criteria

Cat.	Performance goal	Hazard (/yr)	Failure prob.(/yr)
1	Occupant safety	2×10^{-3}	1×10^{-3}
2	Occupant safety, cont'd function	1×10^{-3}	5×10^{-4}
3	Occupant safety, cont'd function; hazard confinement	5×10^{-4}	1×10^{-4}
4	Occupant safety; cont'd function; high confidence of hazard confinement	1×10^{-4}	1×10^{-5}

ASCE Standard 43-05, Seismic design for SCC in nuclear facilities is similar.

Improving disproportionate collapse-resistant practices

- Risk assessment and probabilistic formulation of structural criteria
- Characterization of abnormal loads
- Strategies for mitigation
- Implementation in professional practice

Ingredients of risk

- Probability of occurrence
  - Hazard
  - System response
- Consequences
  - Deaths
  - Dollars
  - Downtime
- Context – who is the decision-maker?

Why base engineering decision on risk assessment?

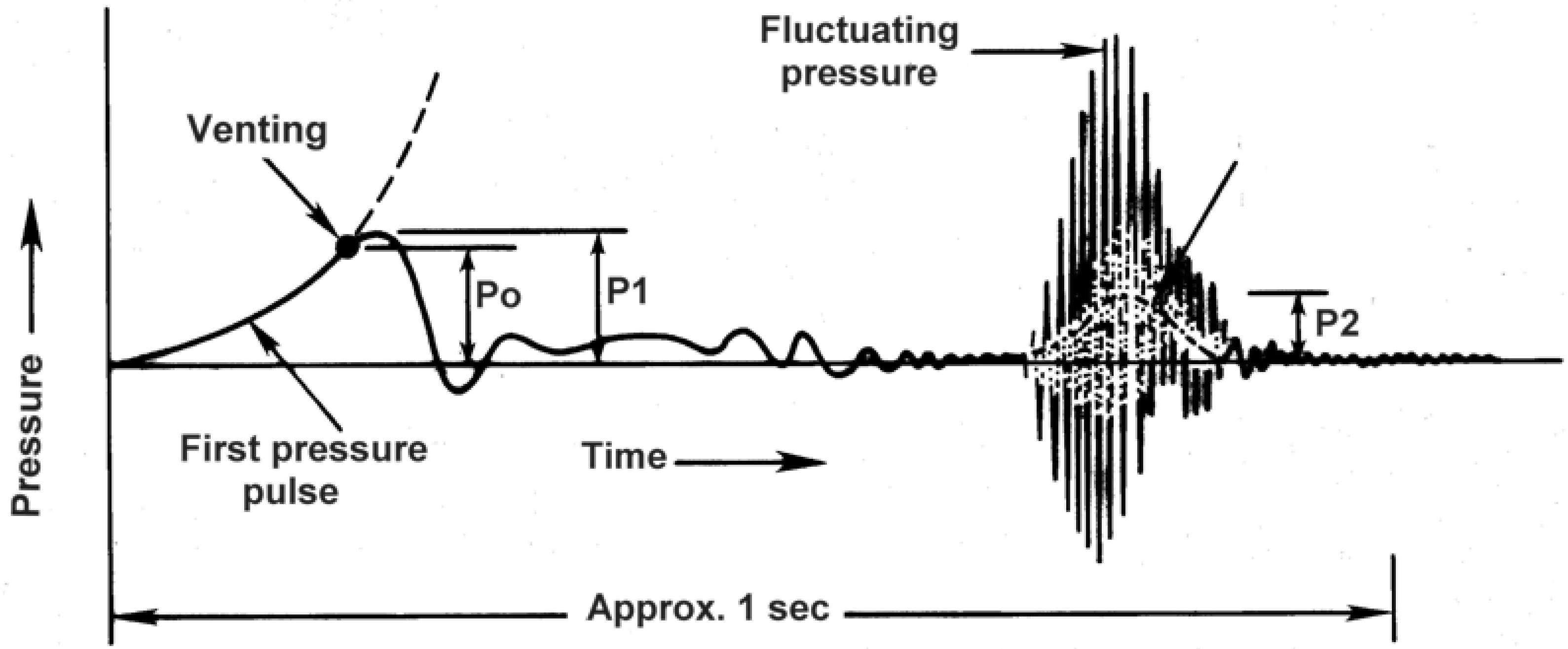
- Uncertainty leads to risk
- Experience is insufficient to define risks due to low-probability, high/consequence events
- Achieve performance consistent with expectations and resources
- Target investments to achieve maximum benefits in risk reduction

Sources and incidence of abnormal loads

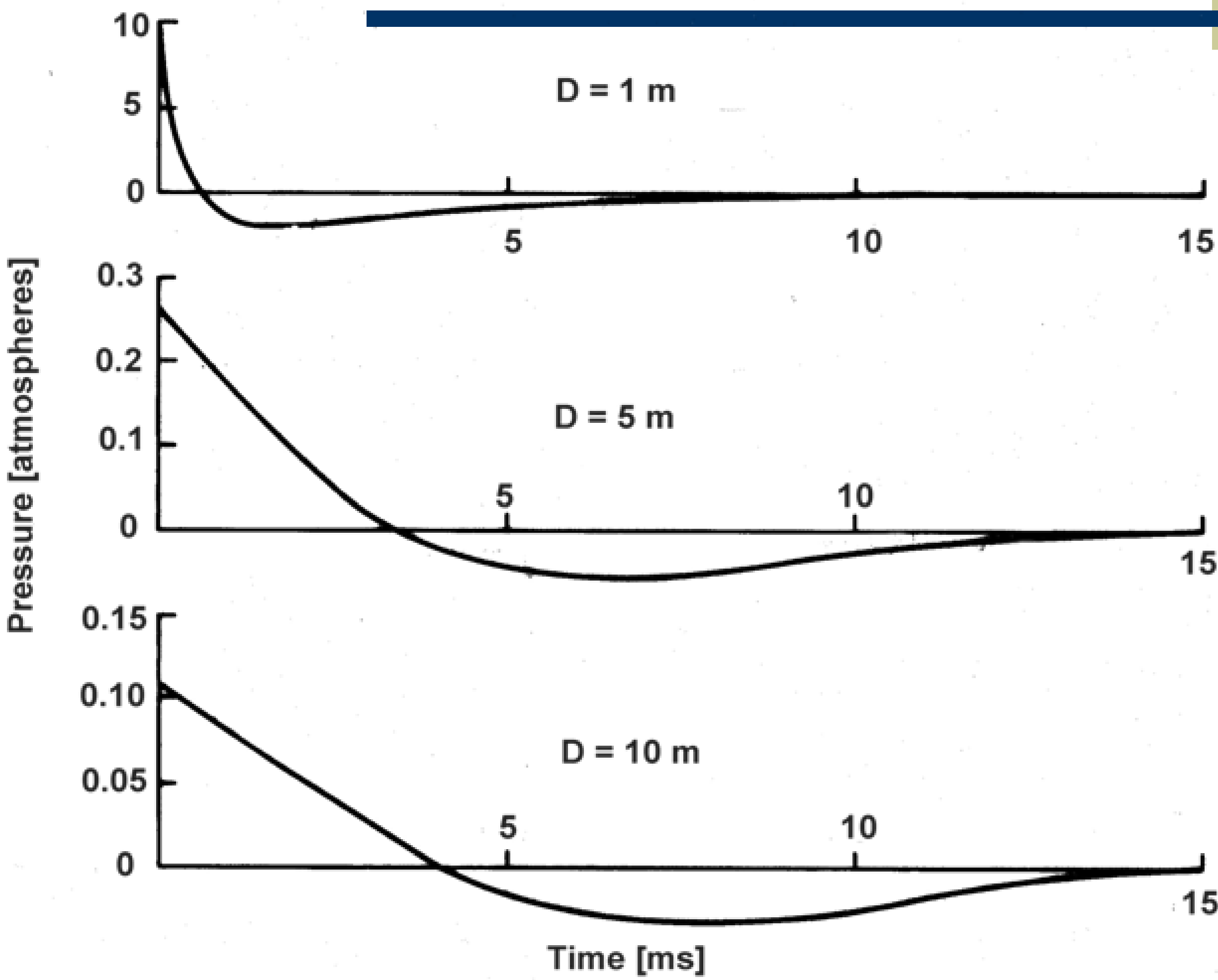
(order-of-magnitude annual frequencies)

- Gas explosions (per dwelling): 2×10^{-5}/yr
- Bomb explosions (per dwelling): 2×10^{-6}/yr
- Vehicular collisions (per building): 6×10^{-4}/yr
- Fully developed fires (per building): $5 \times 10^{-8}/m^2$/yr
- Aircraft impact on building: 1×10^{-8}/yr
- Transportation, storage of hazardous materials: 10^{-6}/yr

Explosion of natural gas in residential compartments

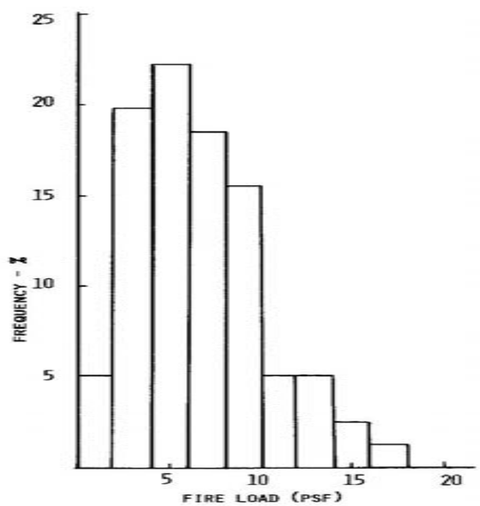


Detonation of explosives

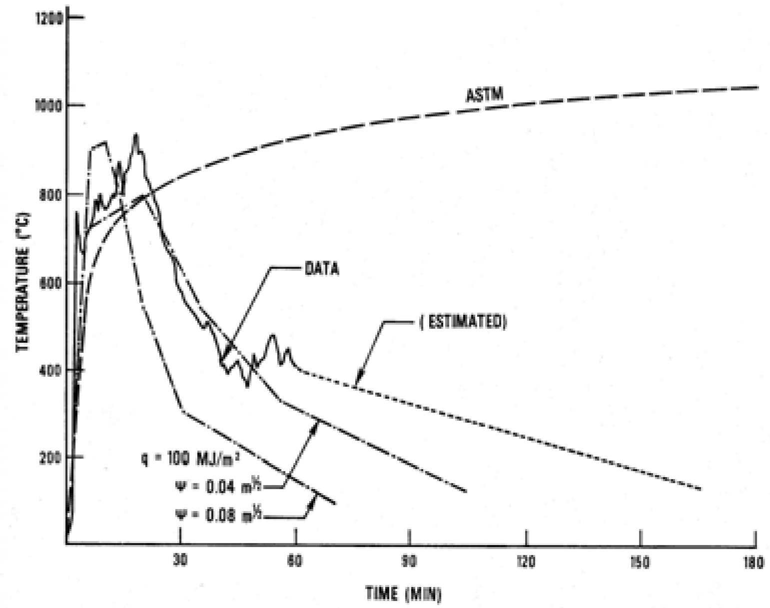


Structural actions due to fire

General and clerical offices



FREQUENCY DISTRIBUTION OF ROOM FIRE LOAD
(N = 419; M = 7.0 PSF; SD = 4.6 PSF)



Deconstructing risk of disproportionate collapse

$$\lambda_{Collapse} = \Sigma_H \Sigma_D \, P(Collapse|D)\, P(D|H)\, \lambda_H$$

- λ_H = mean rate of hazard/yr
- $P(D|H)$ = probability of structural damage, given hazard
- $P(Collapse|D)$ = probability of collapse, given damage

$\lambda_{Collapse} < 10^{-6}$/yr (*de minimis*)

Scenario analysis of disproportionate collapse risk

$P(\text{Collapse}|\text{Scenario}) = \Sigma_D \, P(\text{Collapse}|D) \, P(D|\text{Scenario})$

- $P(D|\text{Scenario})$ = probability of structural damage, given a postulated scenario (e.g., notional element removal)
- $P(\text{Collapse}|D)$ = probability of collapse, given damage

But what is P(Scenario)?

Abnormal loads and disproportionate collapse

Strategies for risk mitigation

- Control occurrence of hazard
- Indirect design
  - Detailing for continuity and ductility
- Direct design
  - Consideration and provision of alternative load paths
  - Provision for structural element resistance to specified abnormal loads (key element design)

Control hazard

$$\lambda_{\text{Collapse}} = \Sigma_H \Sigma_D \, P(\text{Collapse}|D) \, P(D|H) \, \boldsymbol{\lambda_H}$$

- Limit access – siting, stand-off distances, perimeter walls
- Provide protective barriers, shields
- Install control systems
- Minimize fuel loads, hazardous materials

Design key structural elements

$$\lambda_{Collapse} = \Sigma_H \Sigma_D \, P(Collapse|D) \, \mathbf{P(D|H)} \, \lambda_H$$

- Normative abnormal loads to prevent failures of essential structural elements (threat-specific; limited number of key elements)
- Permit development of alternative paths

Design system to absorb damage

$$\lambda_{Collapse} \approx \Sigma_H \, \mathbf{P(Collapse|H)} \, \lambda_H$$

- Stability and robustness
- Ductility and connectivity
- Ability to withstand load reversals
- Compartmentation

General design principles

- Performance objective
  - Life safety
  - Economic losses
- Guidelines to when *specific* progressive collapse provisions should be considered
- Load combinations
- Structural system stability

Risk mitigation by building occupancy

Buildings at substantial risk

Building type and occupancy	Risk mitigation options
High occupant load Key governmental, international institutions Monumental or iconic buildings Critical or essential facilities Incidence rate 10^{-4}/yr or greater ASCE 7-10 Category II, III, IV	Threat and probabilistic risk assessment Engineer structural systems to develop alternative load paths Engineer key elements to preserve system stability Architectural features to allow rapid evacuation and access to first responders Peer review of design concept

NCSEA Proposal to ICC
Section 1614 – Structural integrity

1614.1 Buildings classified as high rise buildings in accordance with Section 404 *and* assigned to Occupancy Category III or IV shall comply with the requirements of this section.

1614.3 Frame structures

- 1614.3.1 Concrete frames – ACI 318 sections 7, 13, 16 and 18
- 1614.3.2 Steel frames – minimum tension capacity in beam connections

1614.4 Bearing walls – minimum longitudinal, transverse, perimeter and vertical ties

Status: Passed; IBC, 2012

ASCE Standard 7-10

1.4 General structural integrity

§1.4 “Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage…”

§1.4.1 Load combinations of integrity loads

§1.4.2 Load path connections (continuous load path)

§1.4.3 Lateral forces (complete lateral force-resisting system)

§1.4.4 Connections to supports

§1.4.5 Anchorage of concrete or masonry walls

ASCE Standard 7-10

2.5 Load combinations for extraordinary events

§2.5.1 "…strength and stability shall be checked to ensure that structures are capable of withstanding the effects of extraordinary (i.e., low-probability) events…"

§2.5.2 Load combinations for extraordinary events

Capacity: (0.9 or 1.2) D + 0.5L or 0.2S

Residual capacity: (0.9 or 1.2) D + $\mathbf{A_k}$ + 0.5L + 0.2S

§2.5.3 Stability shall be provided for the structure as a whole and for each of its elements. Second-order effects shall be considered.

AISC 2010 Specification for Structural Steel Buildings

Appendix 4: Structural design for fire conditions

- Performance objective:

  "Structural components, members and frames shall be designed so as to maintain their load-bearing function throughout the design-basis fire and to satisfy other performance requirements stipulated for the building occupancy."

- Load combinations:

  Gravity: $(0.9 \text{ or } 1.2)D + \mathbf{T} + 0.5L + 0.2S$

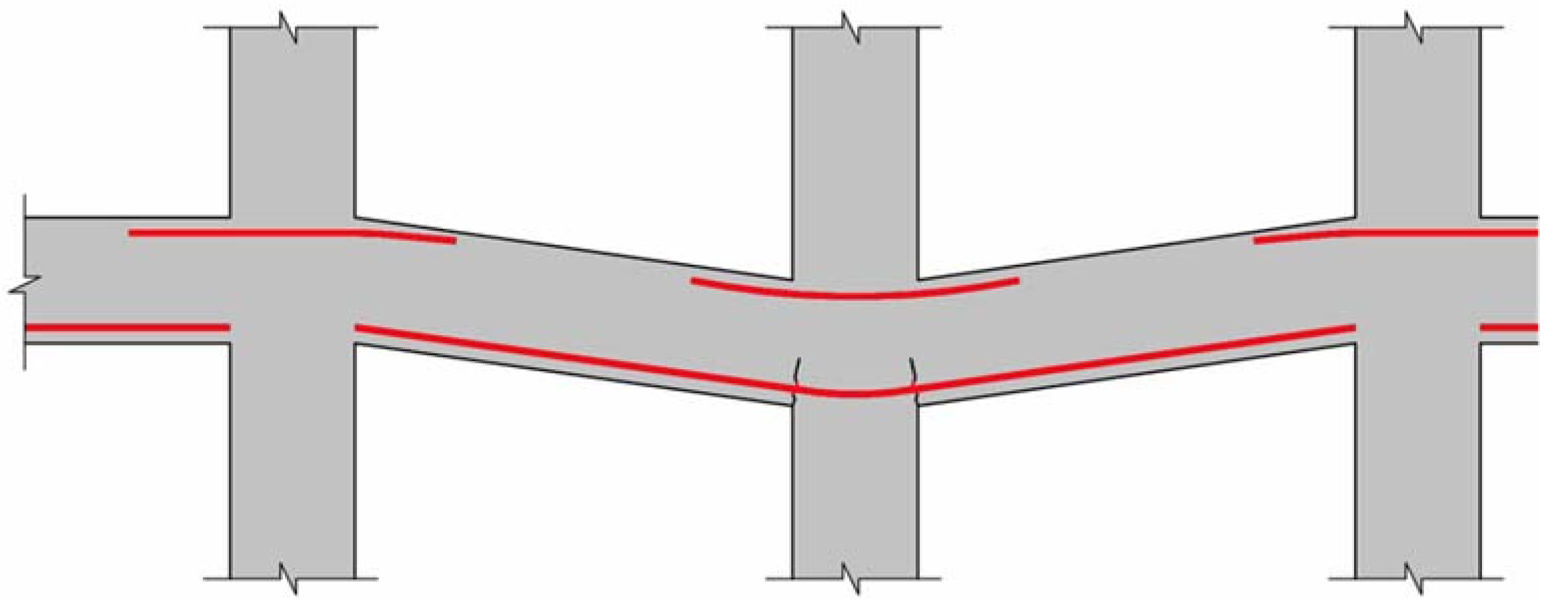
- Stability: Lateral force = $0.002\Sigma P$ at each floor

Specific design requirements

- Indirect design
  - Detailing for continuity and ductility
- Direct design
  - Consideration and provision of alternative load paths
  - Provision for structural element resistance to specified abnormal loads (key element design)

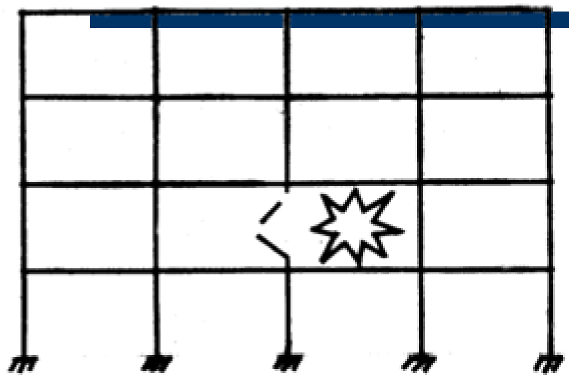
Indirect design

Continuous positive reinforcement

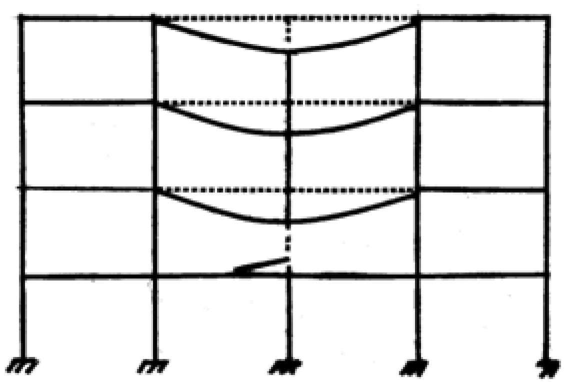


Direct design

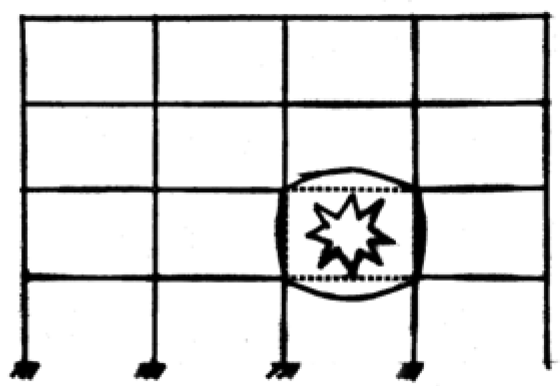
Alternative path and/or local resistance



ABNORMAL LOADING

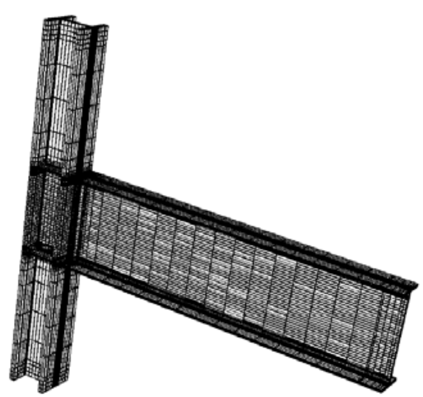


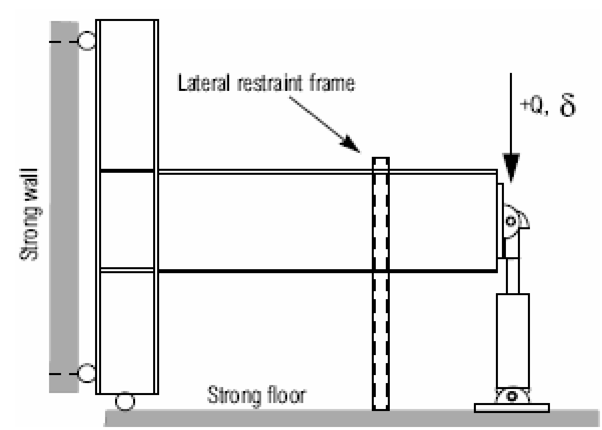
ALTERNATE PATH MECHANISM

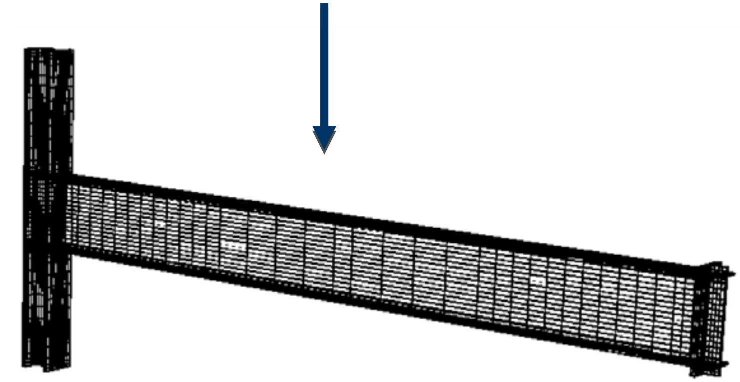


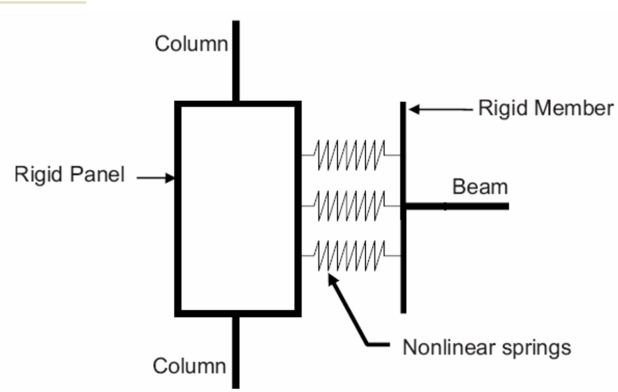
ELEMENTS RESIST LOADING

Ongoing research –models of connection behavior

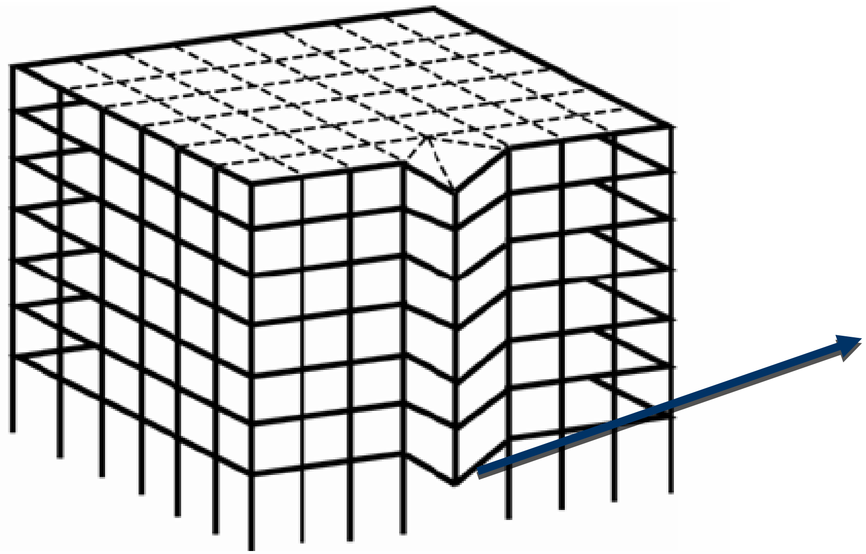


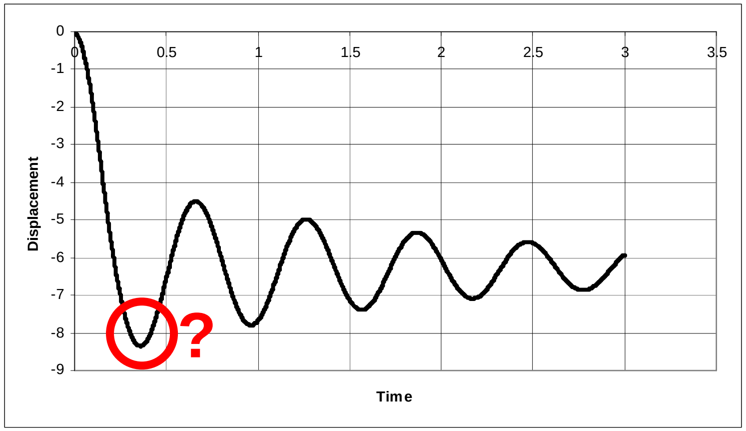




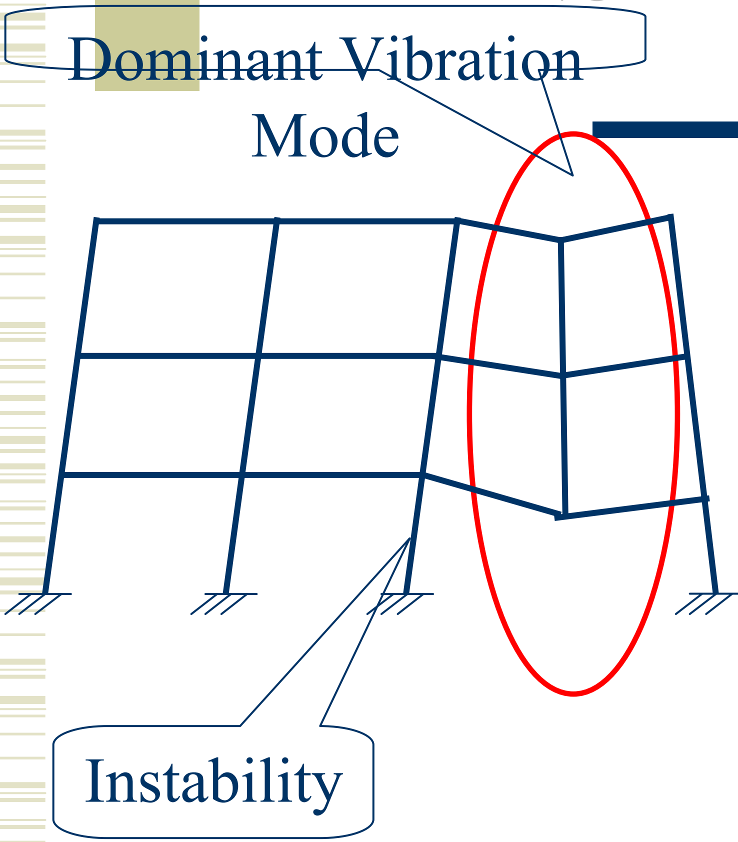


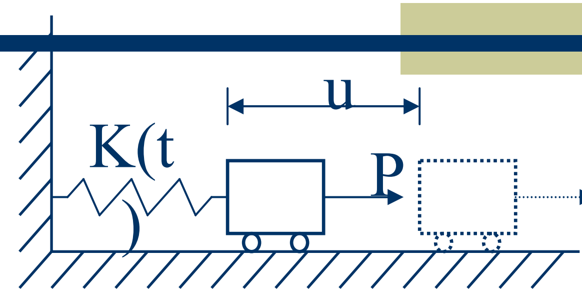
Ongoing research - simplified nonlinear analysis of frames



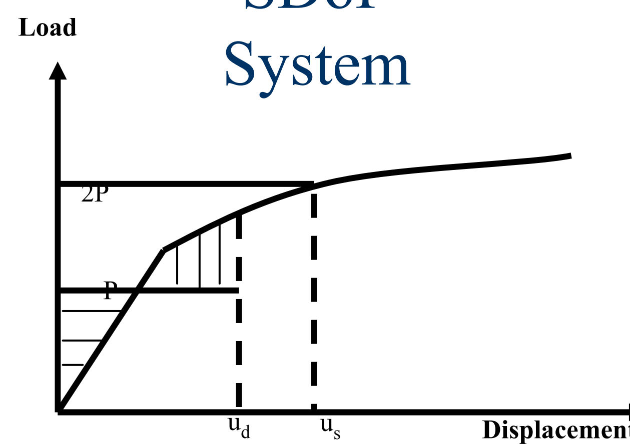


Nonlinear static analysis





SDoF System



Energy Balance

Current professional activities

- National Institute of Standards and Technology
- American Society of Civil Engineers/SEI
- American Institute of Steel Construction
- Joint Committee on Structural Safety

Best practices for reducing the potential for progressive collapse in buildings

NISTIR Report 7396 (February, 2007)

1. Introduction
2. Acceptable risk bases
3. Means of risk reduction
4. Indirect and direct design approaches
5. Practical design to prevent progressive collapse
6. Summary
7. References

Appendix A – Comparison of design standards

Appendix B – Research needs

Appendix C – Case studies

www.bfrl.nist.gov

Concluding remarks

- Good design involves looking beyond code minimums
- Vulnerability assessment may demonstrate added value of engineering disproportionate collapse resistance into a building
- Peer review and code enforcement must play a role
- Competing hazards and risk assessment targets mitigation efforts on effective solutions
- Engineers must communicate the consequences of extreme events on building performance to building developers, architects, and owners

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Thank you!