Strategies for achieving robustness in buildings and mitigating risk of disproportionate collapse

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Progressive (disproportionate) 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

- Abnormal/accidental loads
- Design/construction error
- Occupant misuse

Ronan Point (1968)

Bailey’s Crossroads, VA (1973)

Murrah Federal Building Oklahoma City, OK (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**

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

Motivation

Is there a need for improved design practices?

- New building systems
- Demands for design beyond building code minimums
- Perception of increasing risk for certain facilities
- Public awareness of building performance and demands for safety

Overview

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

Current code provisions addressing progressive 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…"

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

Prescriptive detailing requirements for general structural integrity

- Chapter 7 - Details of reinforcement (§7.13)
  - **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)
  - 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 Jan 2005)**
  - Non threat-specific
  - Tie forces, alternative path (notional element removal)
  - Net upward load on floor system: 1.0D + 0.5L
  - Alternate path: [(0.9D or 1.2D) + 0.5L]* + 0.2W
  - Material-specific strength, deformation limits
- ***General Services Administration* (June 2003)**
  - Non threat-specific
  - Tie forces alternative path (notional element removal)
  - Notional element removal
  - Alternate path: [D + 0.25L]*
  - DCR (elastic); Rotation, ductility (inelastic)

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

NATIONAL BUILDING CODE OF CANADA

§4.1.1.3(1) "Buildings... shall be designed to have sufficient structural capacity and **structural integrity**…"

Commentary C to Part 4

"**Structural integrity** is defined as the ability of the structure to absorb local failure without widespread collapse."

"Key components which can be severely damaged by an accident with a significant probability of occurrence (approximately **10^{-4}/yr** or more) should be identified, and measures taken to ensure adequate structural safety."

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
- Approaches
  - 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 1: General design and structural load requirements

Section 2: "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

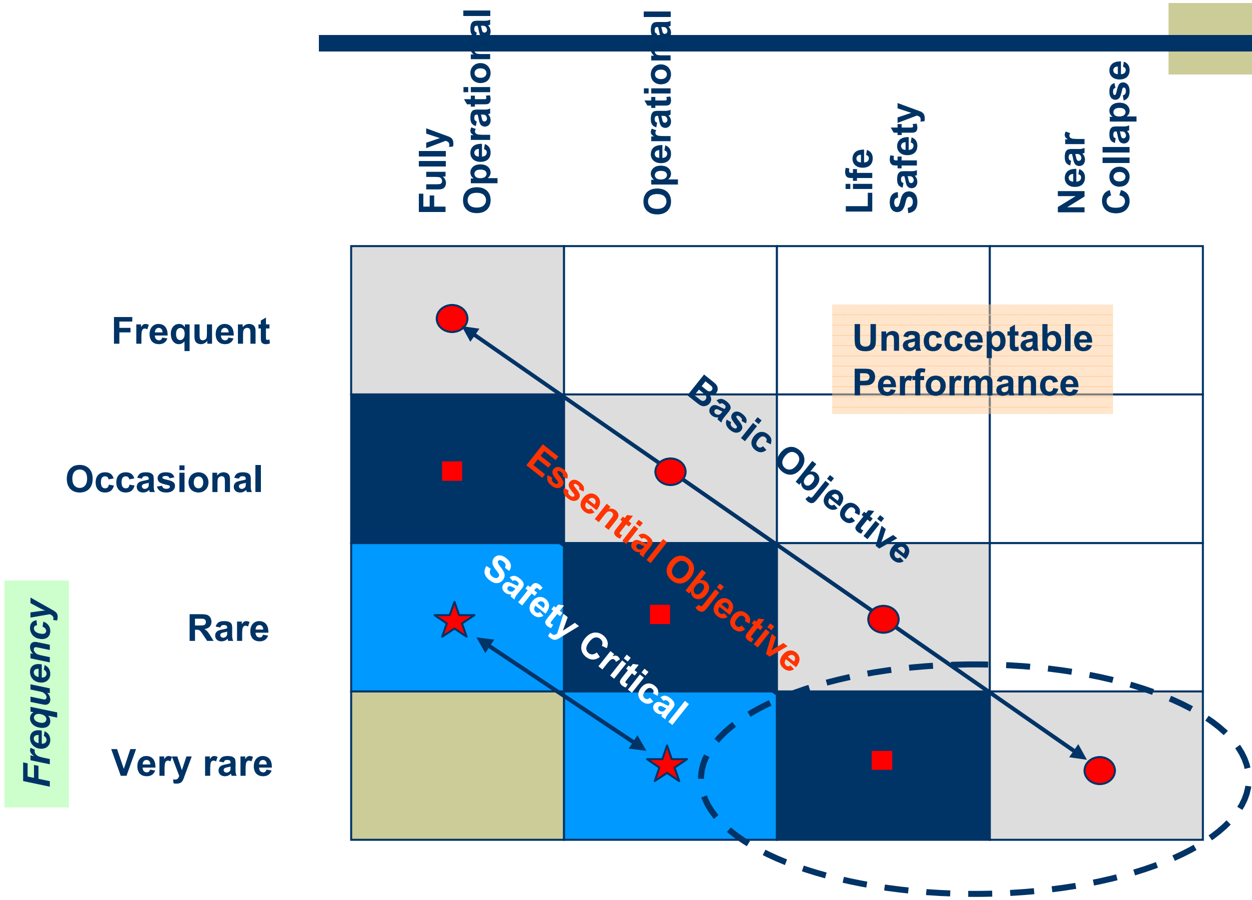
An early performance code

"If a builder has built a house for a man and his work is not strong, and if the house he has built falls in and kills the householder, the builder shall be slain."

Code of Hammurabi (18th Cen. BCE)

Performance objectives

SEAOC Vision 2000



Improving progressive collapse-resistant practices

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

Sources of abnormal loads

- Aircraft impact
- Bomb explosions (esp. vehicle-borne)
- Design/construction error
- Fire
- Gas explosion
- Occupant misuse
- Transportation, storage of hazardous materials
- Vehicular collision

Incidence of abnormal loads

(in order of magnitude)

- 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

Deconstructing risk of progressive 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

Scenario analysis of progressive collapse

P(Collapse|Scenario) = Σ_D P(Collapse|D) P(D|Scenario)

- P(D|Scenario) = probability of structural damage, given a postulated scenario
- P(Collapse|D) = probability of collapse, given damage

But what is P(Scenario) = ???

Control hazard

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

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

Design key structural elements to withstand damage

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

- Normative abnormal loads to prevent failures of essential structural elements
- Permit development of alternative paths

Design system to absorb damage

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

- Redundancy/overall stability
- Ductility and connectivity
- Shear strength
- Ability to withstand load reversals
- Compartmentation

General design principles

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

International Code Council Proposal S5 (2006)

1605.1 General

- The building structure or portion thereof shall be constructed to the building will not suffer collapse as the result of an accident or incident to an extent disproportionate to the cause.

Class 3 buildings

- Shall be provided with horizontal ties, anchorage and vertical ties or shall be designed using alternate load path analysis

Class 4 Buildings

- Comply with all requirements for Class 3
- Perform systematic risk assessment taking into account all normal hazards that may be reasonably foreseen, together with any abnormal hazard

Status: Failed

NCSEA Proposal to ICC 2008

- 421.1 Buildings requiring a risk assessment
  - Buildings more than 420 ft (128 m) in height with occupant load greater than 5,000
  - Buildings and other structures with occupant load greater than 10,000
  - Buildings and other structures deemed to be at higher than normal risk
- 421.2 Risk assessment
- 421.3 Peer review
- 421.4 Mitigation

Status: Pending (Feb 2008)

ASCE Standard 7-05

General structural integrity

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§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…”

§C2.5 Load combinations for extraordinary events

$$\mathbf{(0.9 \text{ or } 1.2)\, D + (0.5L \text{ or } 0.2S) + 0.2W^{*}}$$

$$\mathbf{(0.9 \text{ or } 1.2)\, D + A_k + (0.5L \text{ or } 0.2S \text{ or } 0.2W^{*})}$$

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*In lieu of 0.2W, impose lateral notional force $H = 0.002\, \Sigma P$ at each floor

Specific design requirements

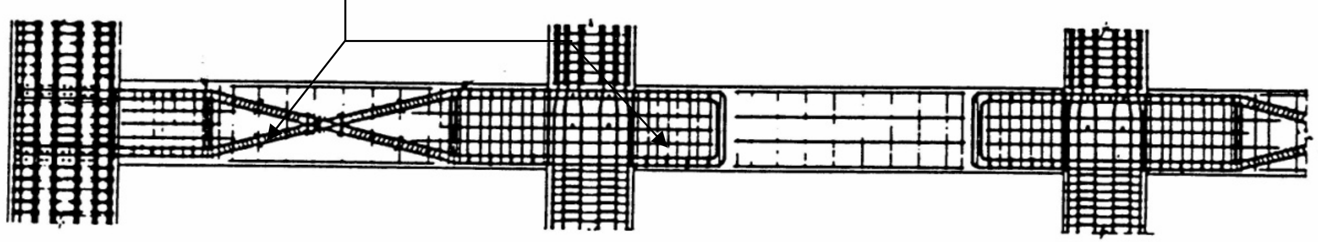
- Indirect design
  - Detailing for continuity and ductility
- Direct design
  - Consideration and provision of alternative load paths
  - Provision for structural element resistance to specified abnormal loads (key element design)

Structural demands from competing hazards

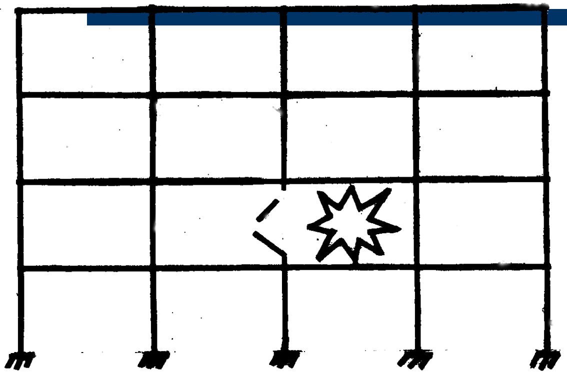
(Courtesy M. Ettouney)

- Different hazards can result in conflicting demands
  - Blast: inversely proportional to mass
  - Seismic: Directly proportional to mass
  - Wind: Independent of mass

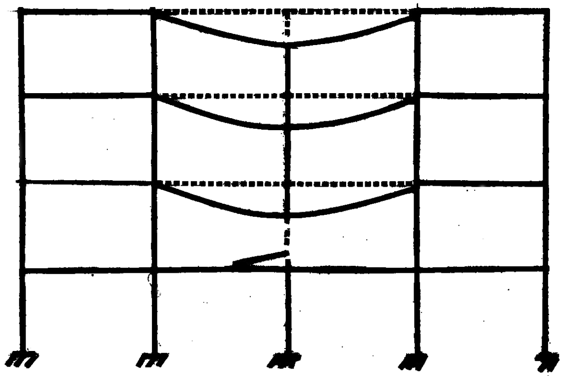
Note lack of ductile detailing at center, where plastic hinges will form during blast events



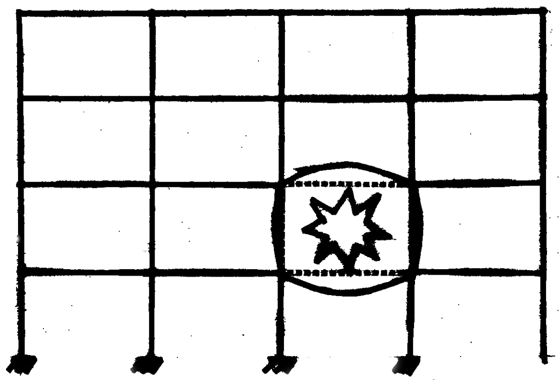
Direct design approaches



ABNORMAL LOADING



ALTERNATE PATH MECHANISM



ELEMENTS RESIST LOADING

Direct design approaches
Structural actions

- Vierendeel
- Catenary
- Arch
- Truss

Concluding remarks

- Good design involves looking beyond code minimums
- Progressive collapse provisions should appear in codes and standards, even though risk to most buildings is low
- Building vulnerability assessment may demonstrate added value of engineering progressive collapse resistance
- Design approaches
  - Advanced engineering analysis
  - Prescriptive or deemed-to-satisfy provisions
- Design review and code enforcement must play a role
- Engineers must communicate the consequences of extreme events on building performance to building developers, architects, and owners