International seminar on Precast Concrete Structures

Accidental Actions and Progressive Collapse

Arnold Van Acker
Progressive collapse

- Ronan Point, London 16 May 1968

Progressive collapse of a part of an apartment building after a gas explosion at the 18th floor.
Modern threats and building design

Steadily higher and more slender precast building structures

Dexia Tower Brussels, 37 storeys

Ellipse building Brussels, 26 storeys
Progressive collapse - timeline

- 1970 PC in UK Building Regulations
- 1972 – PC in ANSI A58.1
- 1975 - NBC Canada
- 1976 - PCI recommends ties
- 1980
- 1983 - U.S. Marine Barracks Lebanon
- 1987 - L’Ambiance Plaza Collapse
- 1989 ACI 318 Structural Integrity provisions
- 1990
- 1995 - Oklahoma City Federal Building
- 1999 – DOD Interim ATFP Standards
- 2000 – GSA Standards for PC
- 2001 – DOD ITG on PC
- 2004 – UFC on PC
- 1960
- 1968 - Ronan Point
- 1970
- 1973 - Skyline Plaza Collapse
- 2000
- 9/11/01 - 1996 - Khobar Towers
Apartment building Maastricht

Progressive collapse of balconies after failure of balcony anchorage at fifth storey
Phenomenon

- A local failure results in the collapse of the whole building or a large part of it.

Scenario of possible effects caused by gas explosion
Types of accidental actions

- **EN 1991-1-7:**
  - Impact by car collision
  - Impact by lift trucks
  - Impact by trains
  - Impact by ships
  - Hare landing od helicopters on roofs

- **fib study**
  - Impact by the accidental action itself
  - Impact by falling debris
  - Impact by transition from the original structure to the alternative structure

- **UFC (USA):**
  - Explosives
Acting forces

Gas explosion

Explosives
Sequence of building damage

1. Blast wave breaks windows. Exterior walls blown in. Columns may be damaged

2. Blast wave forces floors upward

3. Blast wave surrounds structure. Downward pressure on roof. Inward pressure on all sides
Design strategies

The three basic physical protection strategies for buildings to cope with accidental actions are

1) prevention of accidental actions;
2) protective measures to eliminate accidental actions;
3) structural measures preventing progressive collapse.

Influencing factors

a. Type of loading (gas explosion, impact, blast, ...)
b. Magnitude and location accidental loading
c. Structural system
Effect of building shape on air blast impacts

SHAPES THAT DISSIPATE AIR BLAST

SHAPES THAT ACCENTUATE AIR BLAST
Example of lay-out to decrease the risk of progressive collapse
## Categorisation of buildings

### Eurocode 1 part 1-7

<table>
<thead>
<tr>
<th>Class</th>
<th>Building type and occupancy</th>
<th>Action required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Houses not exceeding 4 storey’s. Agricultural buildings. Buildings into which people rarely go, provided no part of the building is closer to another building, or area where people do go, than a distance of 1.5 times the building height.</td>
<td>No additional measures</td>
</tr>
<tr>
<td>2A</td>
<td>5 storey single occupancy houses. Hotels not exceeding 4 storey’s. Flats, apartments and other residential buildings not exceeding 4 storeys. Offices not exceeding 4 storey’s. Industrial buildings not exceeding 3 storey’s. Retailing premises not exceeding 3 storey’s of less than 2000 m² floor area in each storey. Single storey Educational buildings. All buildings not exceeding 2 storeys to which members of the public are admitted and which contain floor areas exceeding 2000 m² at each storey.</td>
<td>Horizontal ties to be provided or effective anchorage of floors to supports.</td>
</tr>
<tr>
<td>2B</td>
<td>Hotels, flats, apartments and other residential buildings greater than 4 storeys but not exceeding 15 storey’s. Educational buildings greater than 1 storey but not exceeding 15 storey’s. Retailing premises greater than 3 storey’s but not exceeding 15 storey’s. Hospitals not exceeding 3 storey’s. Offices greater than 4 storey’s but not exceeding 15 storeys. All buildings to which members of the public are admitted and which contain floor areas exceeding 2000 m² but less than 5000 m² at each storey. Car parking not exceeding 6 storey’s.</td>
<td>Horizontal ties to be provided together with either vertical ties or allowance made for the notional removal of support</td>
</tr>
<tr>
<td>3</td>
<td>All buildings defined above as Class 2A and 2B that exceed the limits on area and/or number of storey’s. All buildings, containing hazardous substances and/or processes. Grandstands accommodating more than 5000 spectators.</td>
<td>Specific consideration to take account of the likely hazards.</td>
</tr>
</tbody>
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Design concepts

• Design for prevention of progressive collapse

a. Indirect method
   Minimum tie provisions

b. Alternative load path method
   A critical element is removed from the structure, due to an accidental loading, and the structure is required to redistribute the gravity loads to the remaining undamaged structural elements.

c. Specific load resistance method
   All critical gravity load-bearing members should be designed and detailed to be resistant to a postulated accidental loading
a) Indirect method

- **Tie force approach**

A weak point in the direct approach method is that the prescriptive tying force requirements neglect ductility issues and relies primarily on bending, cantilever action and compressive arching rather than tensile catenary action for enhanced structural robustness.
b) Alternative load path method

- The alternative load path method implies that:
  - the local damage must be bridged by an alternative load-bearing system: catenary action, cantilevering action, bridging action, suspension. The transition to this system is associated with dynamic effects that should be considered.
  - the structure in its whole must shown to be stable with the local damage under the relevant load combination
Primary local damage

- **Skeletal structures**

Example of location of columns for design removal
Primary local damage

- Load bearing wall structures

Extent of assumed wall damage under accidental actions
Primary local damage

- Floors and roofs

Detailing of hollow core floor support connections to avoid damaged floor falling from support
Mechanisms for alternative load path

Alternative means of protection against progressive collapse in skeletal structures
Catenary action

- Flooded box culvert near Bari, Italy
Membrane action

The by impact damaged roof beam remains in place through the membrane action of the steel deck and is still able to carry the roof structure through partial force transfer in the top and bottom flanges.
Catenary action

Difference between a monolithic and a precast structure

- **Cast in-situ**
  - Floor units are separating
  - Tie reinforcement

- **Precast**
  - Floor beams fall from the supporting corbels
  - Large cracks between slab units and floor beams
  - Large cracks in the floor units due to torsion
Catenary action

- **Suspension**

Depending on the rigidity of the frame structure above the lost column, a part of the column load could also be transferred by the vertical tie reinforcement in the columns above the removed column. When this is not the case, each one of the above floor structures will have to take up his part of the excessive load.
Catenary action

Loss of a corner column

The floor units are separating from each other because of the large deformation and torsion.

Cast in-situ

Precast
Beam & cantilever action

- Wall panel structures

Individual cantilevers

Composite cantilevers

Alternative mechanisms for alternative load path in wall frame structures
Force transfer mechanisms

1. Cantilever action

2. Strut and tie action

3. Cable action

\[ R_{AH} = \omega \left[ G \cdot \gamma_G + \psi_1 \cdot \psi_2 \cdot Q \cdot \gamma_Q \right] \cdot \frac{L}{4h} \]
Alternative load path method - example

- Failure of intermediate façade column

Suspension via column to above structure

Cantilever action action of floor beam

Cable action of floor beam

$R_H$
Alternative solutions

Floor spans in opposite directions
Floor spans in same direction

Diagonal restraint
Wall panels
Diagonal ties
Rigid cornice

Structural systems able to take up vertical loading
Specific load resistance method

- Design of key elements

Where the effect of the removal of any single column or beam carrying a column would result in collapse of any area greater than 100 m² or 15% of the area of the storey, that member should be designed as a key element. Key elements should be designed for an accidental loading not less than 34 kN/m², or the notional load imposed by authorities. Any other member or other structural component which provides lateral restraint vital to the stability of a key element should itself also be designed as a key element for the same accidental loading.
Specific load resistance method

- Practical example wall panel structure

Alternative (a): cross-wall system with key elements at the edge
Specific load resistance method

- Practical example

Alternative (b): cross-wall system with stiffening columns and wall
Detailing

- Ties for catenary action

**Edge beam**

**Intermediate beam**

Tie provisions in skeletal tower buildings
Detailing

- Realisation peripheral ties

Tie provisions in skeletal tower building 26 floors
Detailing

- Provisions for peripheral ties

Sleeves in columns for passage of ties
Detailing

- Column to column connections

Example of column-to-column connection with good strength, anchorage and ductility characteristics to withstand abnormal loads from accidental actions.
Detailing

- **Beam to floor connections**

Examples of transversal tie reinforcements in floor-beam connections

- (a) less good solution
- (b) good solution
Detailing

- Wall to wall and wall to floor connections

Examples of wall-to-wall-to-floor connections
Detailing

- **Wall to floor connections**

Typical section through load bearing edge wall
Detailing

- Wall to floor connection

Typical section through internal load bearing wall
Detailing

• Stairs

Support beam for floor slab

Support beams for half-landing and landing

(a) Reinforcement in stair scarf joint

(b) Intermittent scarf joint

Staircase to landing joint details
Detailing

- Ineffective positioning of tie bars

Transversal tie bars should be inside projecting loops
fib Guide to good practice

1. Terms and definitions
2. General
3. Actions and properties for good structural response
4. Strategies to cope with accidental actions
5. Design methods to prevent progressive collapse
6. Detailing
7. Calculation examples