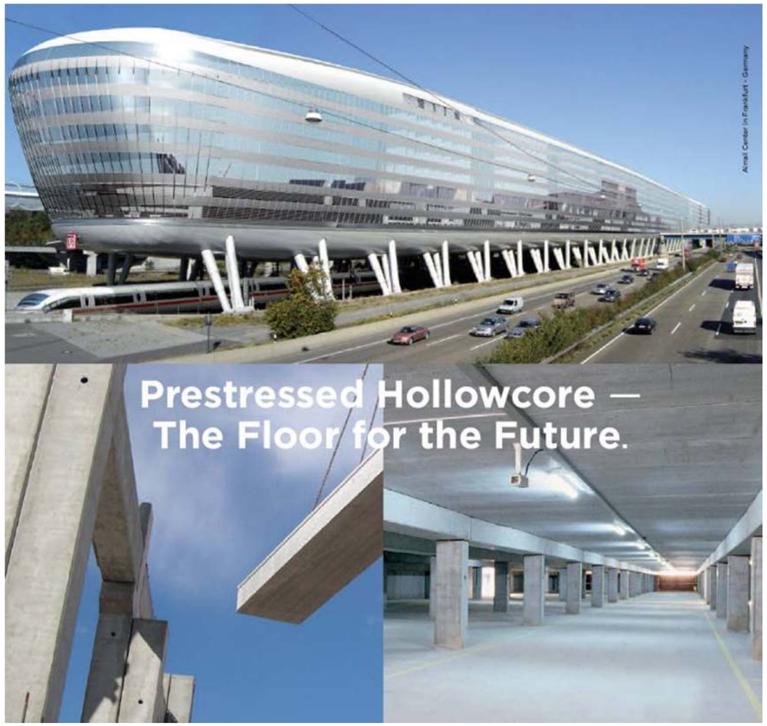
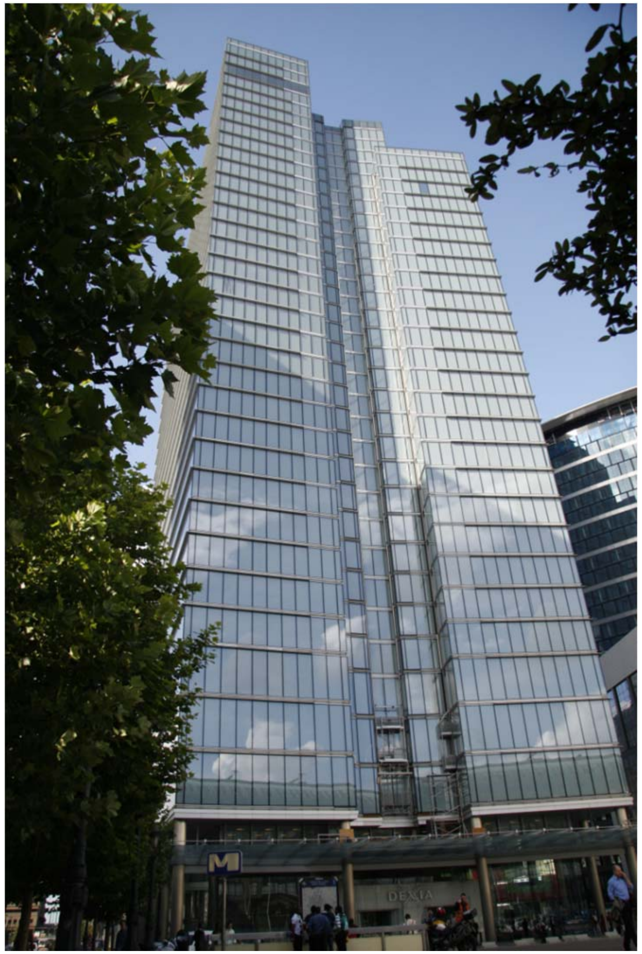
INTERNATIONAL PRESTRESSED
HOLLOWCORE ASSOCIATION

Design of Precast Concrete Structures Against Accidental Actions

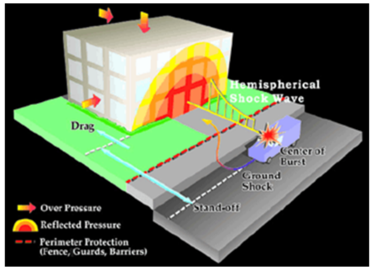


Arnold Van Acker
fib Commission on Prefabrication

Modern threats and building design



Dexia Tower Brussels, 37 storeys



Ellipse building Brussels, 26 storeys

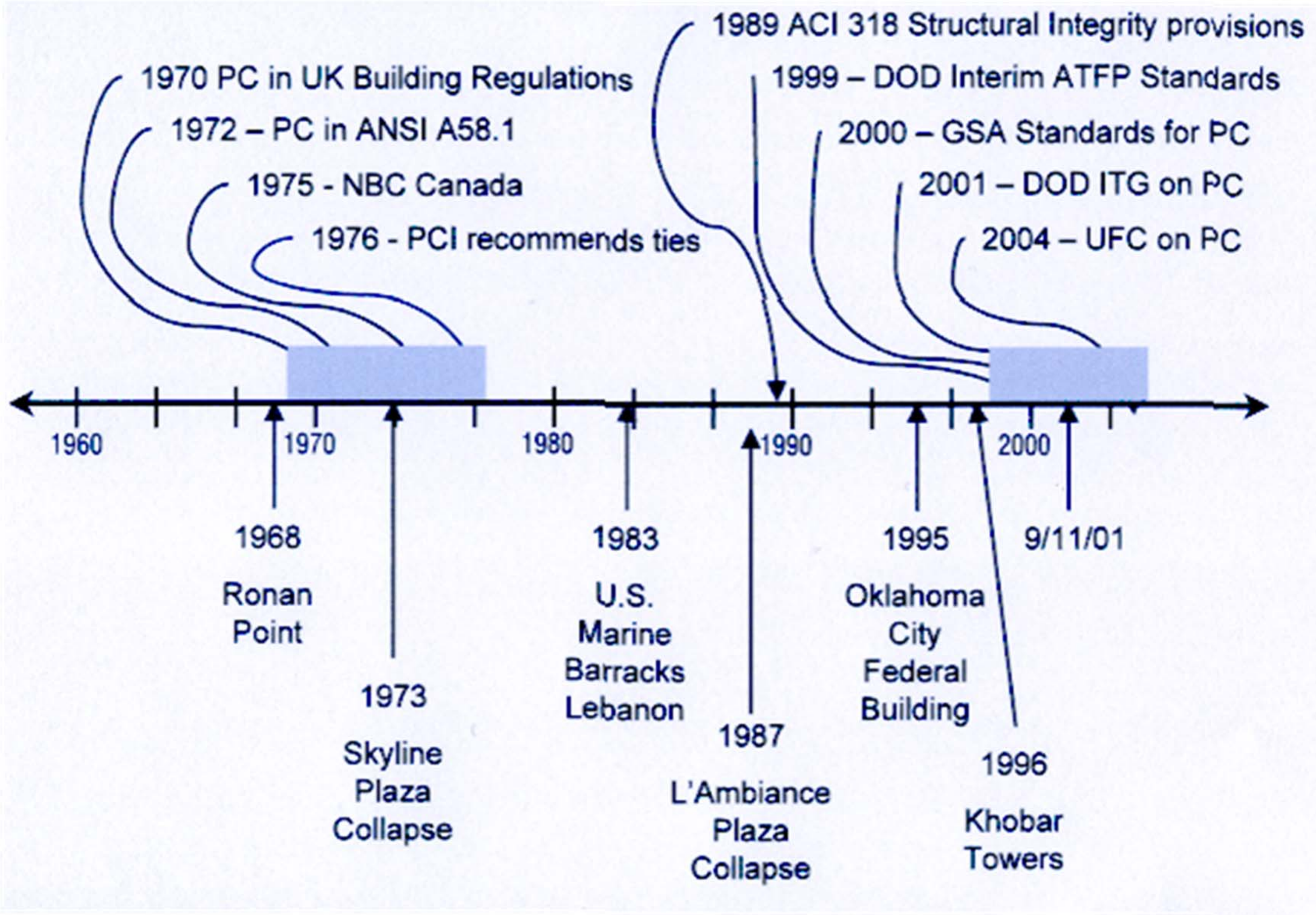
Steadily higher and more slender precast building structures

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

Progressive collapse - timeline

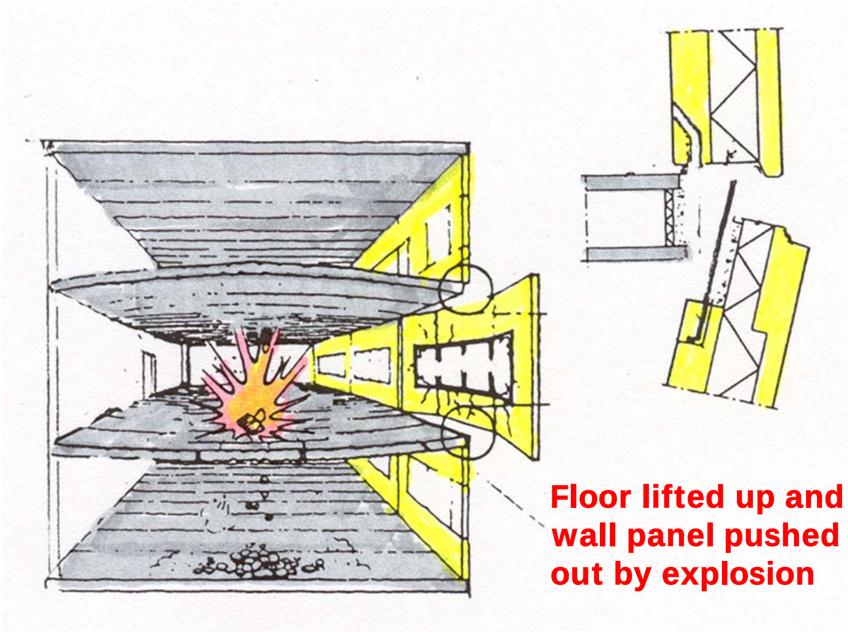


Apartment building Maastricht

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.

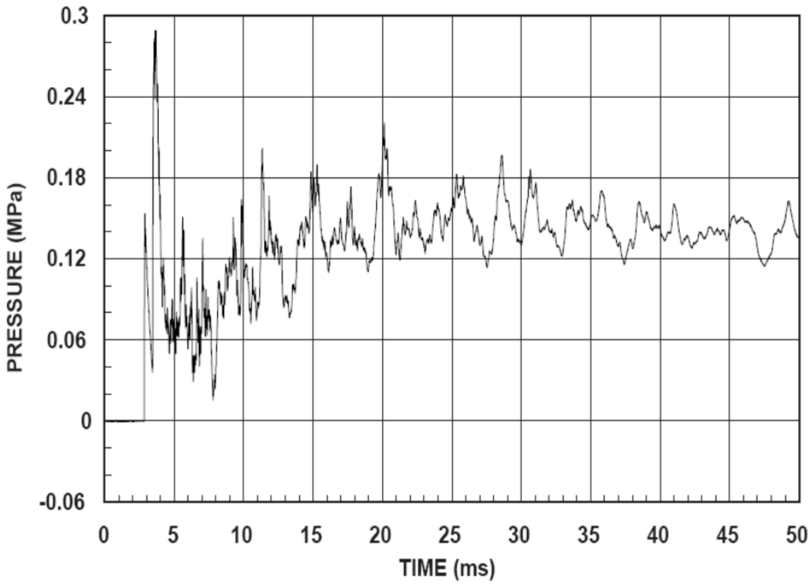


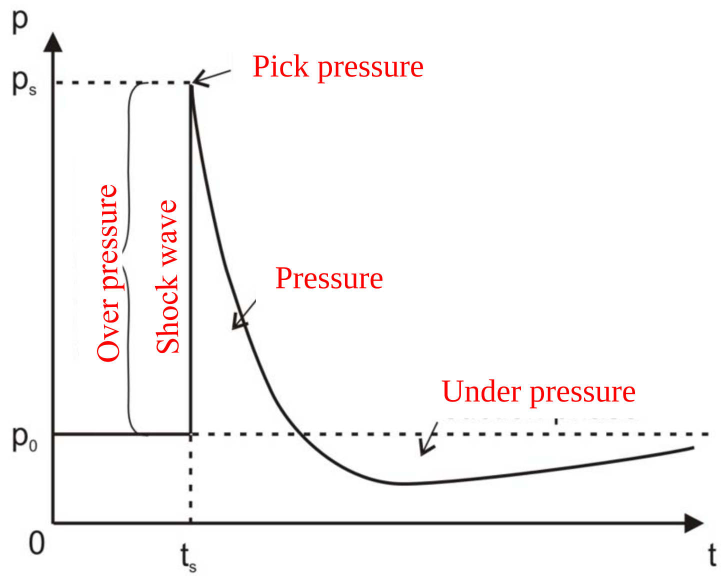
Scenario of possible effects caused by gas explosion

Types of accidental actions

- EN 1991-1-7:
  - Impact by car collision
  - Impact by lift trucks
  - Impact by trains
  - Impact by ships
  - Hard 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

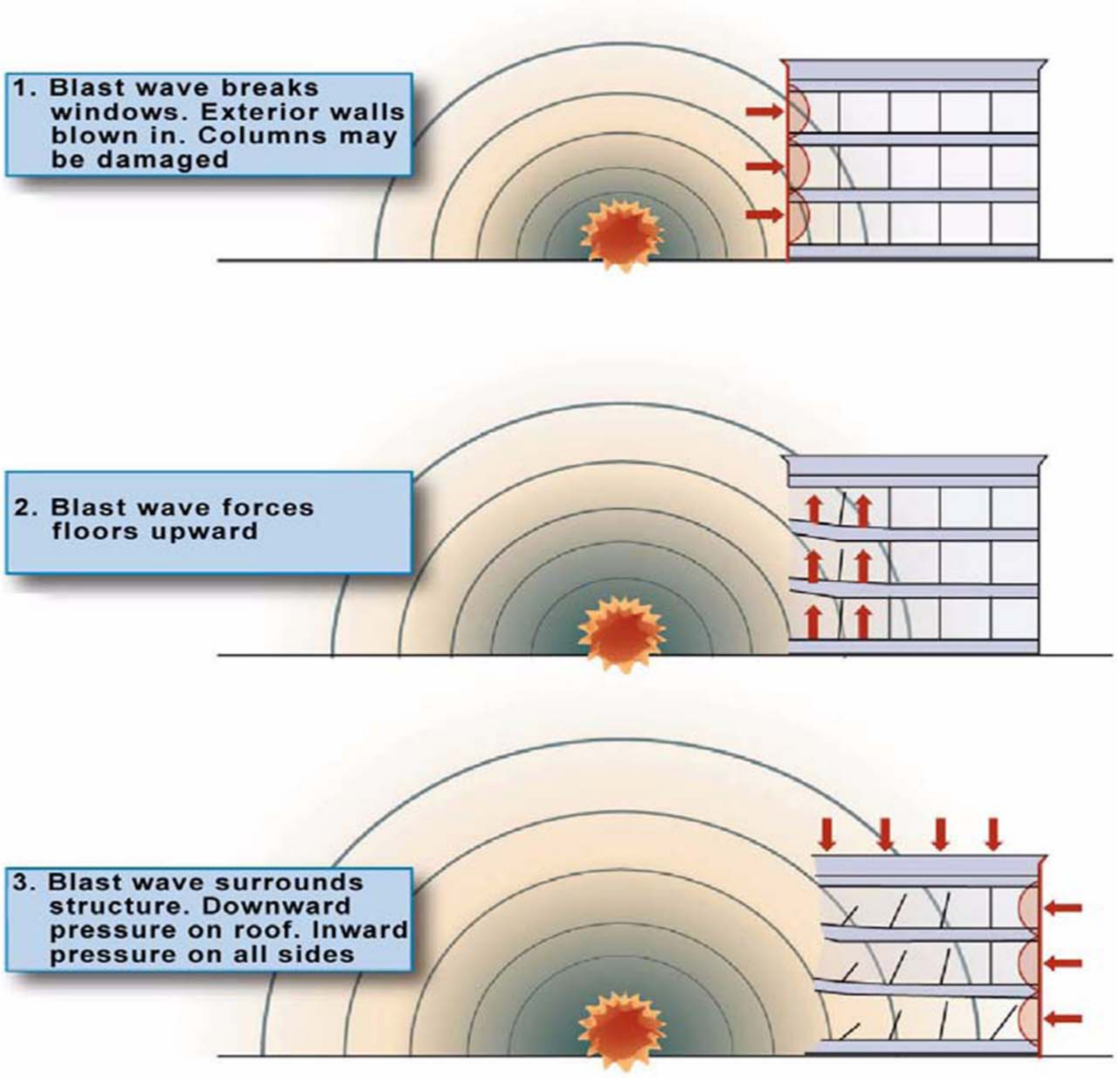




Gas explosion

Explosives

Sequence of building damage



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Design strategies

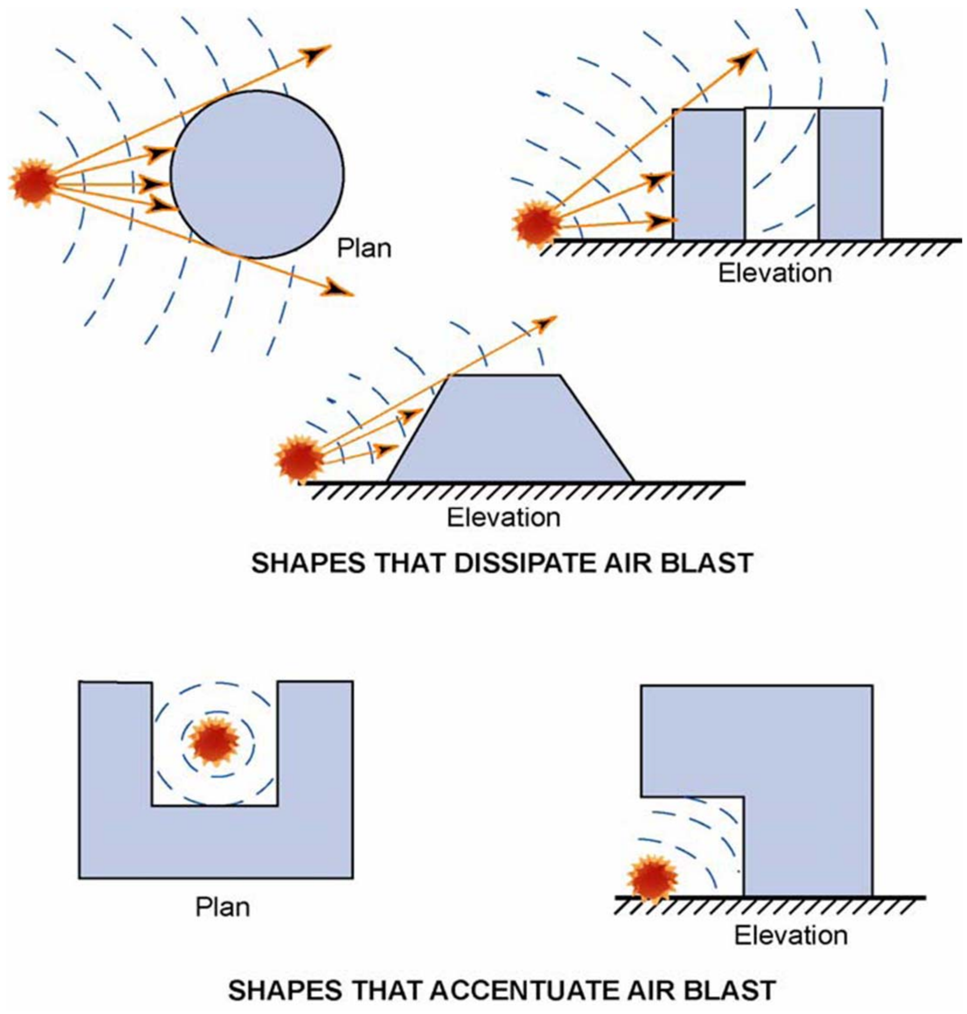
- The three basic physical protection strategies for buildings to cope with accidental actions are

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

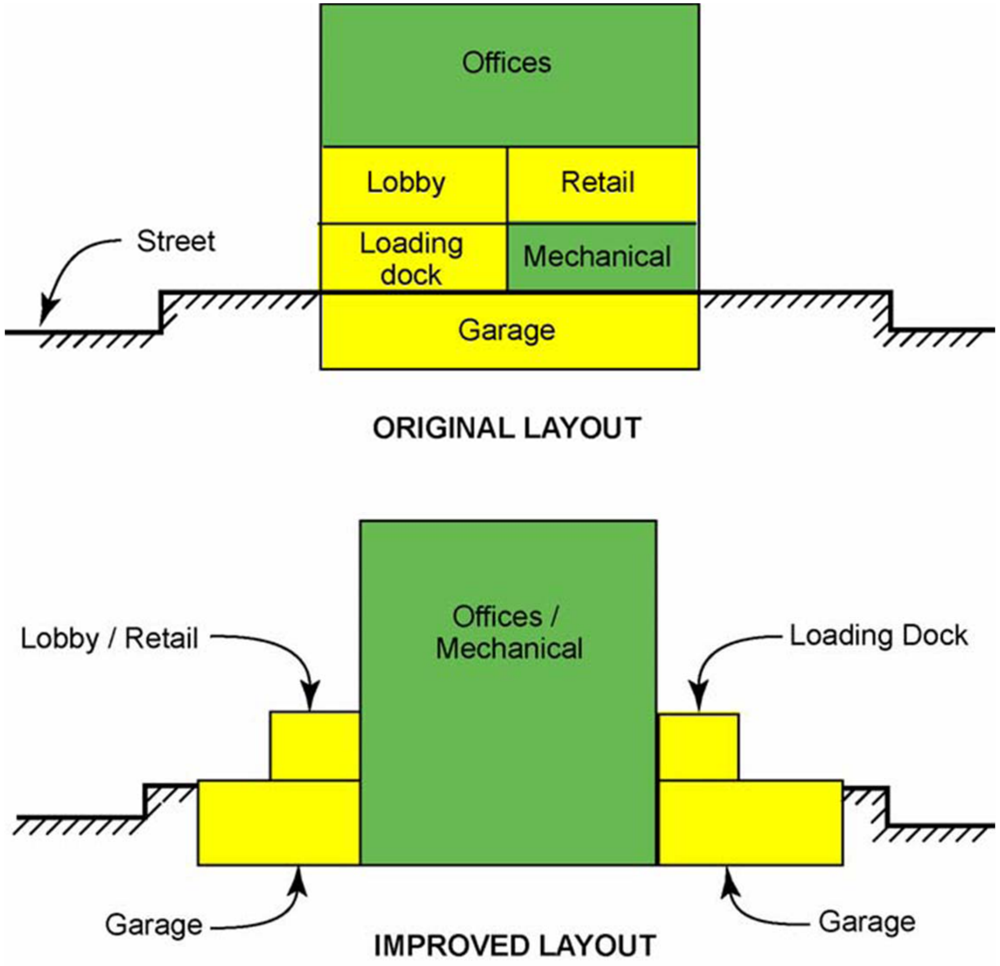
Influencing factors

  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



Example of lay-out to decrease the risk of progressive collapse



Categorisation of buildings

Eurocode 1 part 1-7

Class	Building type and occupancy	Action required
1	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.	No additional measures
2A	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 m^2 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 m^2 at each storey.	Horizontal ties to be provided or effective anchorage of floors to supports.
2B	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 m^2 but less than 5000 m^2 at each storey. Car parking not exceeding 6 storey's.	Horizontal ties to be provided together with either vertical ties or allowance made for the notional removal of support
3	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.	Specific consideration to take account of the likely hazards.

Design concepts

- Design for prevention of progressive collapse

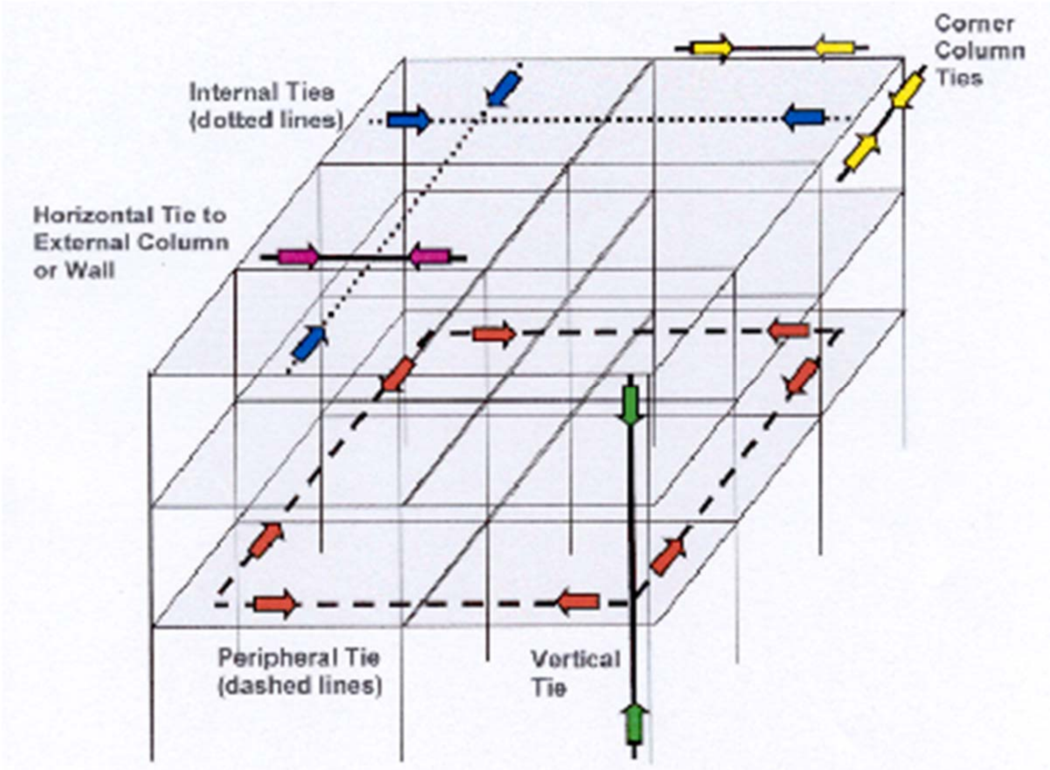
  a. Indirect method
  Minimum tie provisions

  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.

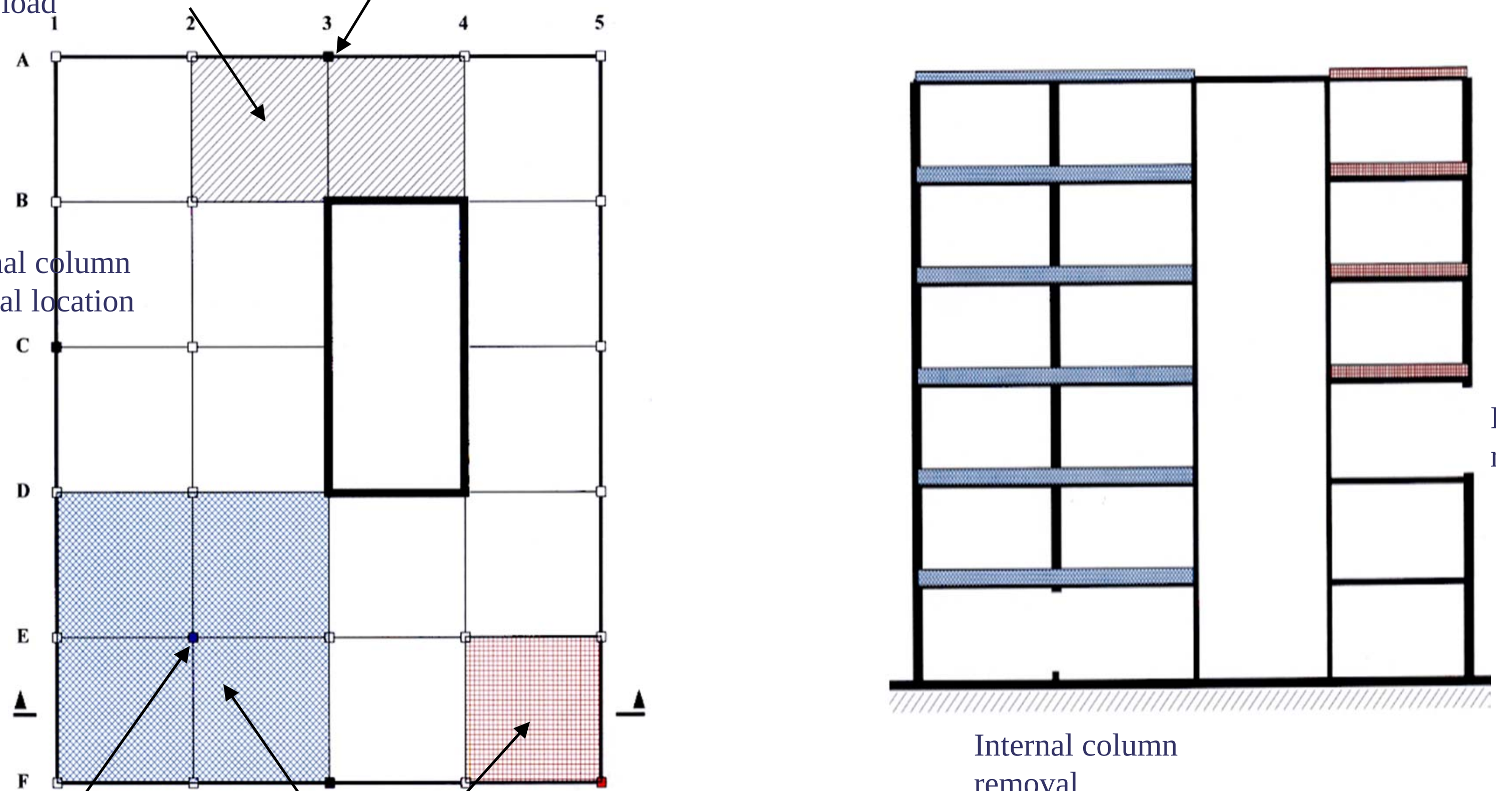
b) Alternative load path method

- 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

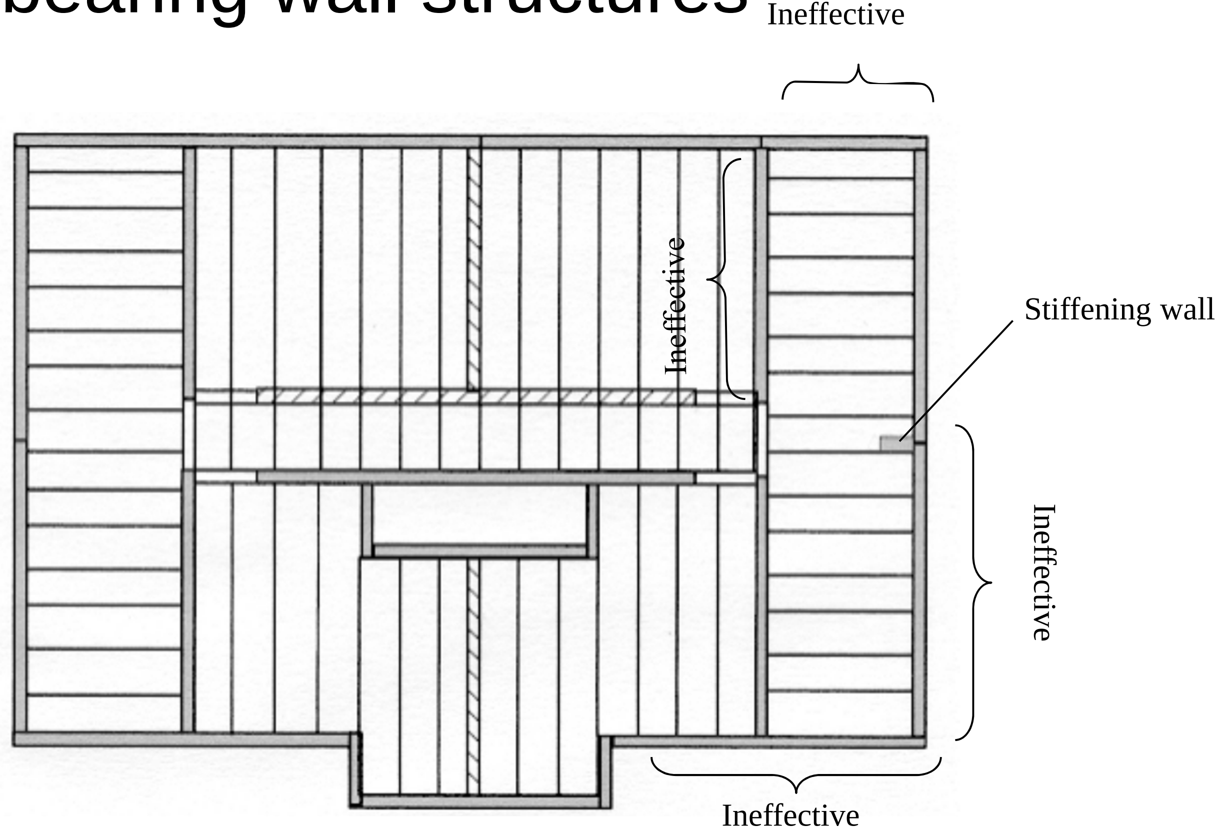
- Skeletal structures



Example of location of columns for design removal

Primary local damage

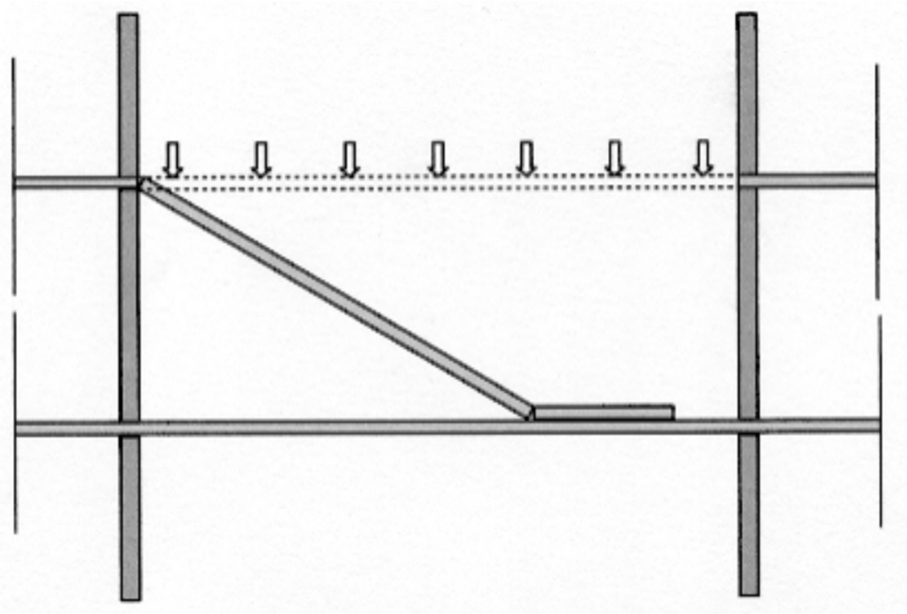
- Load bearing wall structures

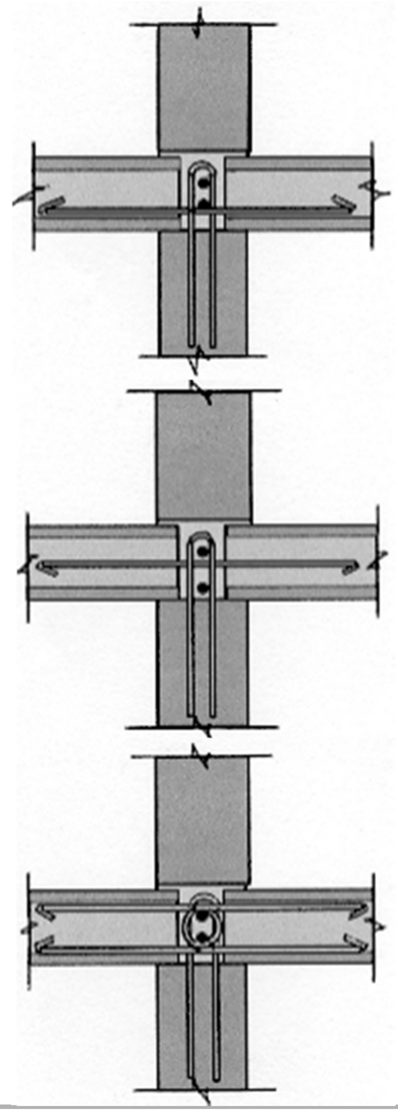


Extent of assumed wall damage under accidental actions

Primary local damage

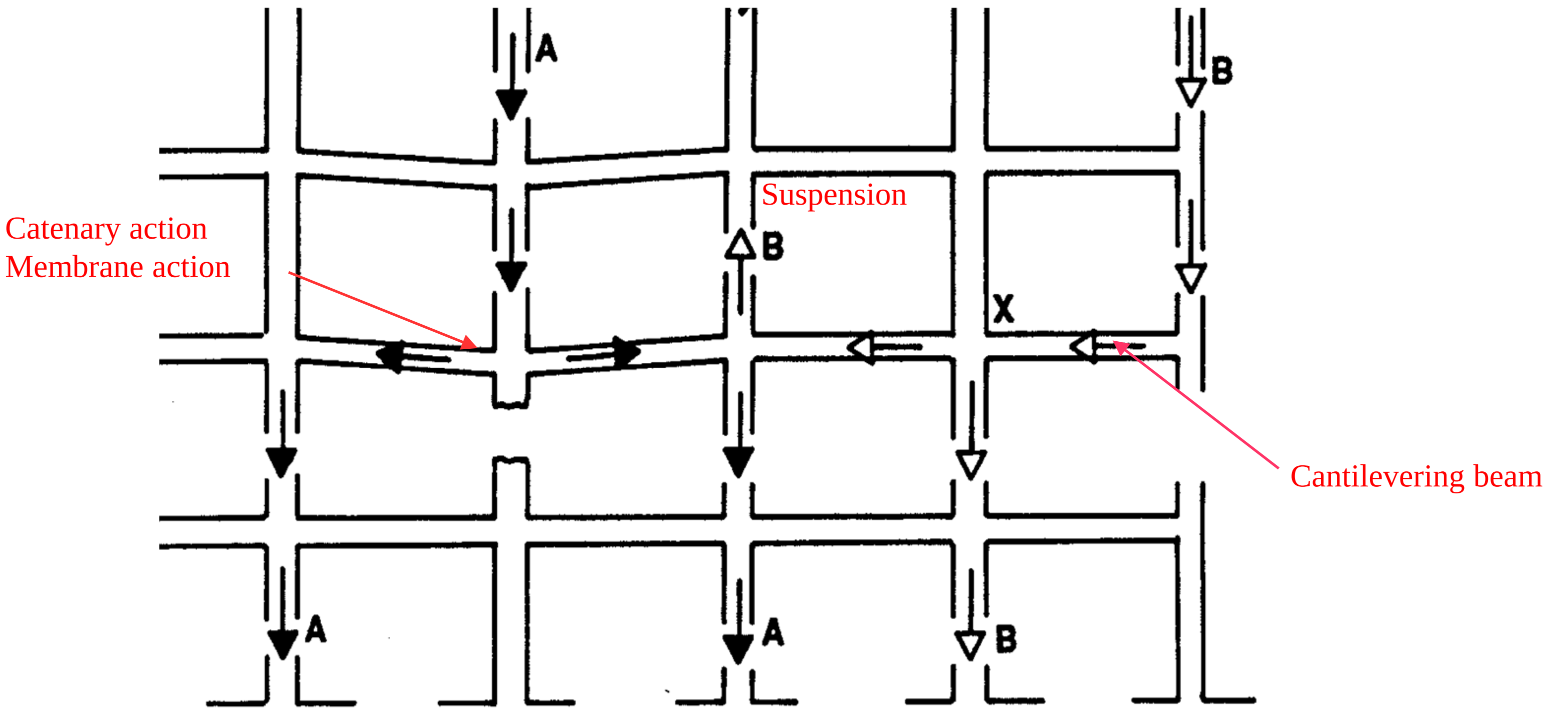
- Floors and roofs





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

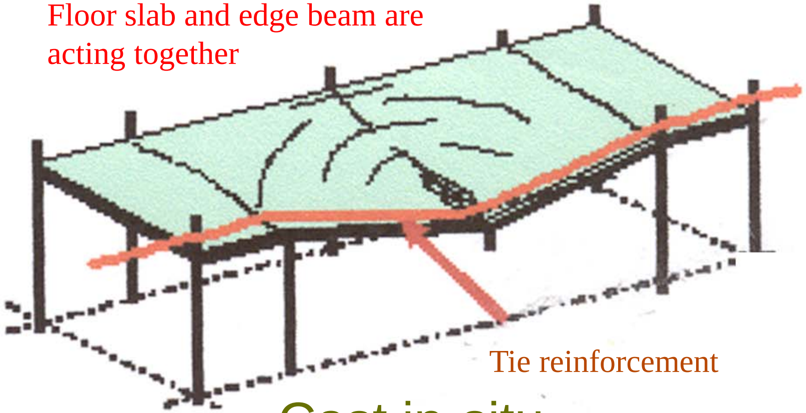
- Flooded box culvert near Bari, Italy

Membrane action

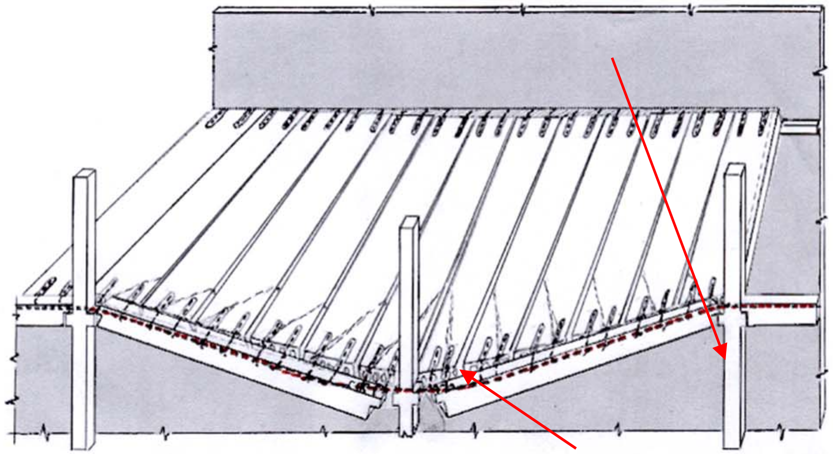
The by impact damaged roof beam remains in place through the membrane action of the steel deck and is still able to carry the roof structure through partial force transfer in the top and bottom flanges.

Catenary action

- Difference between a monolithic and a precast structure



Cast in-situ

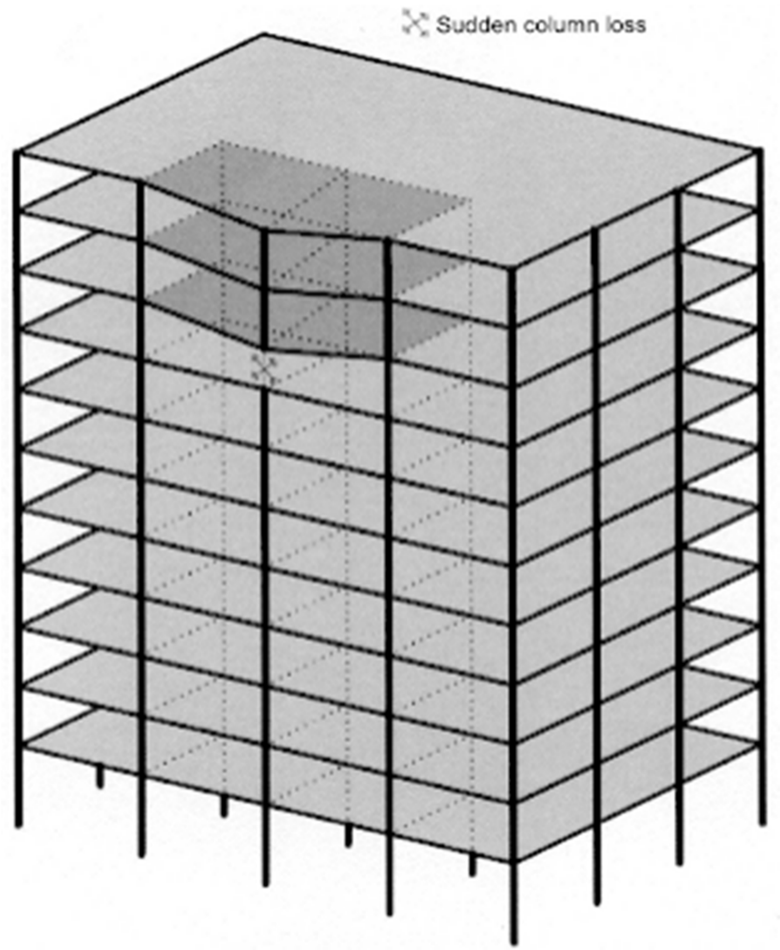


Precast

Catenary action

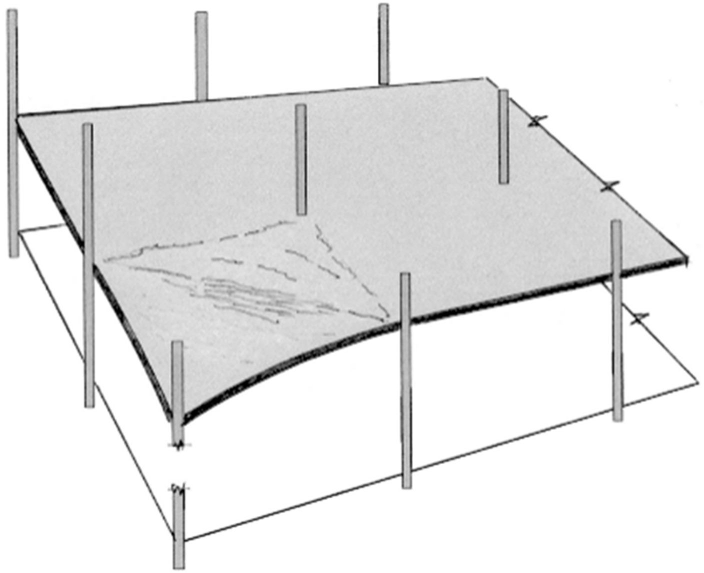
- Suspension

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.

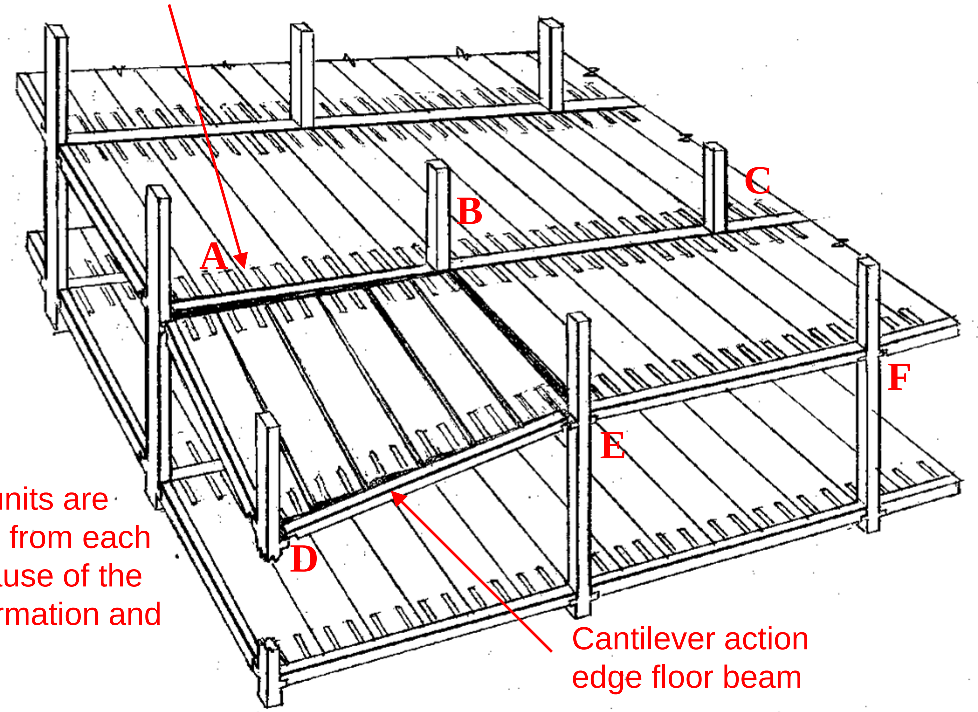


Catenary action

- Loss of a corner column



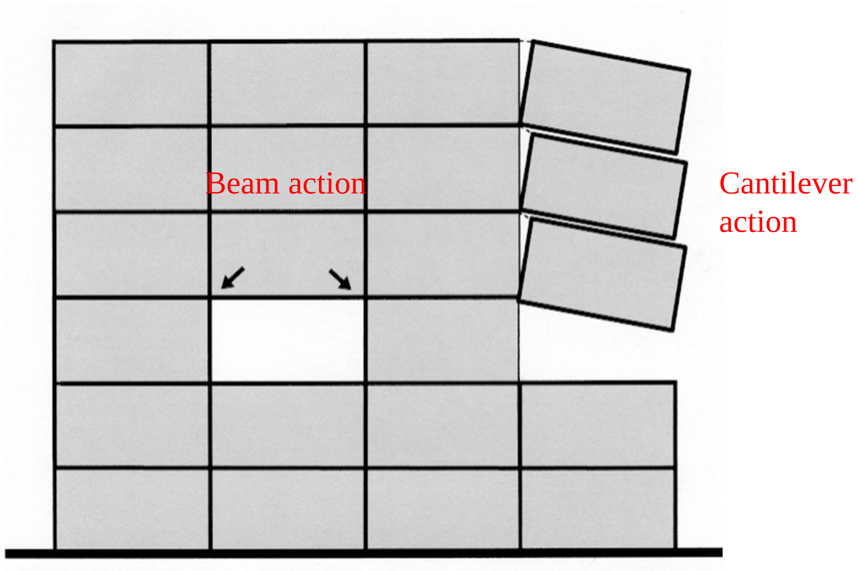
Cast in-situ



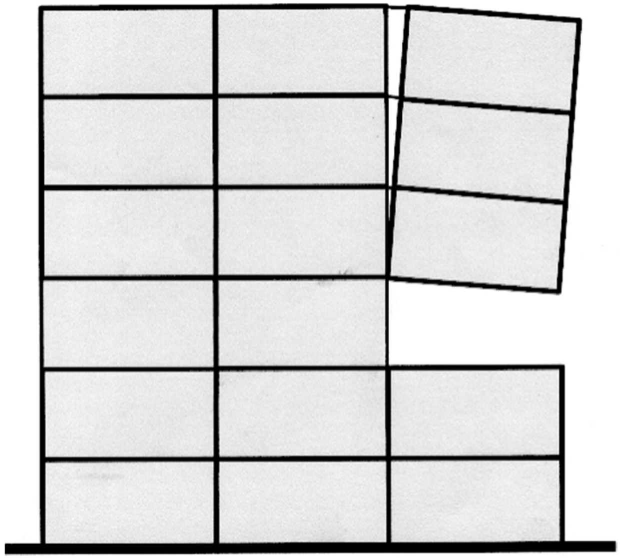
Precast

Beam & cantilever action

- Wall panel structures



Individual cantilevers



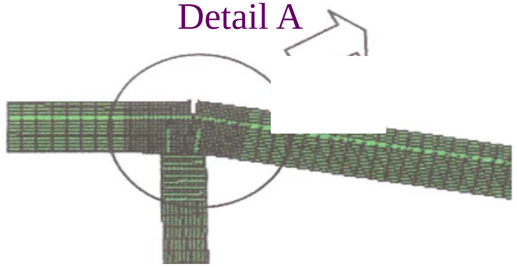
Composite cantilevers

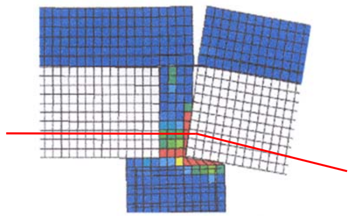
Alternative mechanisms for alternative load path in wall frame structures

Force transfer mechanisms

1. Cantilever action

Detail A

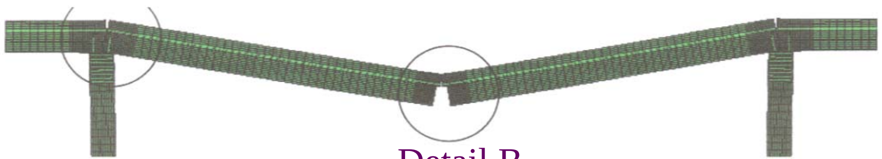




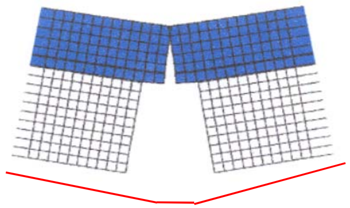
Detail A

2. Strut and tie action

Detail A

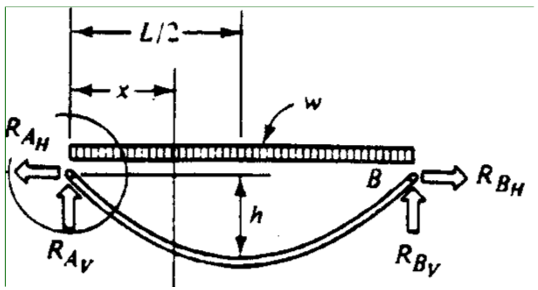


Detail B



Detail B

3. Cable action



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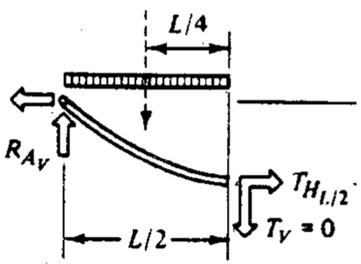


$$R_{A_H} = \omega \left[G \cdot \gamma_G + \psi_1 \, or \, \psi_2 \cdot Q \cdot \gamma_Q \right] \cdot \frac{L}{4u}$$

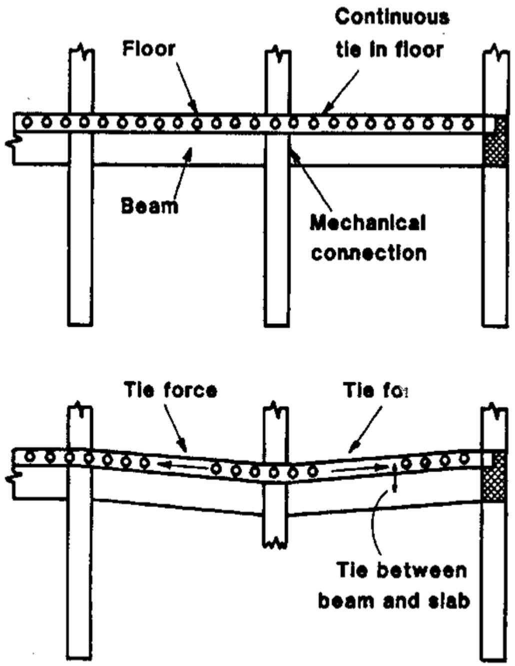
Alternative load path - example

- Failure of intermediate façade column

Suspension via column to
above structure

Cantilever action of
floor beam

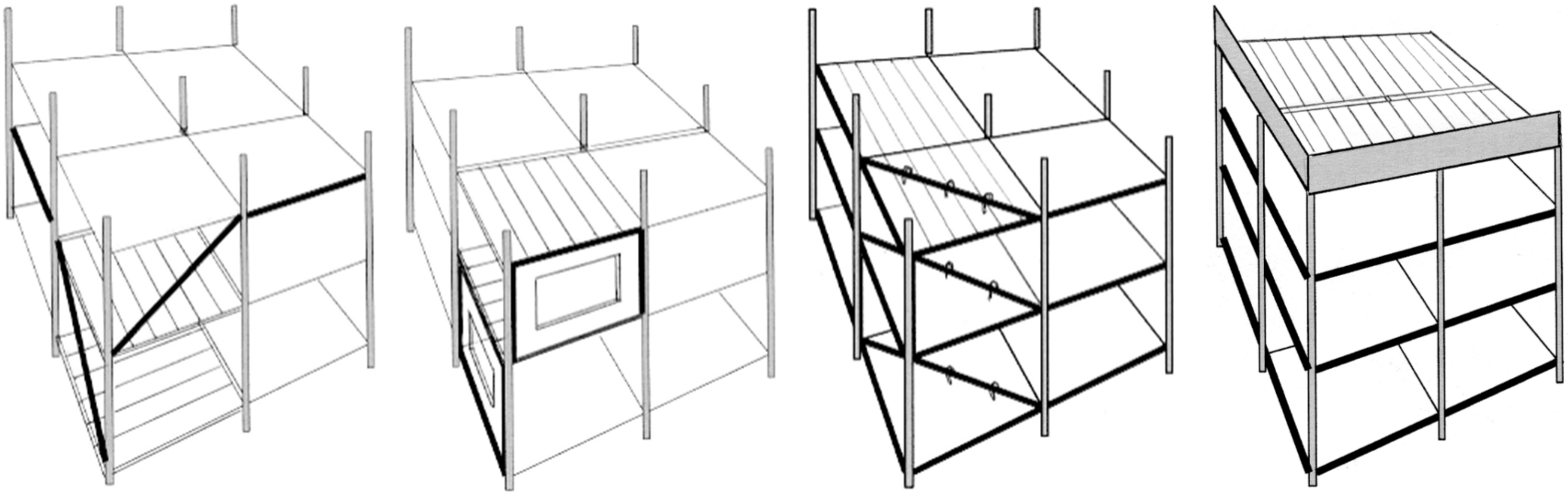
Cable action of floor
beam



Alternative solutions

Floor spans in opposite directions

Floor spans in same direction



Diagonal restrainment | Wall panels | Diagonal ties | Rigid cornice

Structural systems able to take up vertical loading

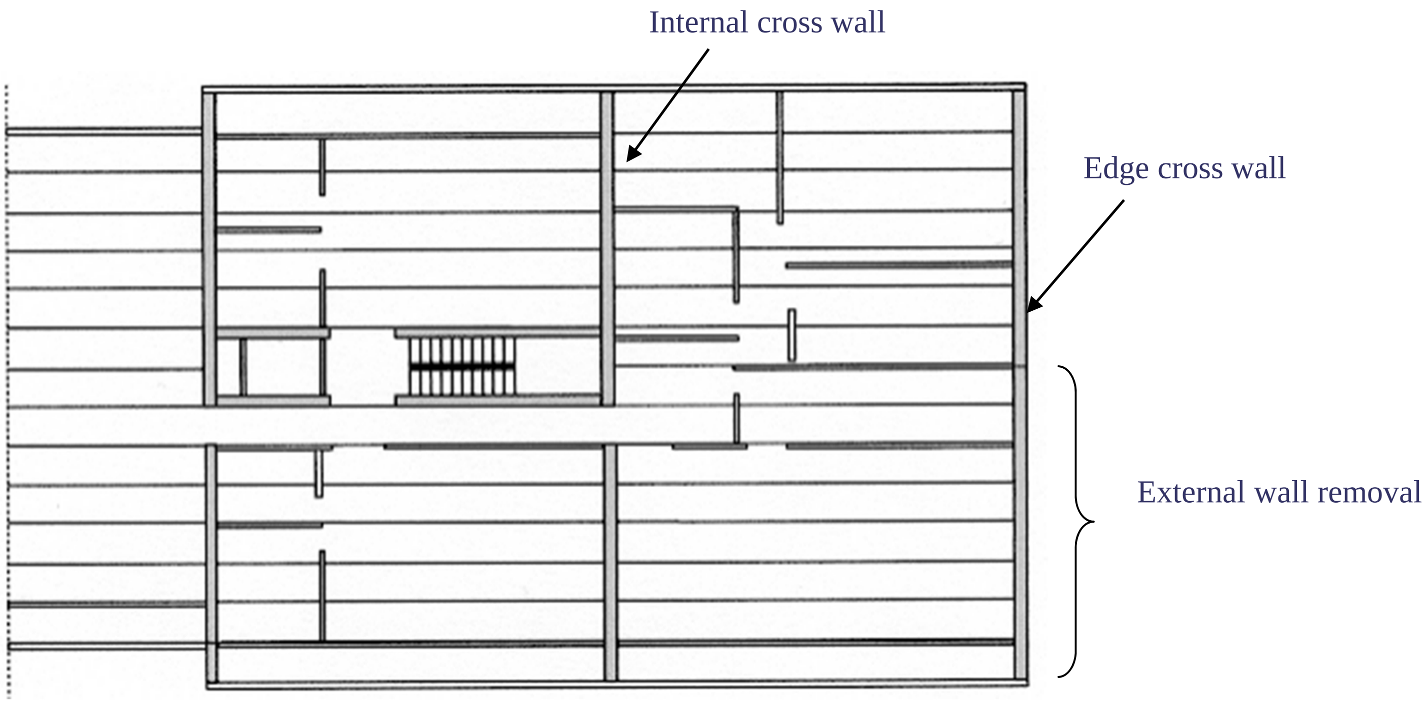
Specific load resistance method

- 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 m^2 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/m^2, 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

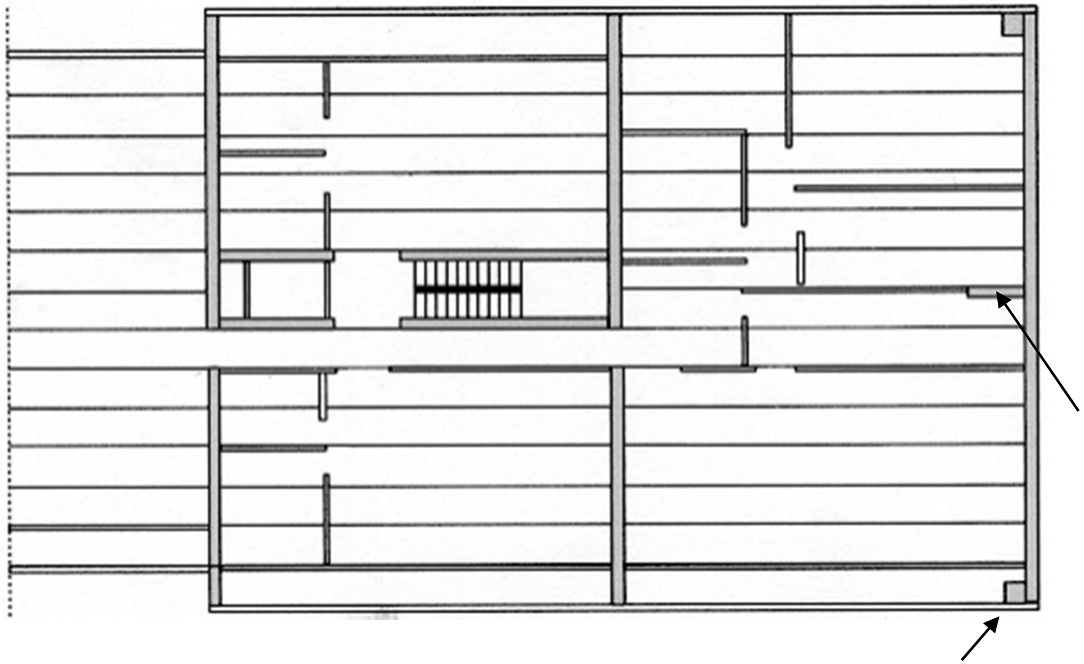
- Practical example wall panel structure

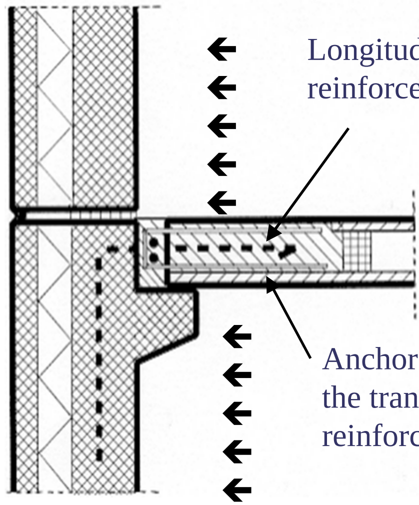


Alternative (a): cross-wall system with key elements at the edge

Specific load resistance method

- Practical example

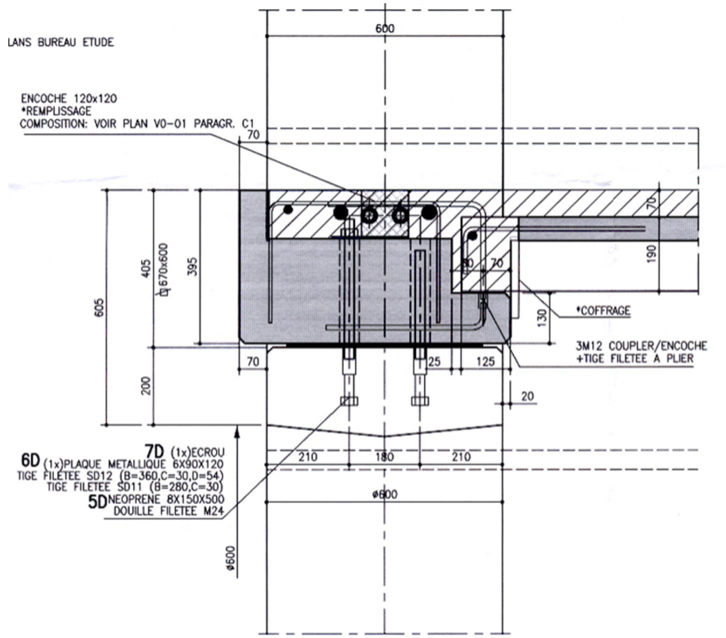




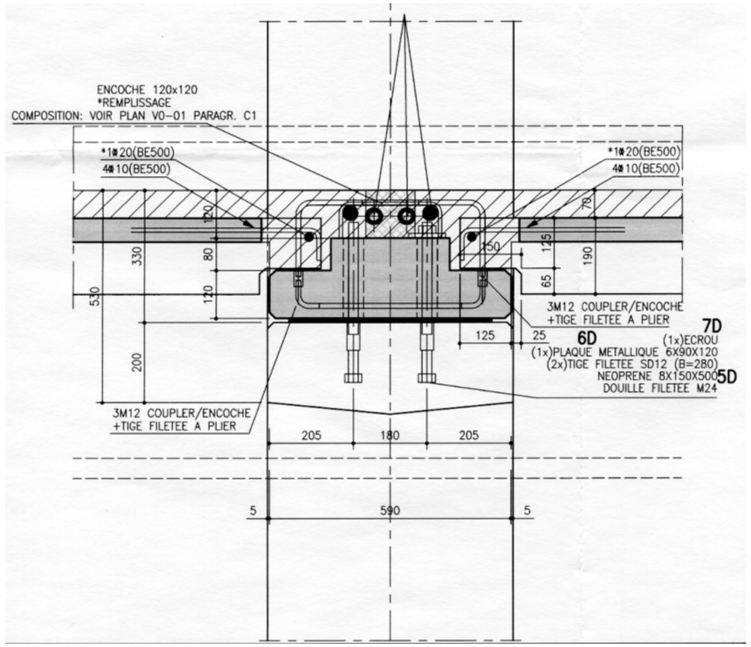
Alternative (b): cross-wall system with stiffening columns and wall

Detailing

- Ties for catenary action



Edge beam



Intermediate beam

Tie provisions in skeletal tower buildings

Detailing

- Realisation peripheral ties

Detail tie beam

Tie provisions in skeletal tower building 26 floors

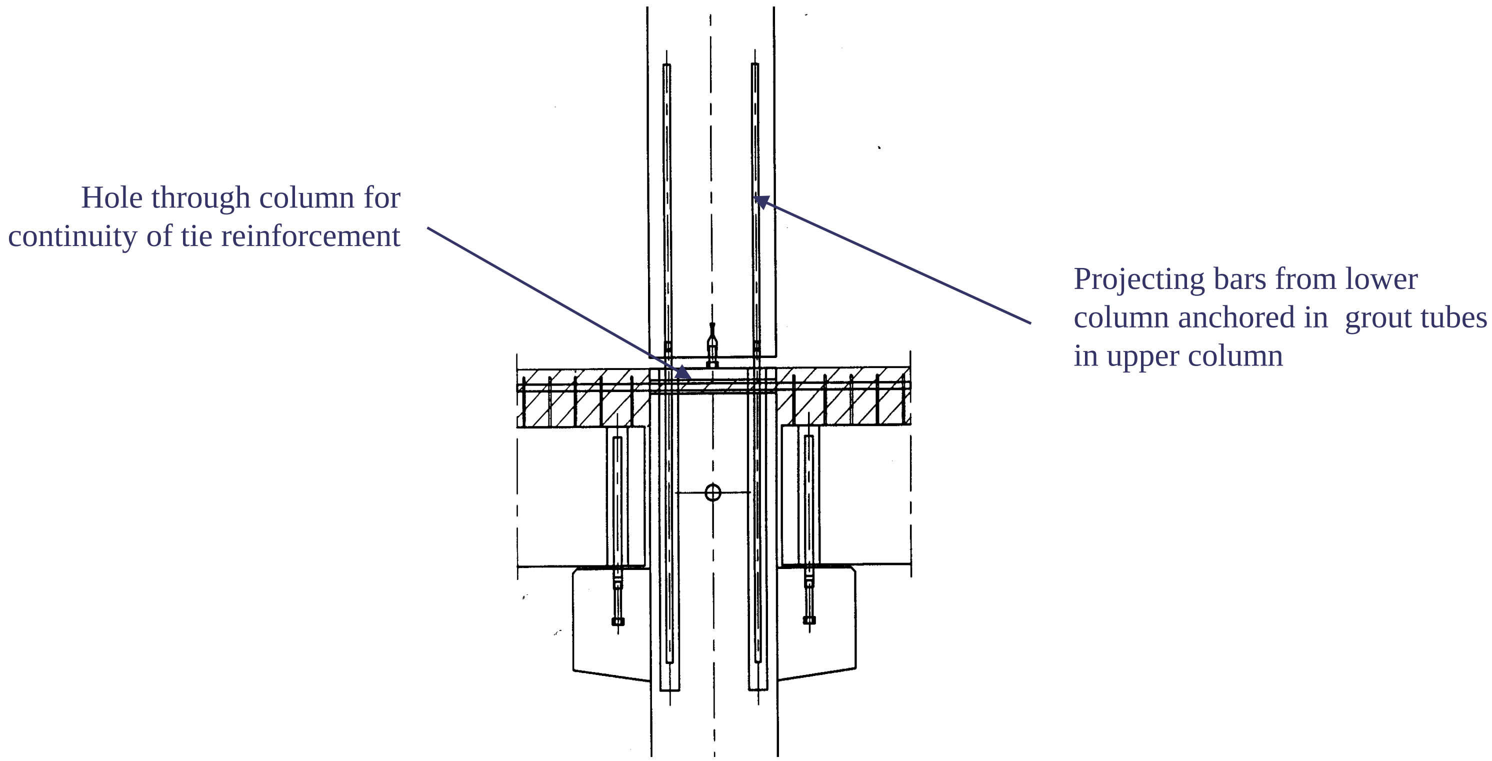
Detailing

- 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

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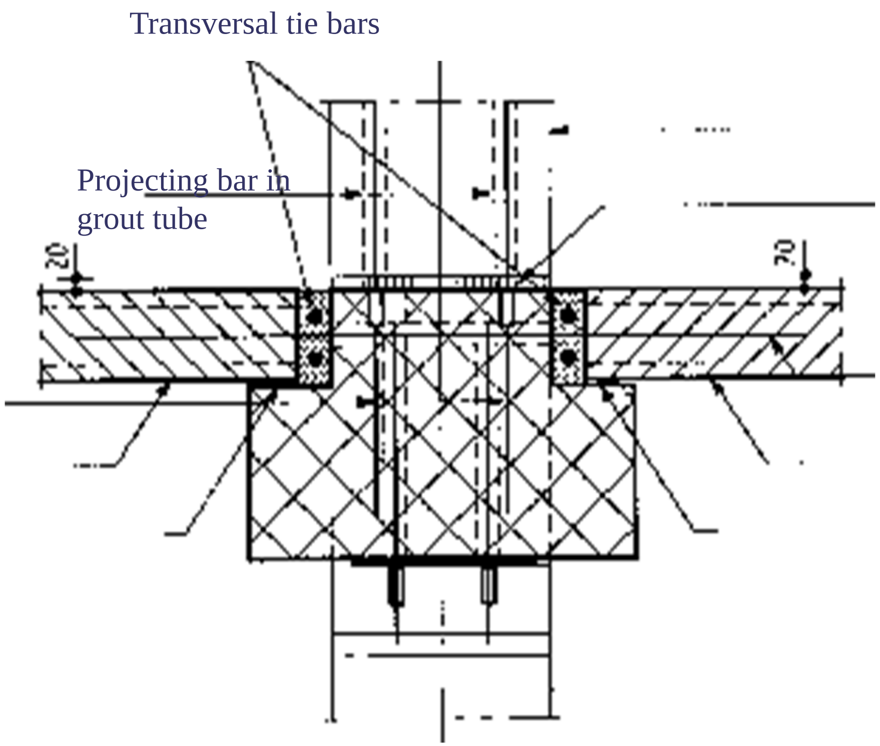
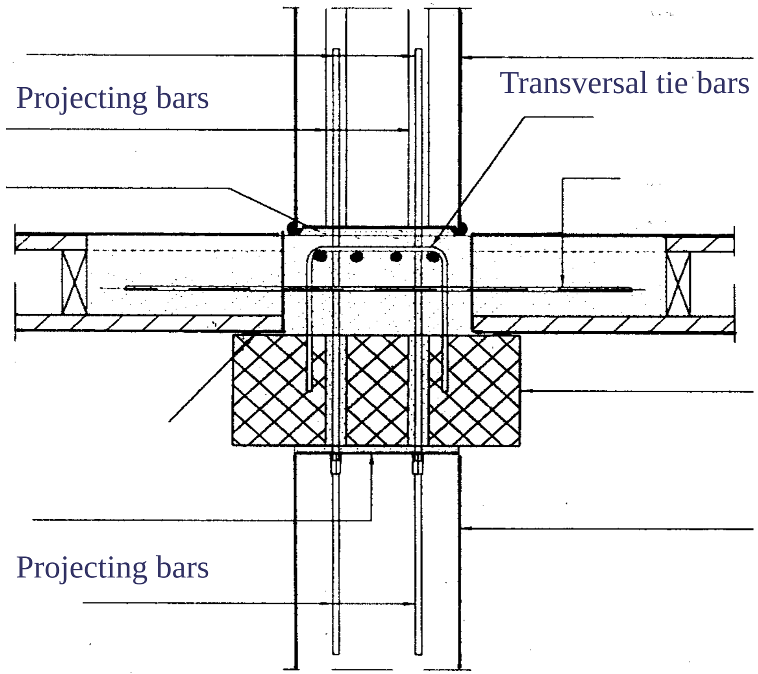
Detailing

- Beam to floor connections



(a) less good solution



(b) good solution

Examples of transversal tie reinforcements in floor-beam connections

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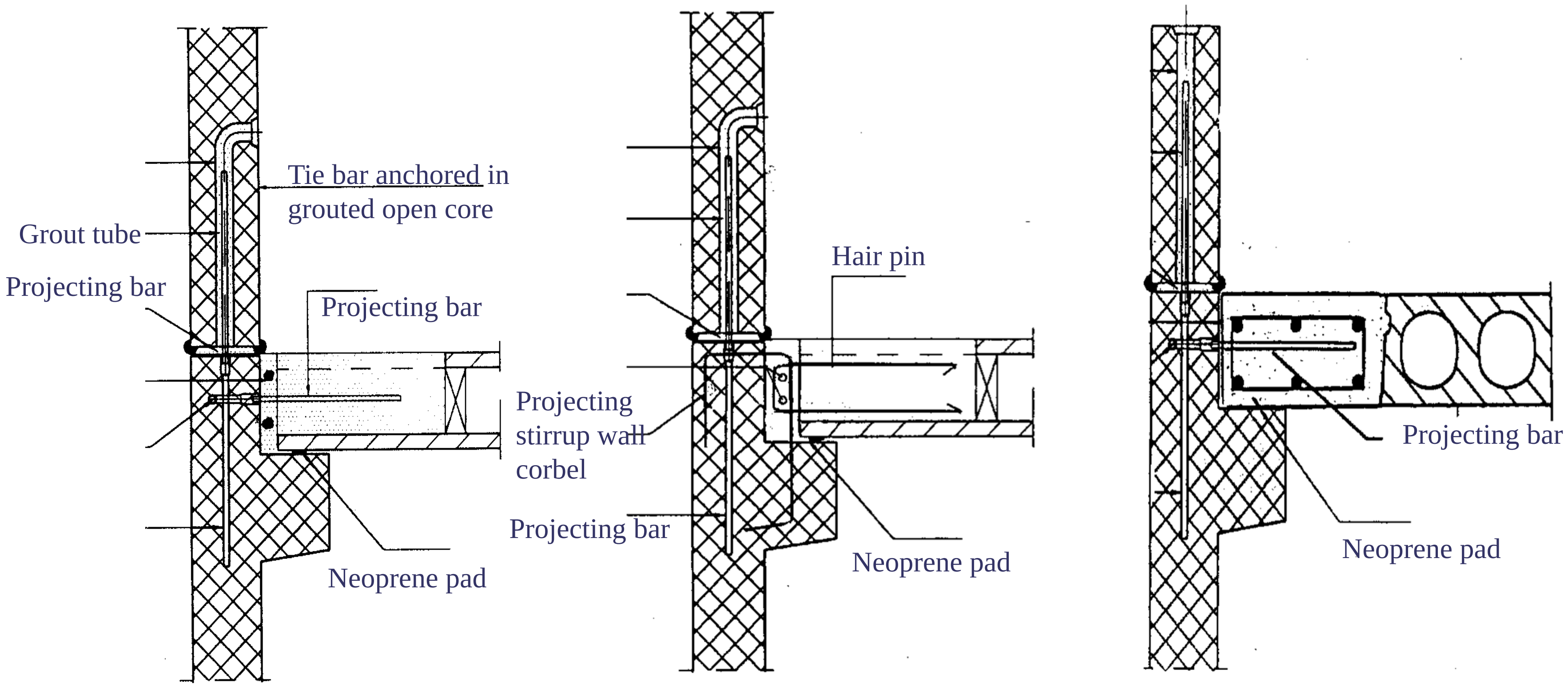
Detailing

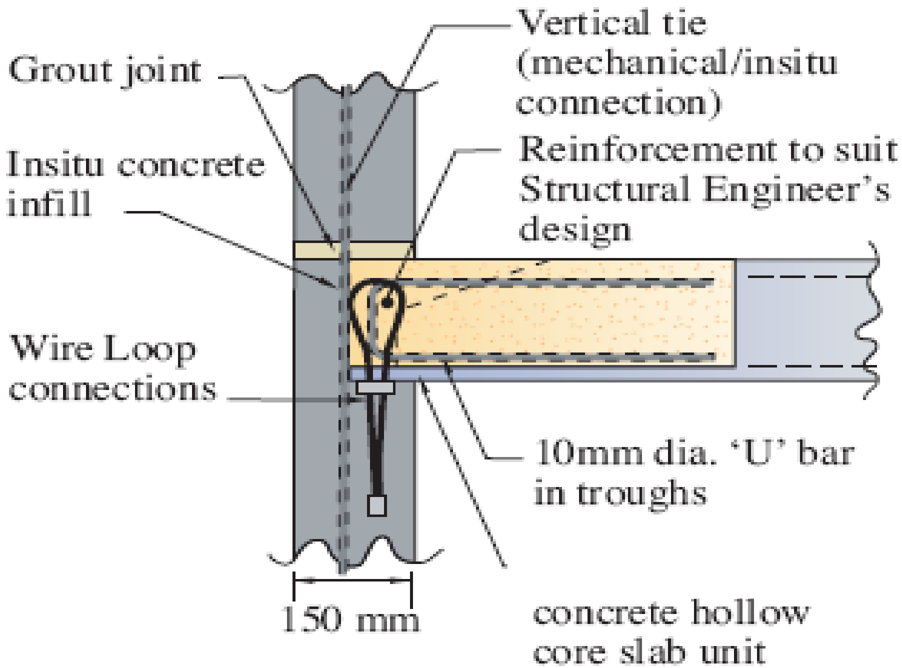
- Wall to wall and wall to floor connections



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

Detailing

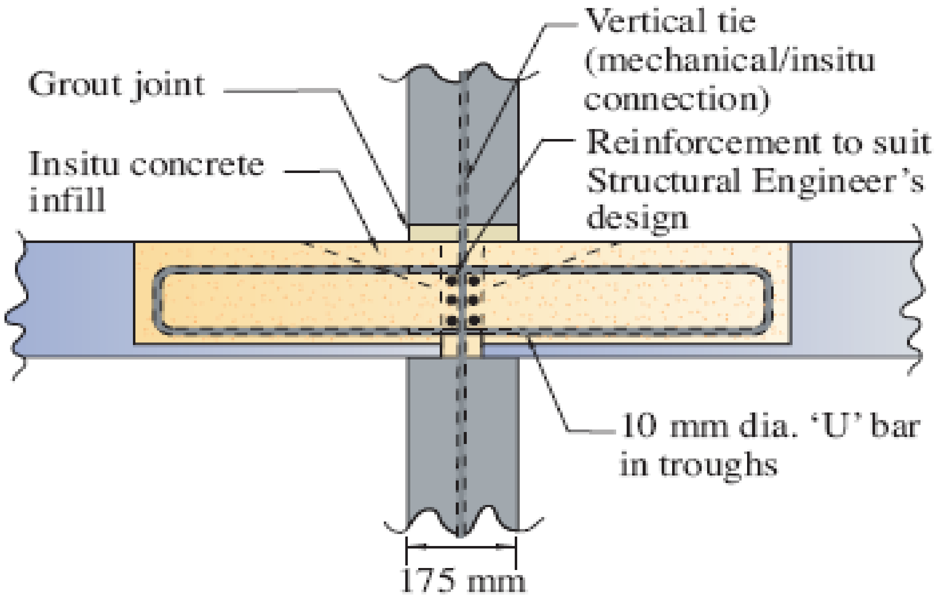
- Wall to floor connections



Typical section through load bearing edge wall

Detailing

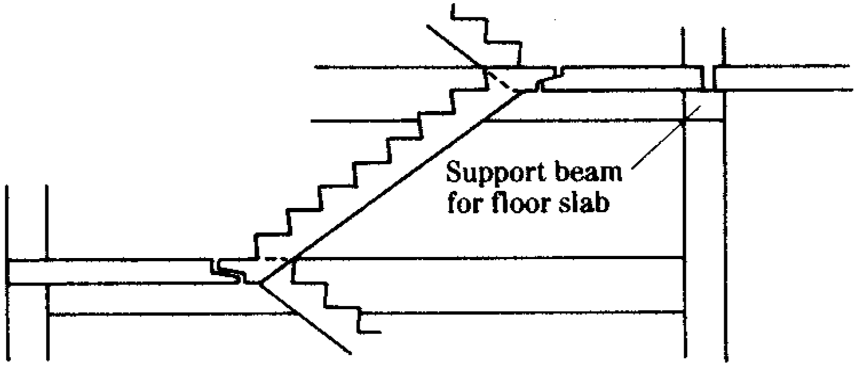
- Wall to floor connection

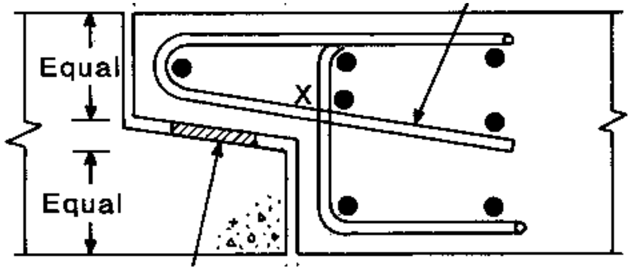


Typical section through internal load bearing wall

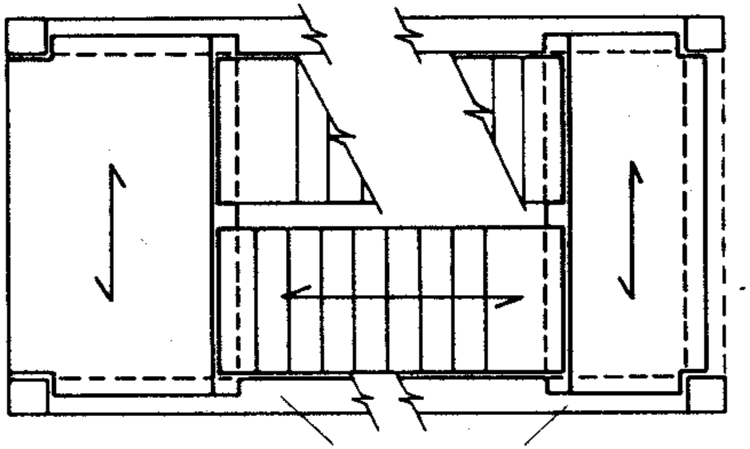
Detailing

- Stairs

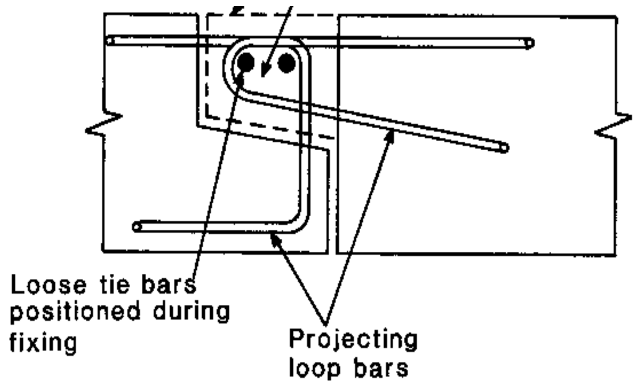




(a) Reinforcement in stair scarf joint



Support beams for half-landing and landing



(b) intermittent scarf joint

Staircase to landing joint details

Detailing

- Examples of good solutions

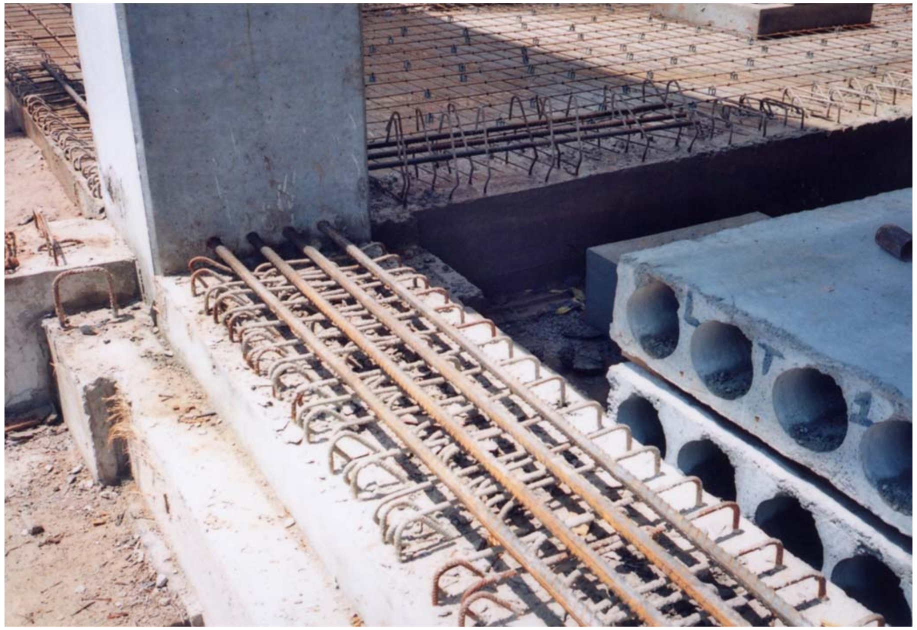
Precast stair flights with steel angle supports that would be site welded to plates cast into the landings

Support angles are anchored to the landing using bolts, after which a finishing screed covers the connection

Stair flight with integrated landings

Detailing

- Ineffective positioning of tie bars



Transversal tie bars should be inside projecting loops on top of beams

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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**