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Structural integrity

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CRH Structural Concrete | Belgium

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DESIGN OF PRECAST CONCRETE BUILDING STRUCTURES

Structural integrity – design for accidental actions

ergon
a CRH company

Pieter van der Zee

Contents

Progressive collapse

- **Ronan Point, London 16 May 1968**

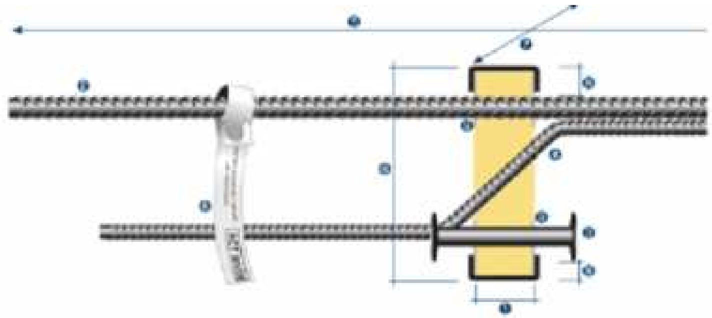
Gas explosion

Progressive collapse of a part of an apartment building after a gas explosion at the 18th floor

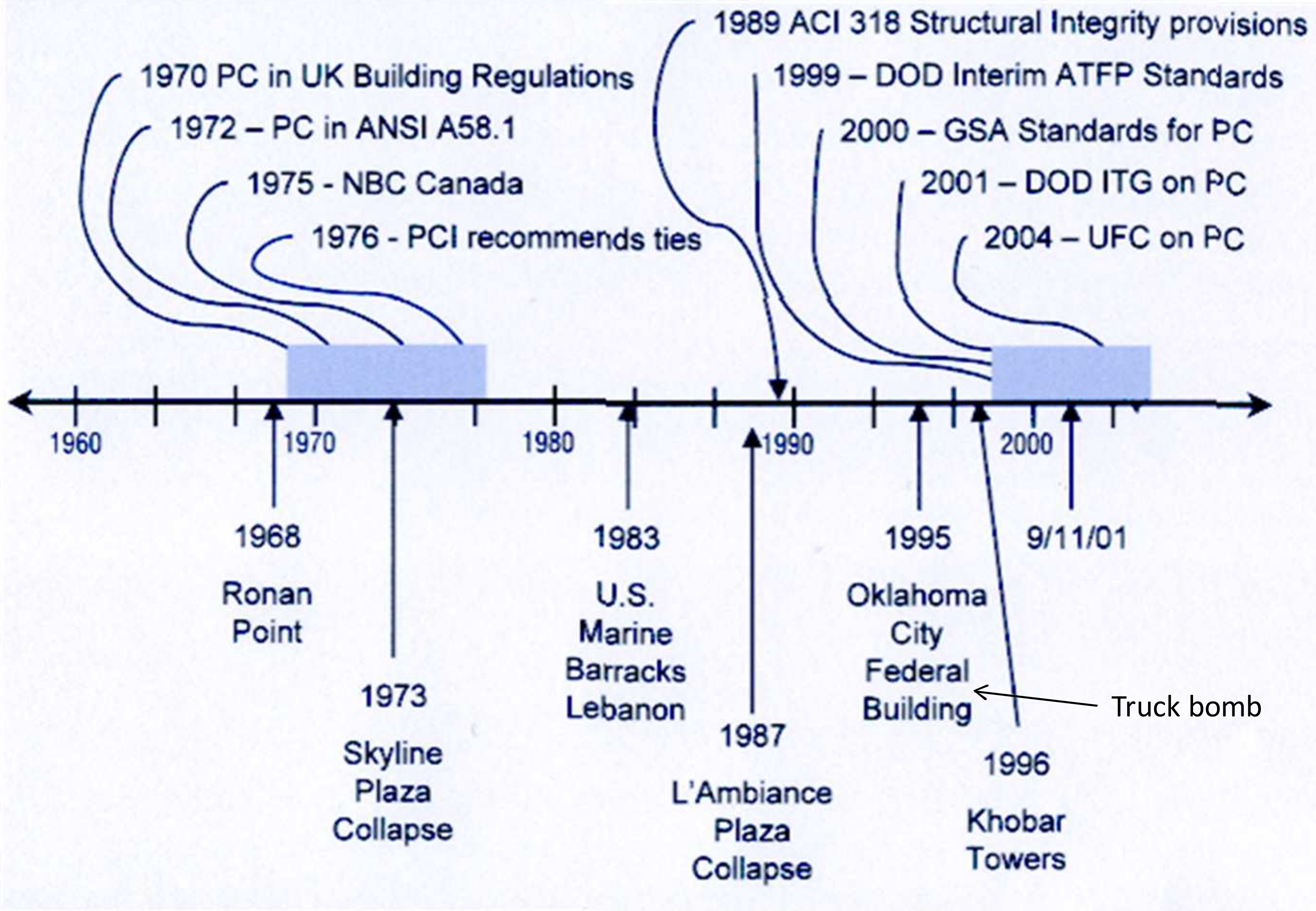
Progressive collapse

Appartment building in Maastricht (NL)

Balcony on 5th floor collapsed due to misplacement of connecting reinforcement. The falling balcony broke all balconies below.

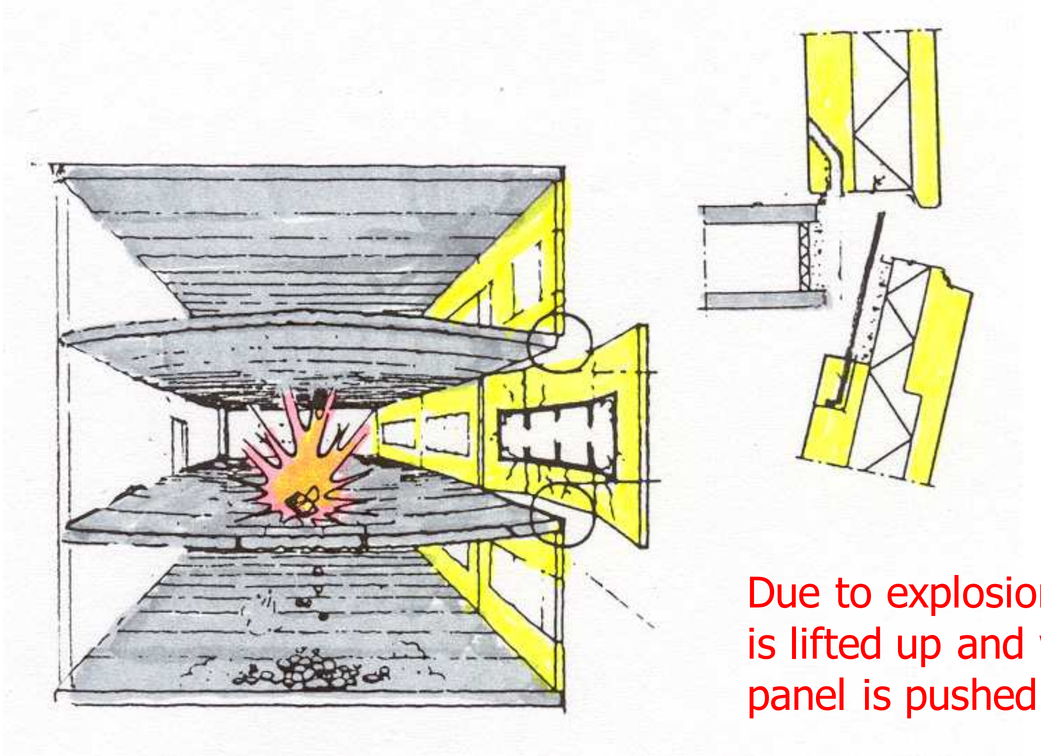


Progressive collapse - timeline



1. Phenomenon

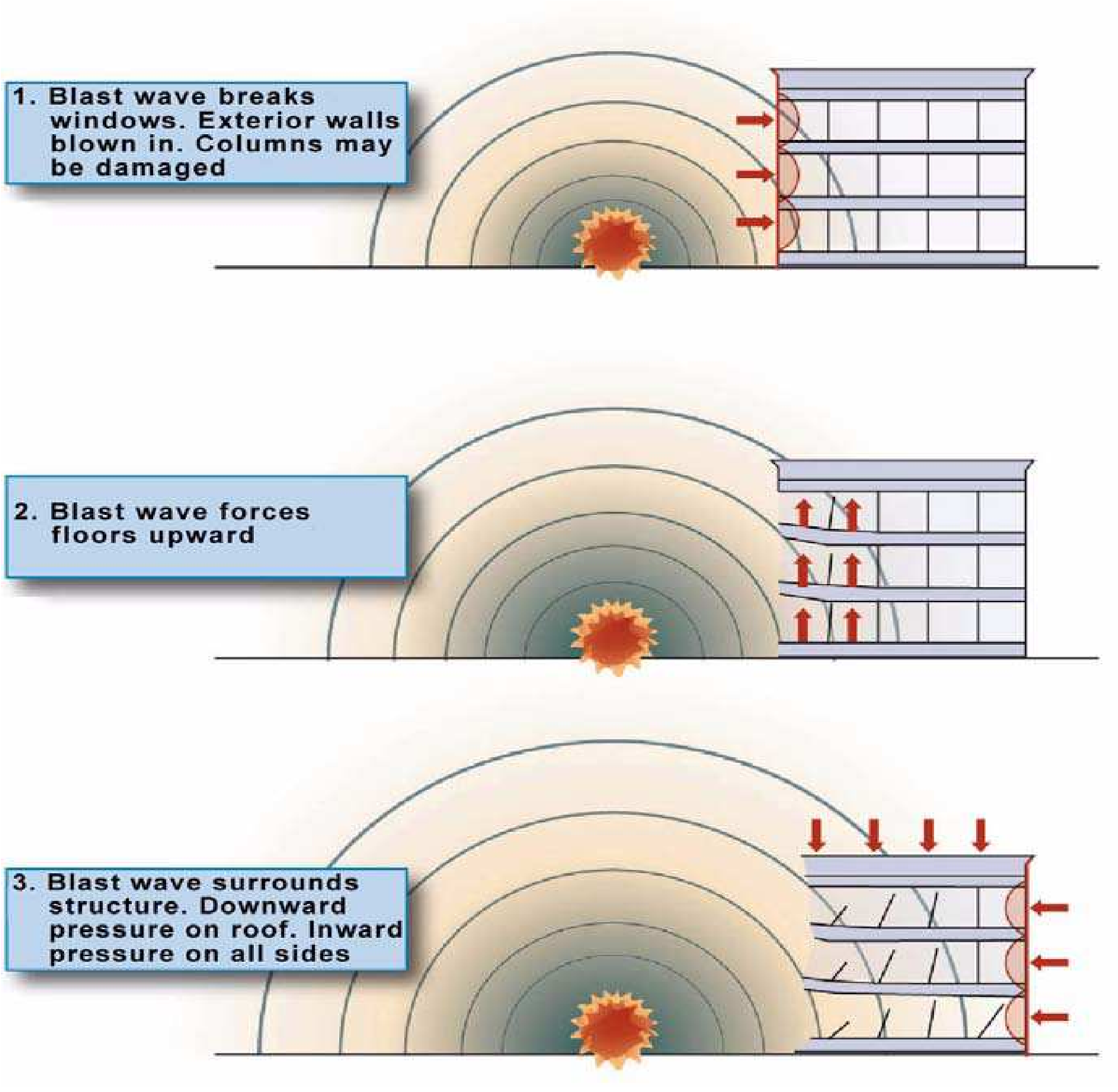
A local failure results in the collapse of a whole building or a large part of it.



Due to explosion floor is lifted up and wall panel is pushed out

Scenario of possible effects caused by gas explosion

Sequence of building damage during blast

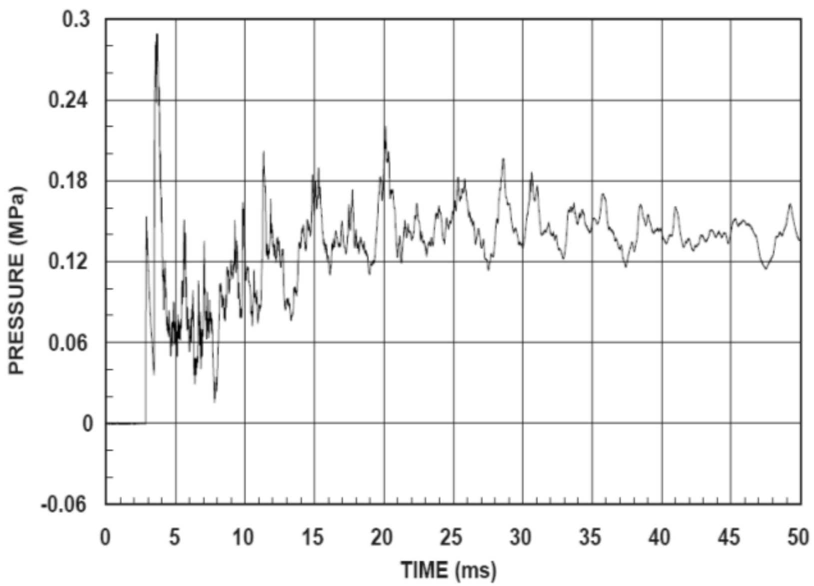


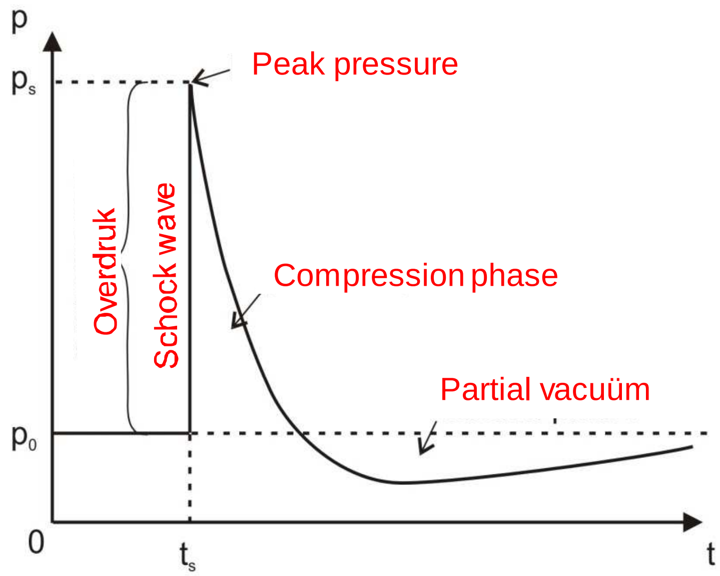
2. Dynamic effects

Accidental action to a building structure is associated with dynamic effects. The following different cases can be distinguished:

- dynamic effects related to the impact of the accidental action itself,
- dynamic effects related to the impact of falling parts in the building,
- dynamic effects related to the transition from the original load-bearing scheme to an alternative path of resistance.

Load-time diagram





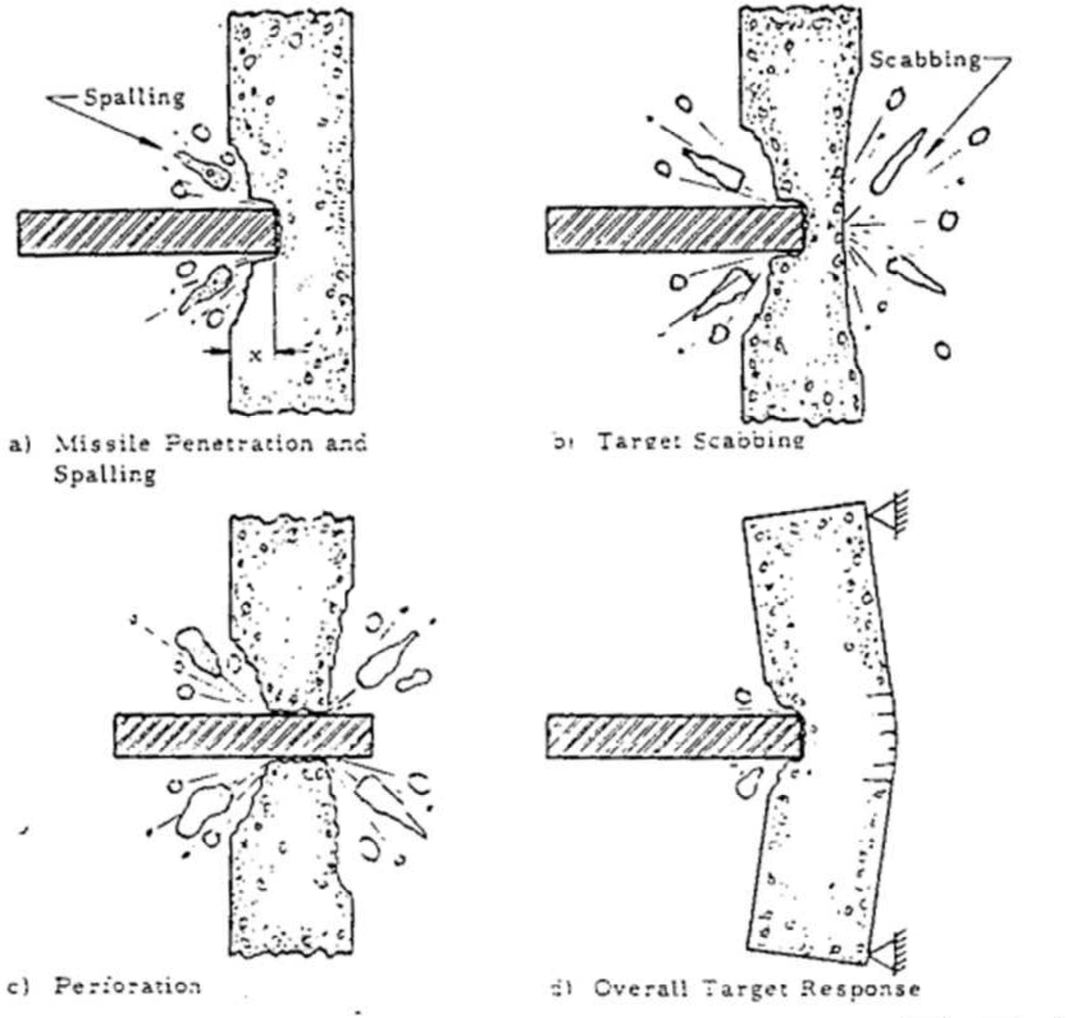
Gas explosion

Explosives

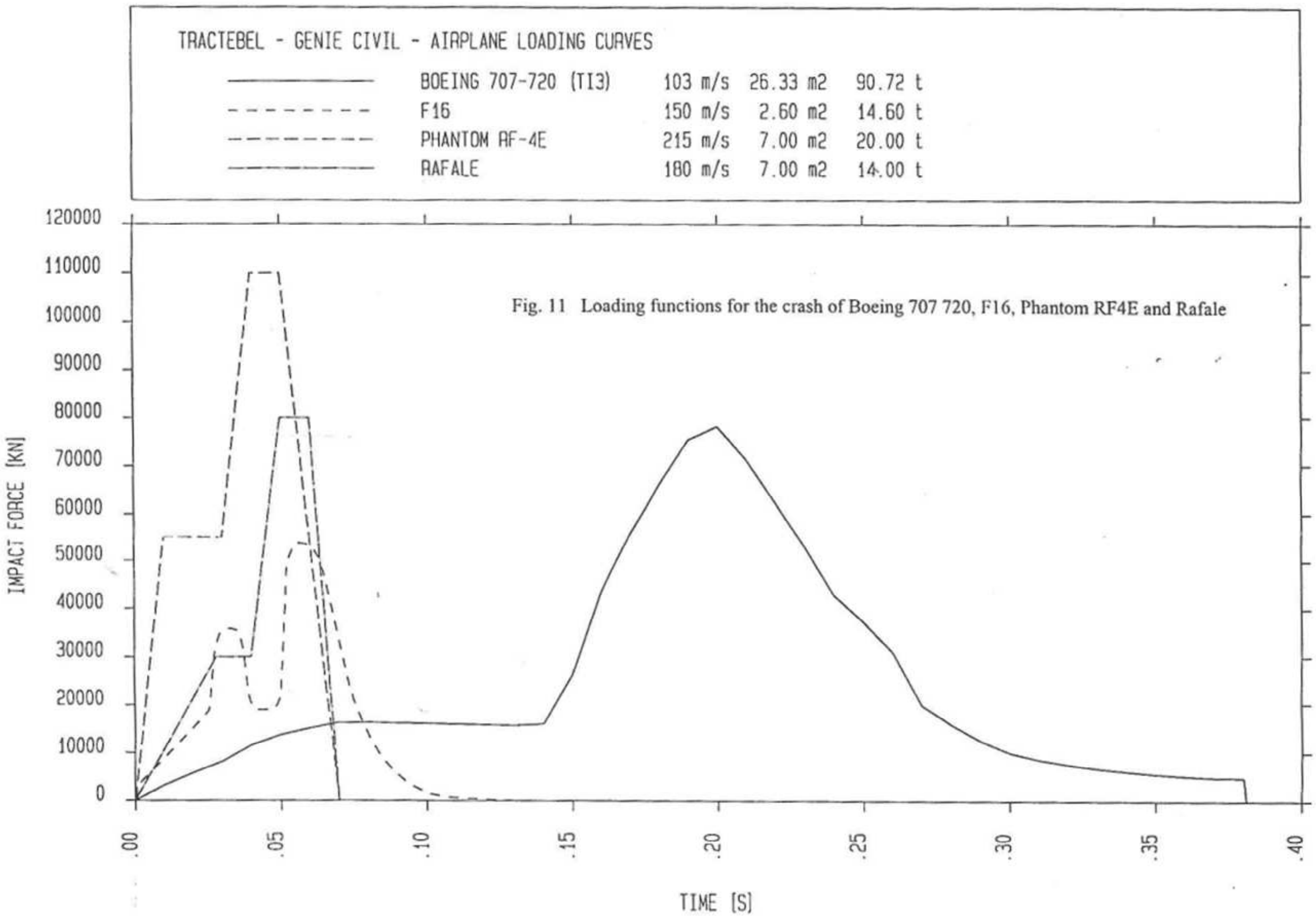
30 – 100 kN/M²

50 kg TNT op 2,0 m: 33 MN/m²

Phases of ballistic impact



Airplane impact force

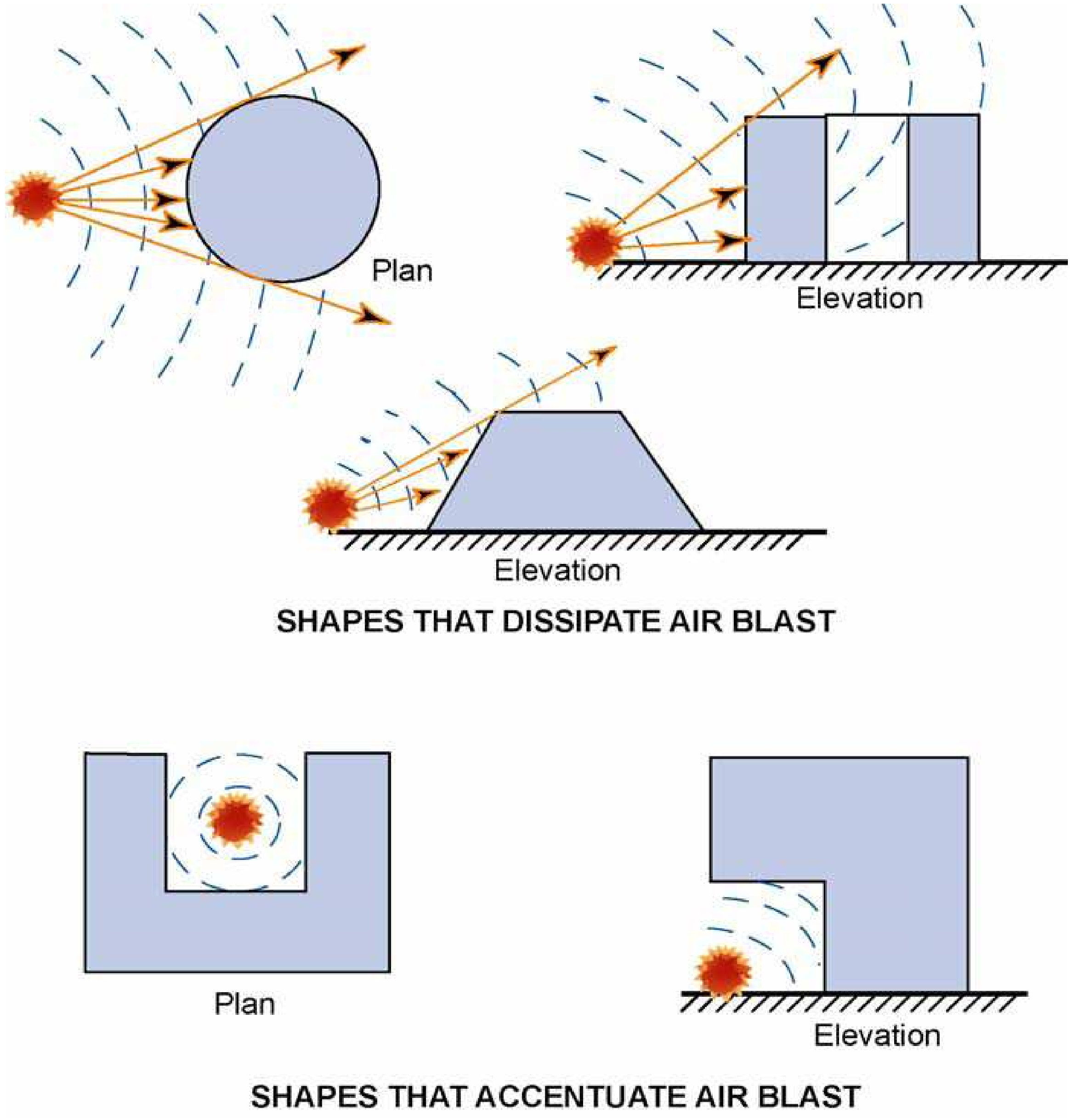


3. Design strategies

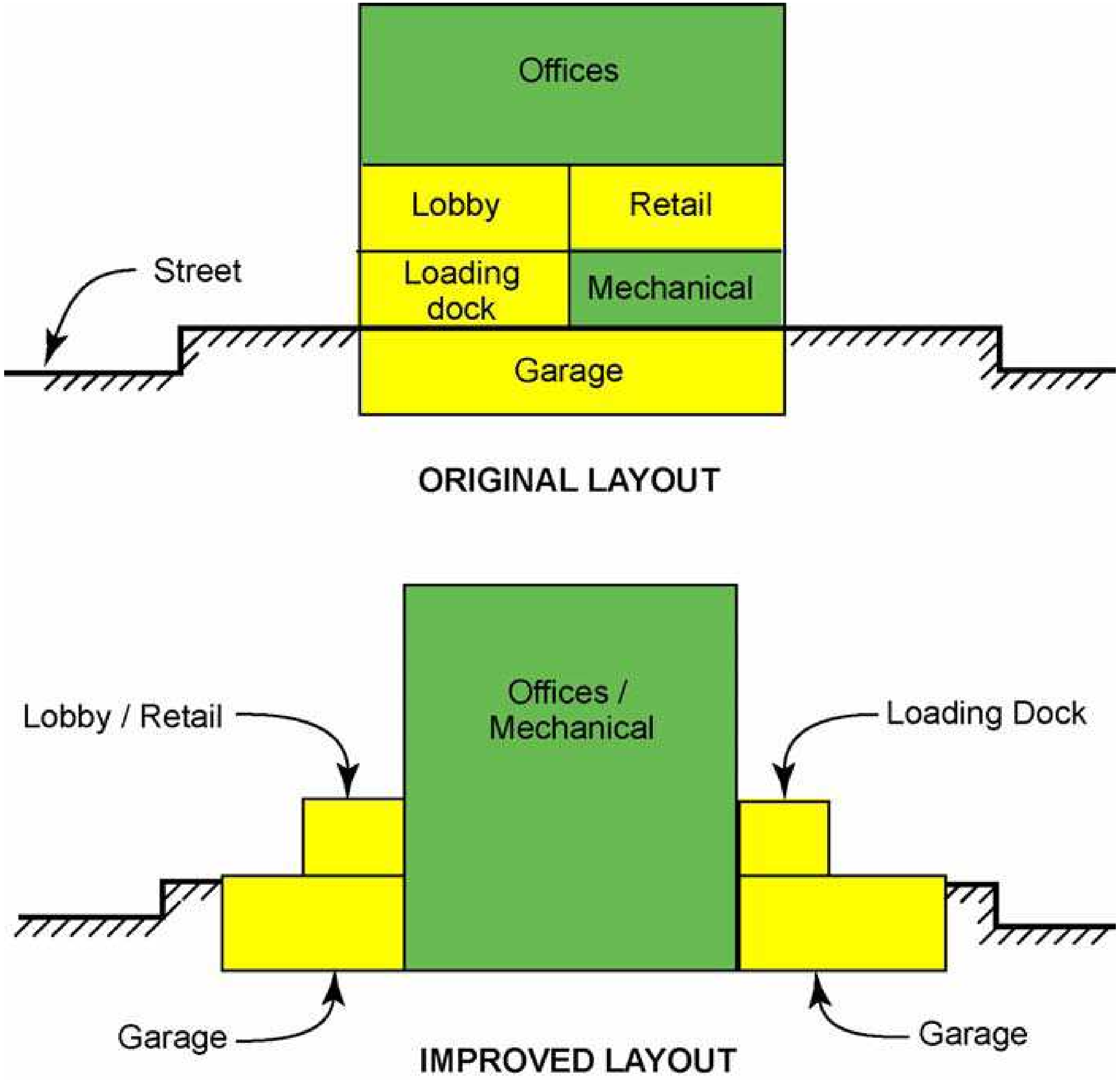
The three basic physical protection strategies for buildings to cope with accidental actions are:

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

Effect of building shape on air blast impacts



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



4. Design concepts

Design for prevention of progressive collapse

a. Indirect method

- Minimum tie provisions

b. Alternate load path method

- A critical element is removed from the structure, due to an abnormal 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 abnormal loading

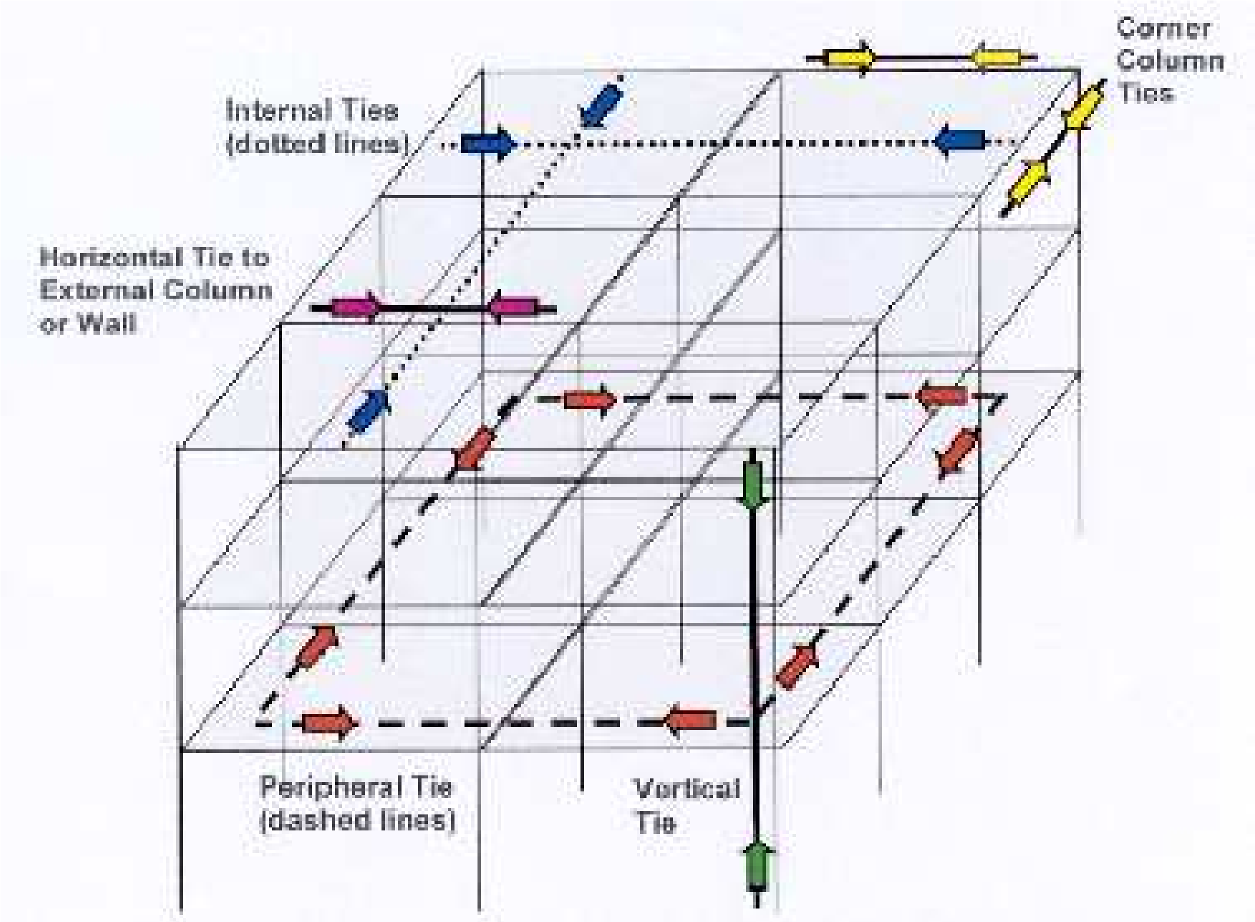
Different building classes

See EN 1991-7 Table A.1 for classification

- Class 1: housing up till 4 floors
  -> no other constructive measurements
- Class 2a low risk: shops < $1000m^2$
  -> indirect method
- Class 2b high risk: $1000\ m^2$ < shops < $5000\ m^2$
  and Class 3 hospitals etc
  -> make calculations or alternative load path or key element pocedure

a) Indirect method

- **Tie force approach**



Schematic of tie forces in a skeletal or bearing wall structure

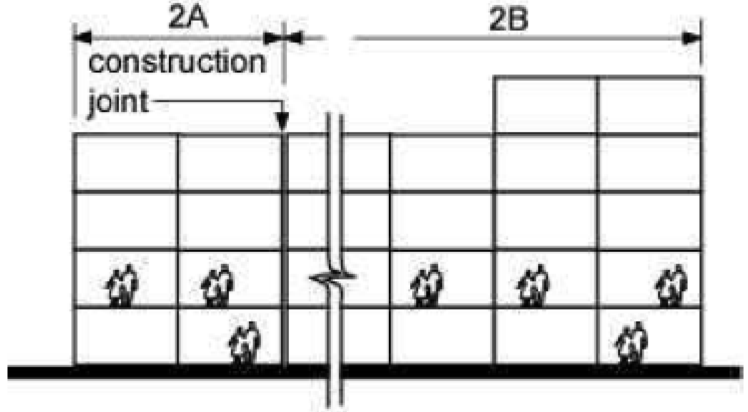
b) Alternate load path method

- **The alternate load path method implies that:**
  - The *alternate load path approach* requires that all 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

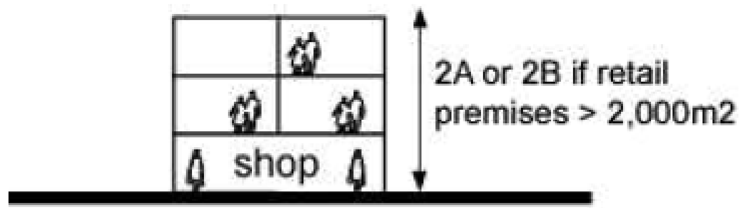
c) Specific load method

- **Critical load-bearing members are designed to resist a notional load**
  - The *specific load approach* requires all critical load-bearing members to be designed and detailed to be resistant to a specified design value of accidental load.
  - Selection of the appropriate type and magnitude of the accidental load is critical and will vary with the occupancy and type of building.
  - Because of the subjective nature of this approach the other parts of the structure, such as tying the offending component into the structure, should be designed according to the alternate load path method.

Categorisation of buildings



4/5 storey flats



2 storey flats
over 1 storey retail

Illustration of building classes

Categorisation of buildings

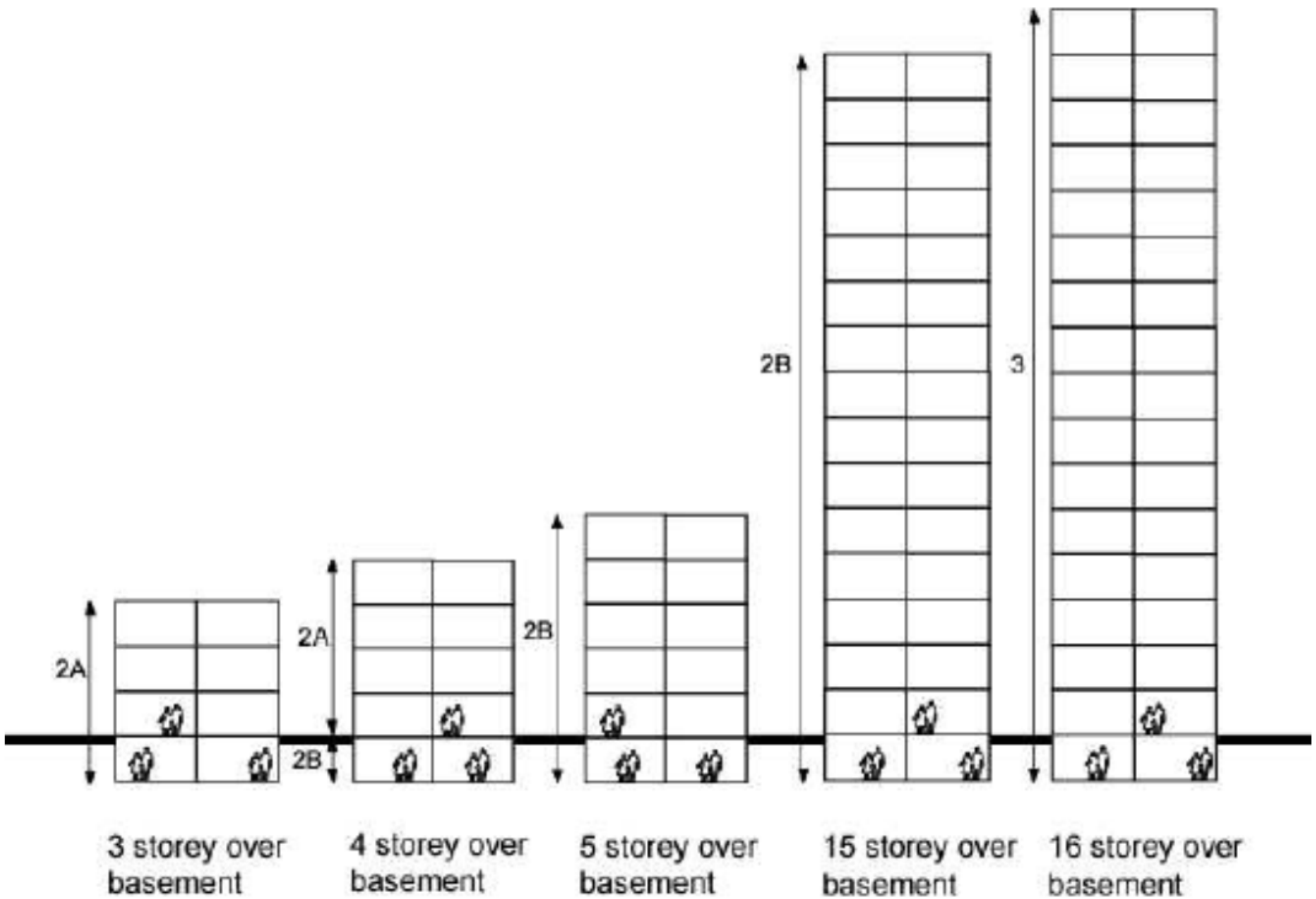


Illustration of building classes

6. Design requirements and assumptions

- **Structural lay-out**
- **Resistance**
- **Continuity**
- **Ductility and energy absorption**

Design requirements and assumptions

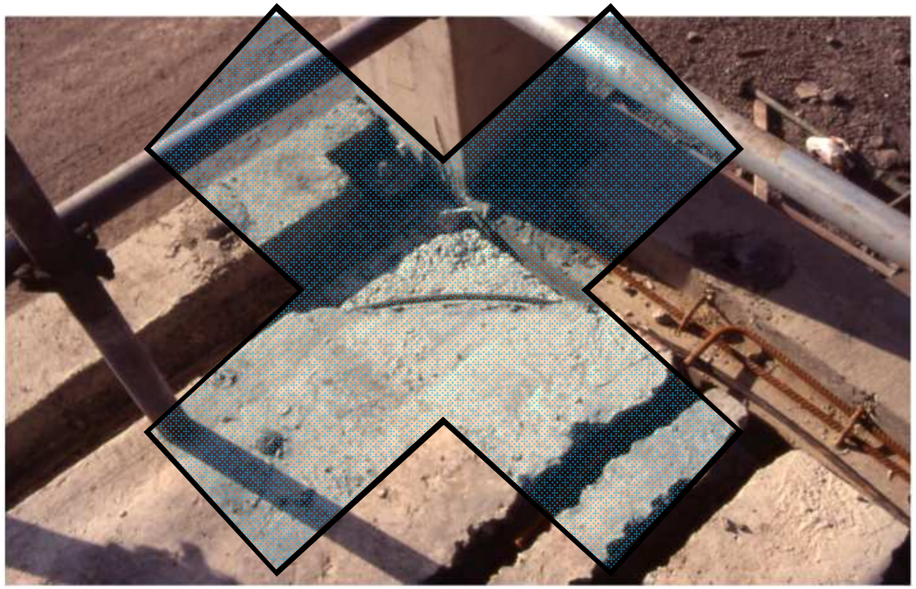
- **Structural layout**

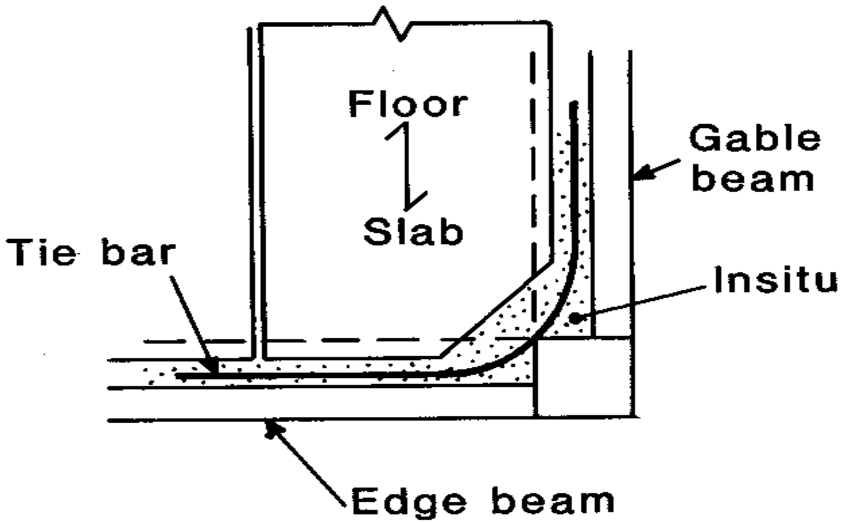
  The layout together with other measures are important. The following general design guidelines and suggestions for improving structural integrity include:

  - Good plan layout. For example, the bracing or shear walls should be so distributed throughout the building that no substantial portion of the structural framework is solely reliant on a single plane of bracing in each direction.
  - Integrated system of ties
  - Returns on walls
  - Changing span directions of floor slabs
  - Load-bearing internal partitions
  - Compartmentalised construction

Continuity

- **Continuity of tie reinforcement around corners**





Essential to develop the bridging capabilities needed for the transmission and redistribution of loadings

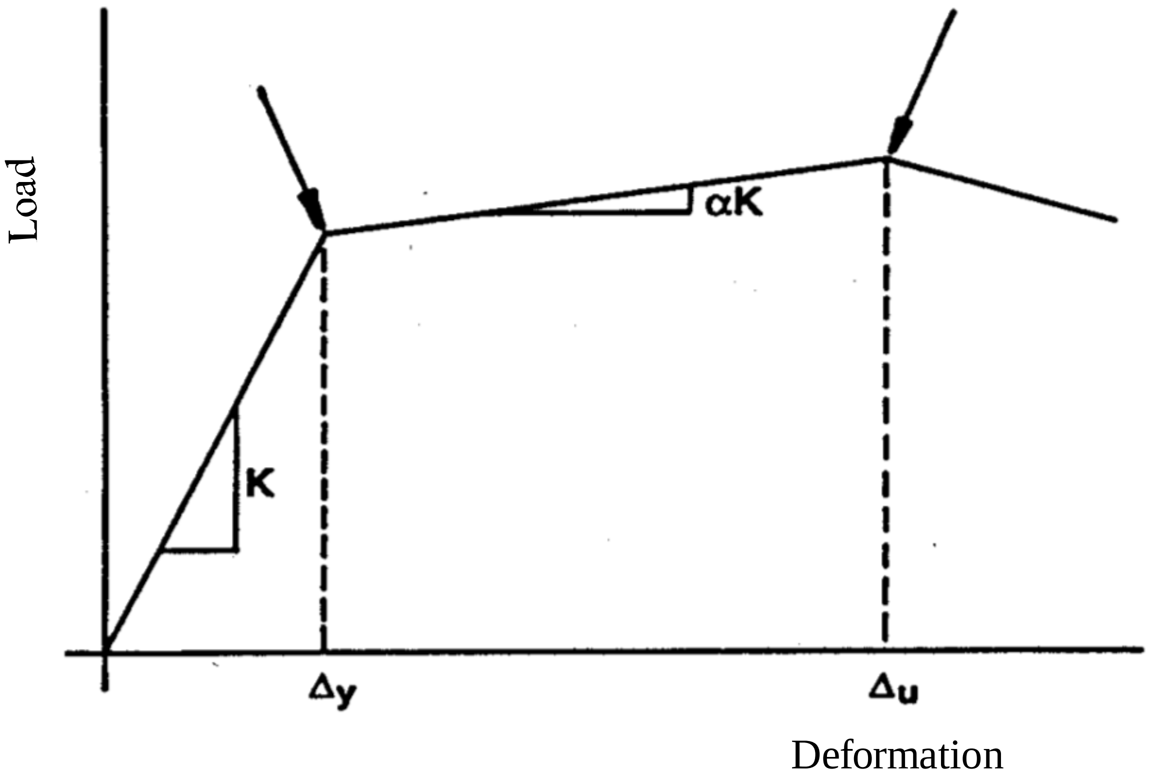
Continuity

- **Tie reinforcement should cross the columns**

Tie reinforcement is placed inside the stirrups of the beam

Ductility

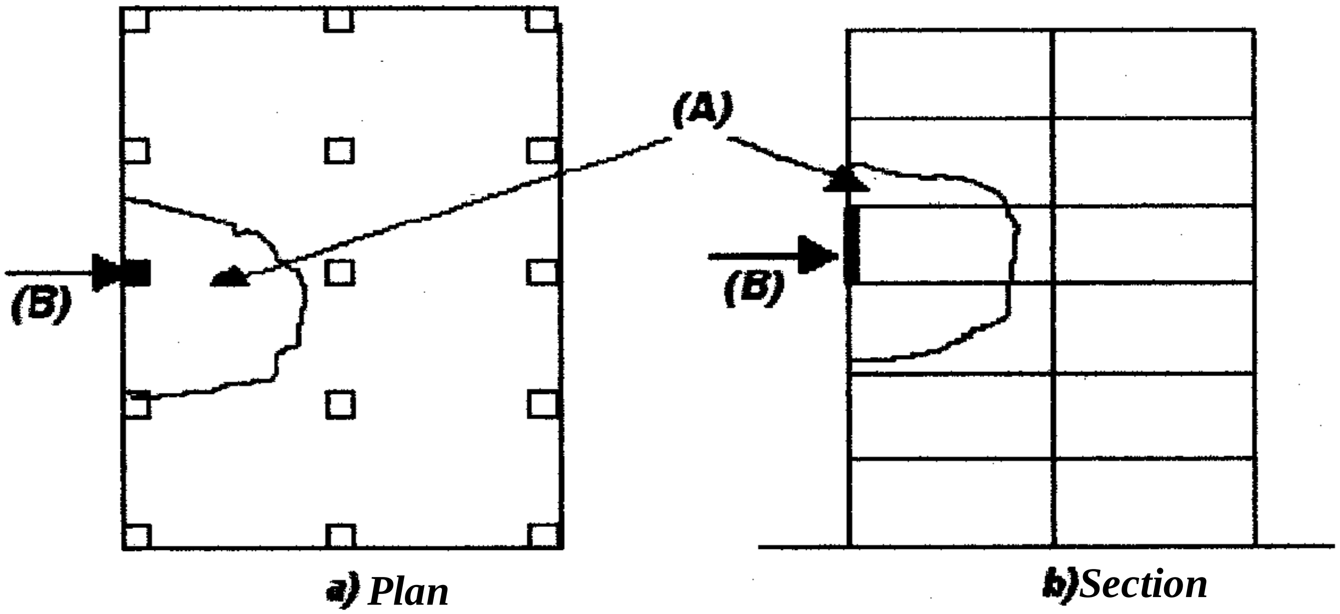
- **Definition**



Ductility is measured in terms of the ductility factor Φ, the ratio between the deformation at the ultimate load Δ_u and the deformation at the yield point Δ_y

7. Primary local damage

- **Eurocode EN 1991-1-7**

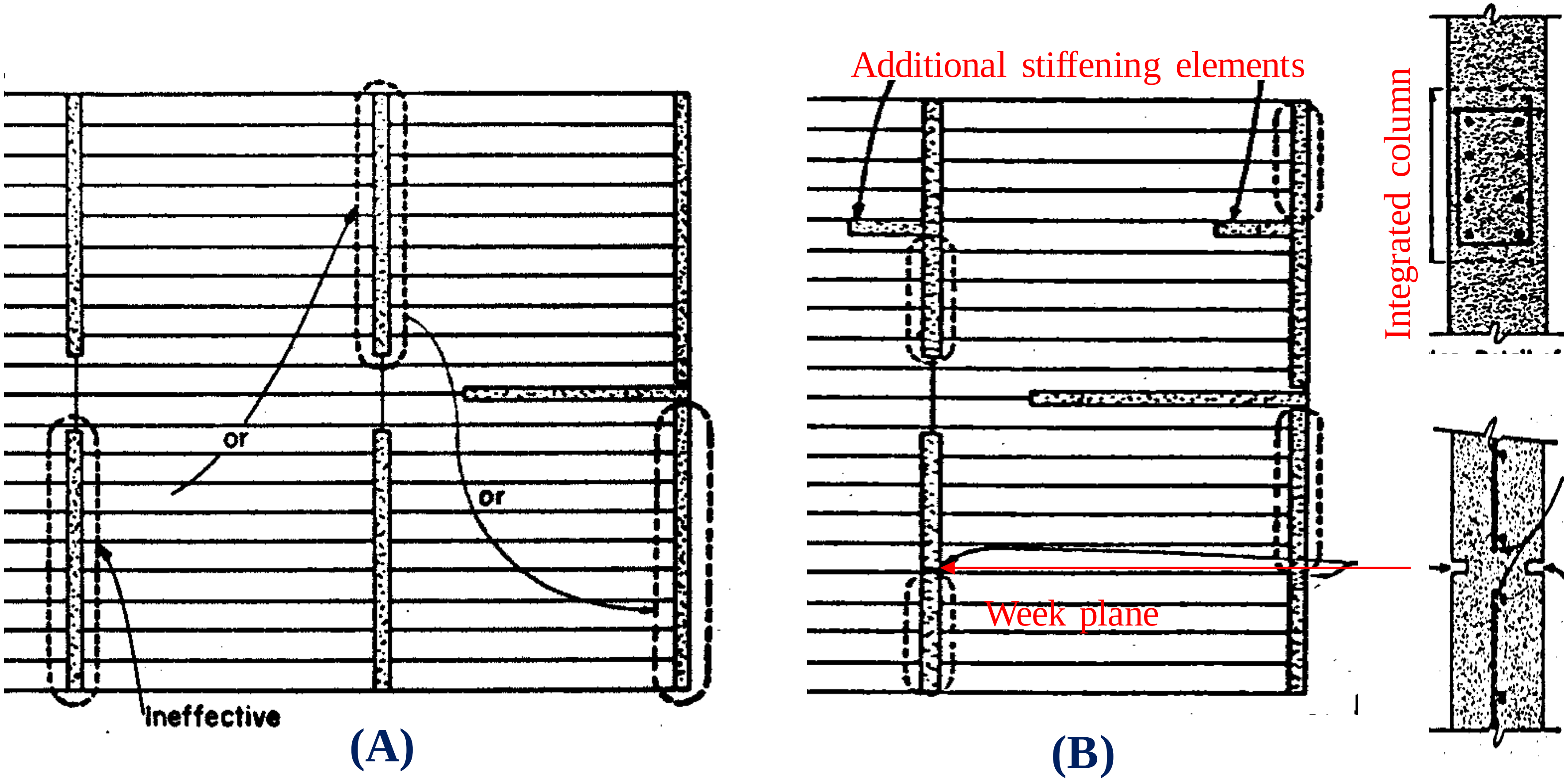


(A) Local damage not exceeding 15% of floor area in each of two adjacent storeys
(B) Notional column to be removed:

Recommended limit of admissible damage

Primary local damage

- **Load bearing wall structures**



Extent of assumed wall damage with limiting measures taken for (B)

8. Design methods

a) The fully tied method (classe 2A)

For classe 2B en 3:

b) The alternate load path method

c) The specific load resistance method

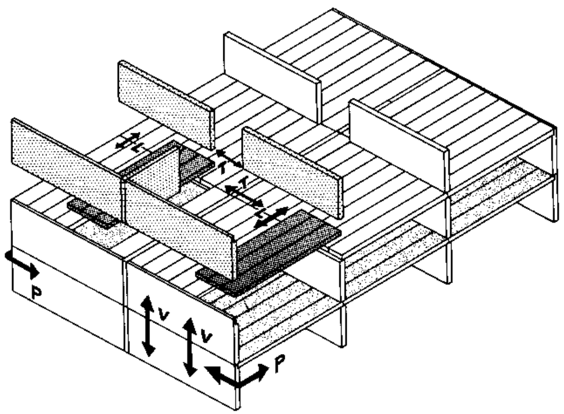
If key-element

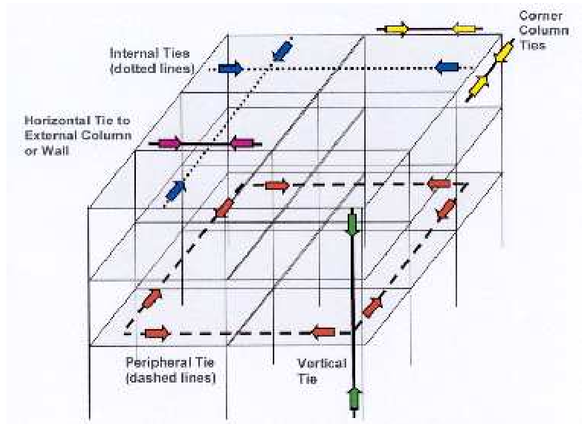
d) System risk assessment

a) The fully tied method

- **Tie functions**

- Peripheral ties ‘P’ : prevent slabs from moving apart and generate the clamping forces that create friction forces in the joints, essential for the diaphragm action
- Longitudinal ties ‘L’ : take up horizontal forces from eccentric loading, wind, etc. and connect floors to the supporting structure
- Transversal ties ‘T’: transversal coherence of the structure and bridging action in case of local damage by catenary action
- Vertical ties: assure alternate load path in case of local damage





Tie reinforcement in wall frame construction

The fully tied method

- **Minimum tie provisions (Eurocode 1)**

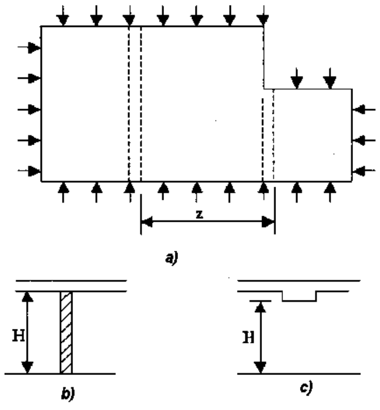
1. Framed structures

for internal ties: $T_i = 0.8(g_k + \psi q_k)sL$ or 75 kN, whichever is the greater

for perimeter ties: $T_p = 0.4(g_k + \psi q_k)sL$ or 75 kN, whichever is the greater

where s is the spacing of the ties

L is the span of the tie



2. Load-bearing wall construction

for internal ties: T_i = the greater of $T_i = F_t$ or $T_i = \frac{F_t(g_k + \psi q_k)}{7.5}\frac{z}{5}$

for peripheral ties $T_p = F_t$

where: F_t is 60 kN/m or 20 + 4 n_s kN/m, whichever is less

n_s is the number of stories

z is the lesser of 5 times the clear storey height, or the greatest distance in metres between the centres of the columns or walls spanned by a single slab

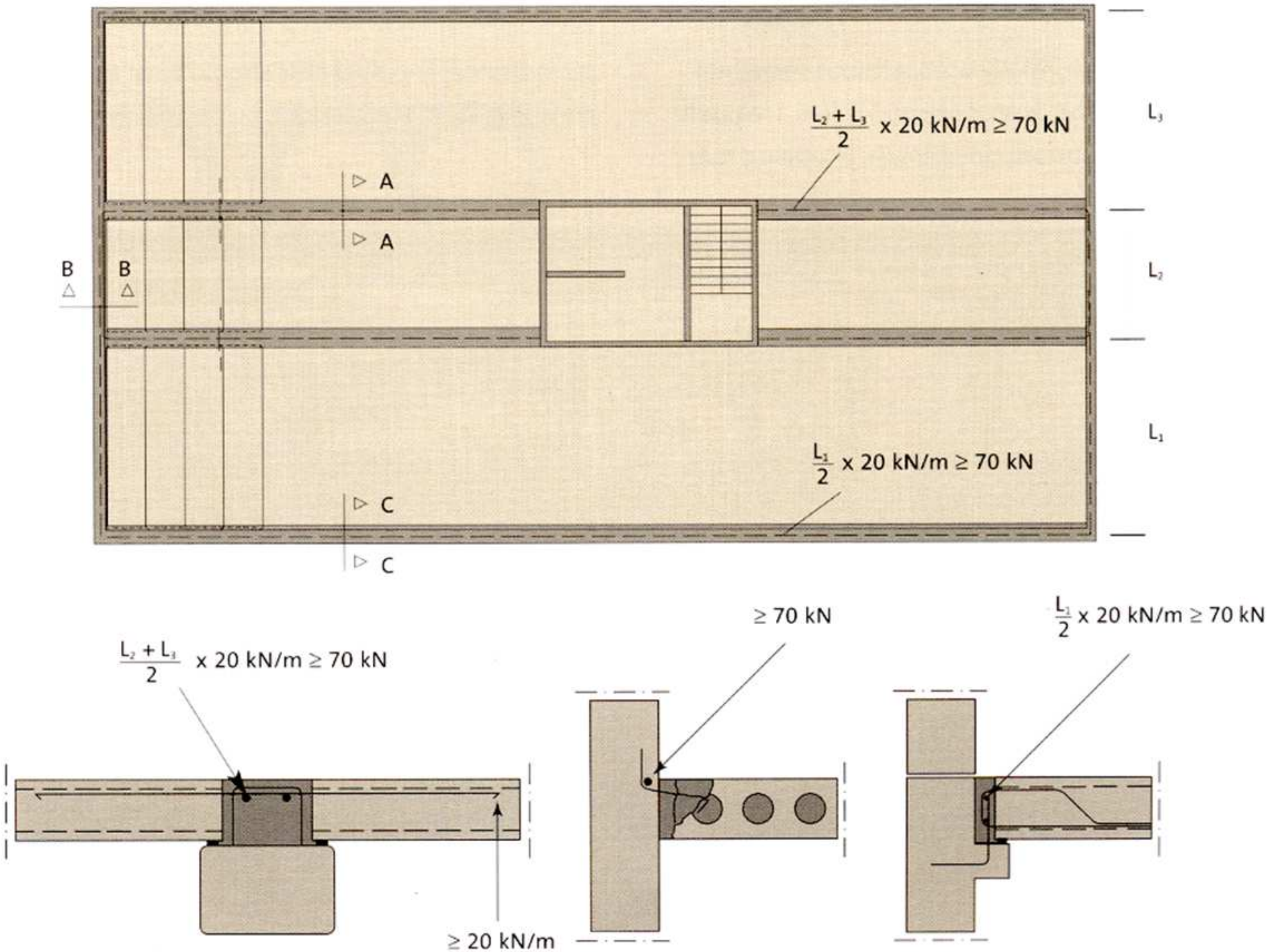
3. Vertical ties

Each column or wall should be tied continuously from the foundations to the roof level

The columns and walls should be capable of resisting an accidental force equal to the largest design vertical permanent and variable load reaction applied to the column from any one storey.

The fully tied method

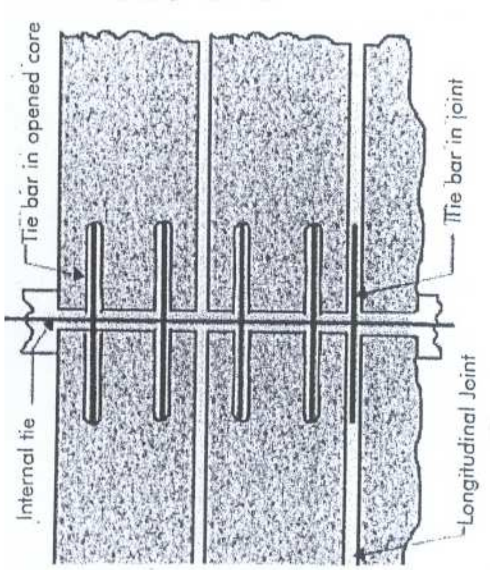
- **Minimum tie reinforcement (EN 1992-1-1 §9.10)**



The fully tied method

- Recommendations Eurocode 2

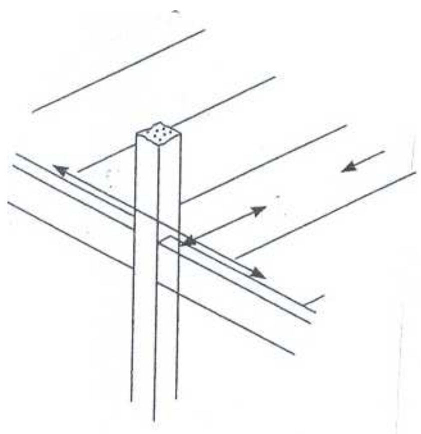
Internal floor ties



F_{TIE} = 20 kN/m x avg span

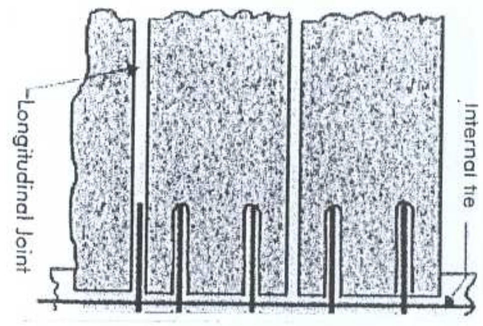
Remark: tensile forces are determined per 1 m length of the support

Direct connection to external column



F_{TIE} = 150 kN

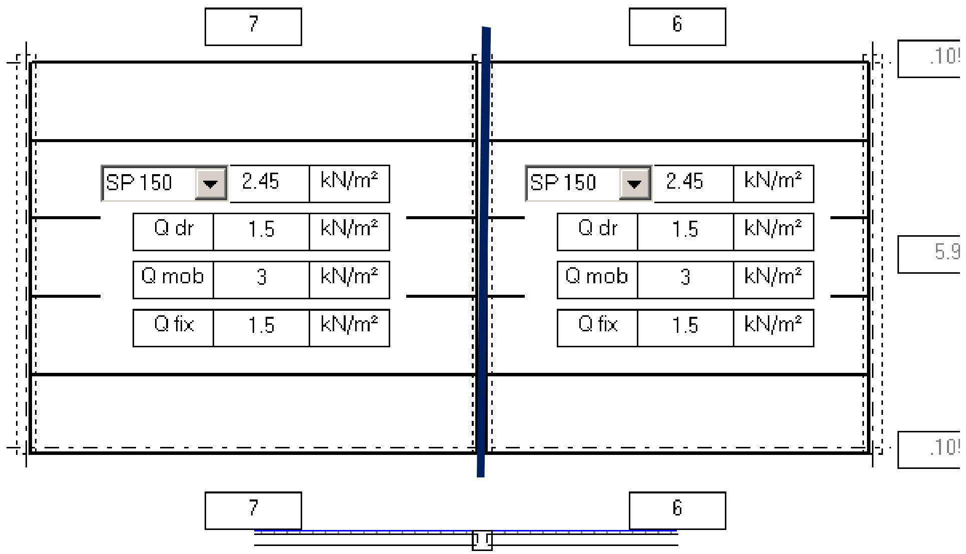
Peripheral floor ties connected to beam or wall



F_{TIE} = 20 kN/m x ½ span

Remark: tensile forces are determined per 1 m length of the support

The fully tied method example

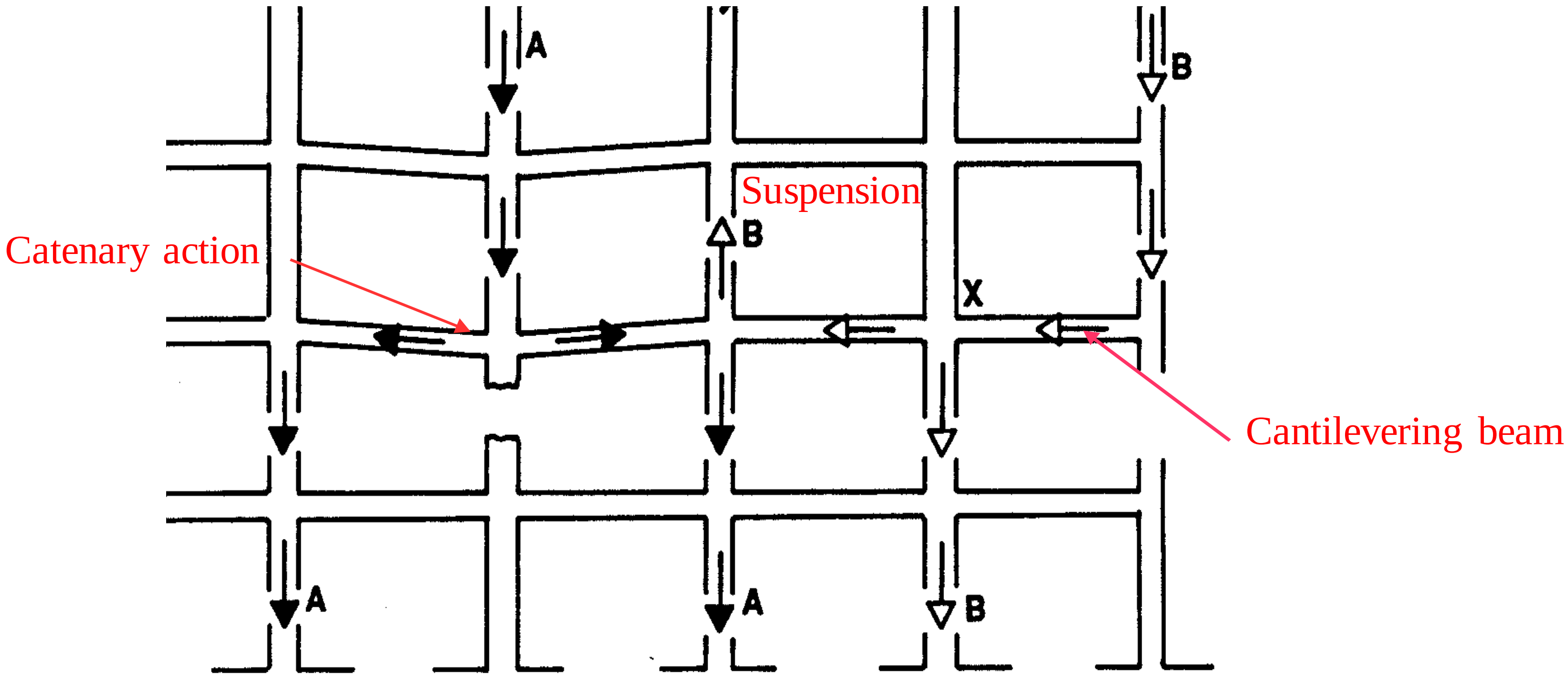


$g_k = 2.45 + 1.5 + 1.5 = 5.45$ kN/m²
$q_k = 3$ kN/m² ; $\psi = 0.7 \rightarrow 2.1$ kN/m²

- Eurocode 1:
  $T_i = 0.8 \times 7.55 \times (7 + 5)/2 \times 5.9 = 214$ kN >75 kN
  $\omega = T_i/f_{yd} = 214\,000/ (500/1.0) = 428$ mm² $\gamma_s = 1.0$
- Eurocode 2 §9.10.1 (4)
  $T_i = (7 + 5)/2 \times 20 = 120$ kN > 70 kN
  $\omega = T_i/f_{yk} = 120\,000/500 = 240$ mm²

b) The alternate path method

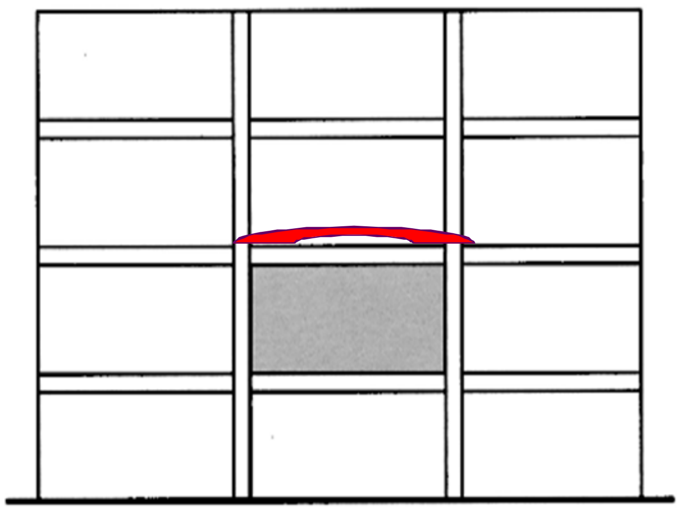
- **Mechanisms to provide for an alternate load path**



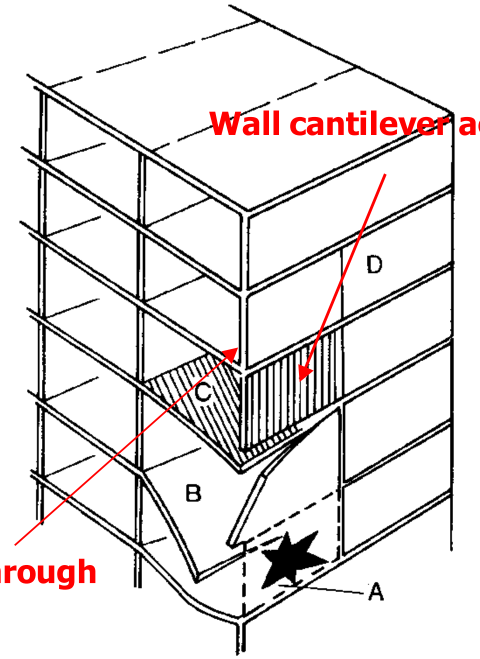
Alternative means of protection against progressive collapse in skeletal structures

Alternate load path method

- **Wall frame structures**



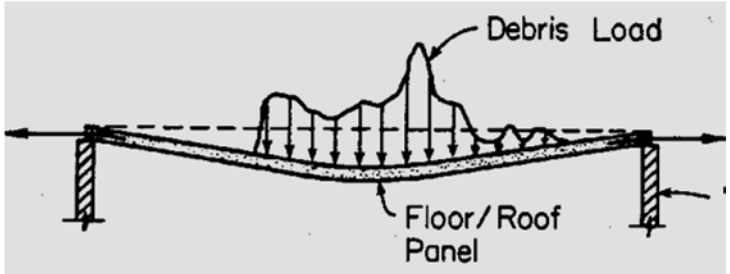
Bridging or catenary action

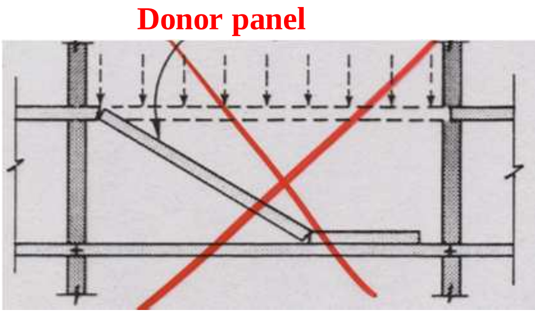


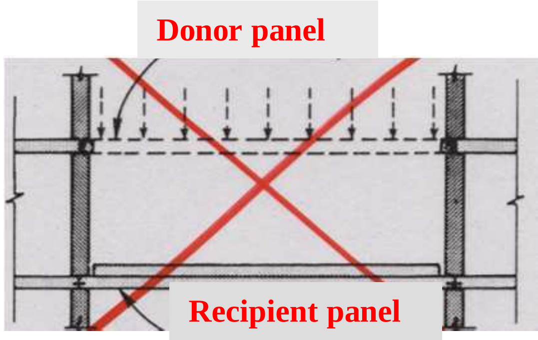
Alternate load path method

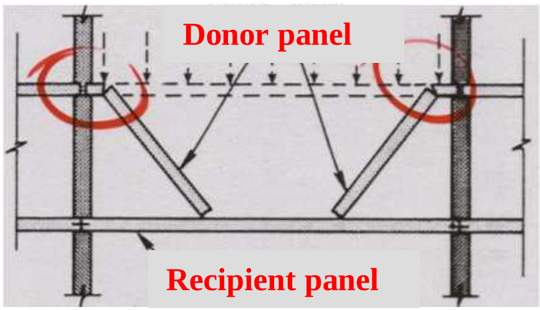
- **Design principles**

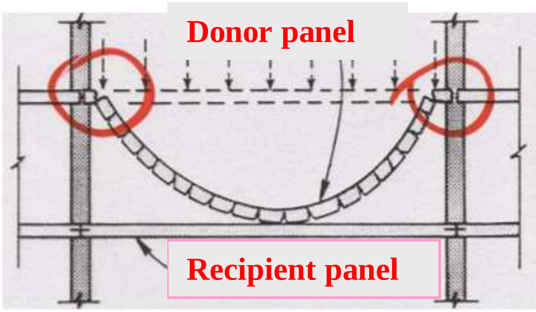
- Avoid impact load by accumulation of debris
- Strength, ductility and continuity of ties
- Good plan lay-out







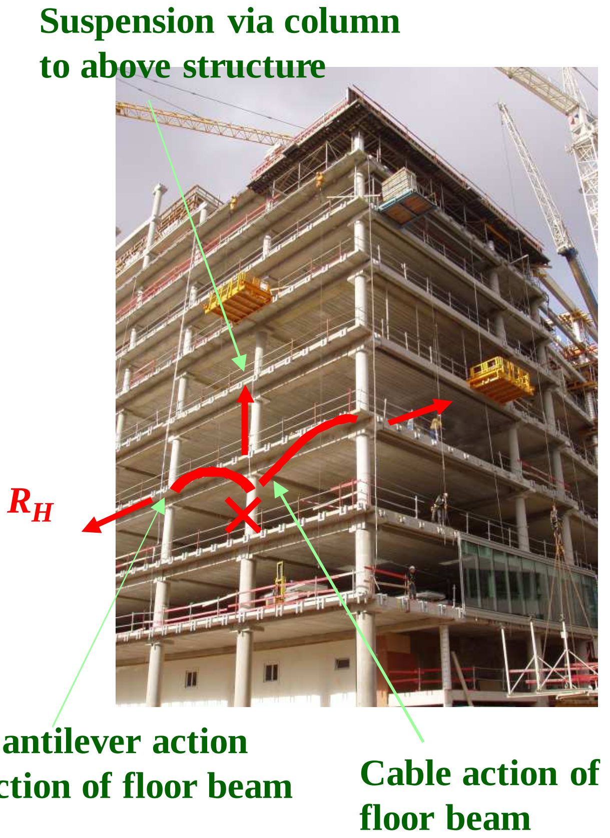


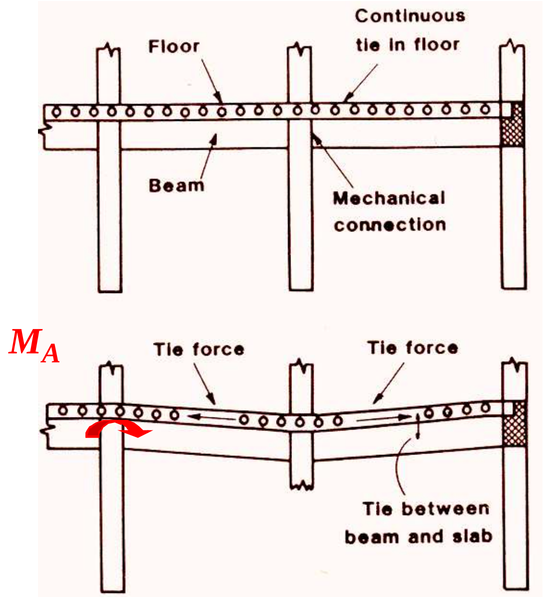


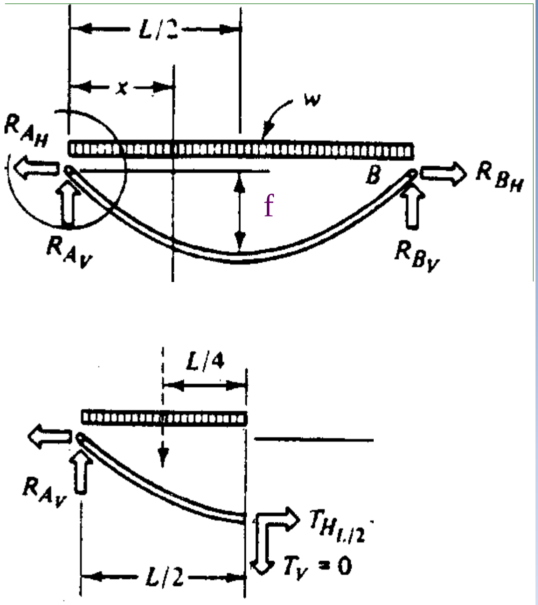
Possible collapse models of floors and roofs

Alternate load path method - example

- **Failure of intermediate façade column**







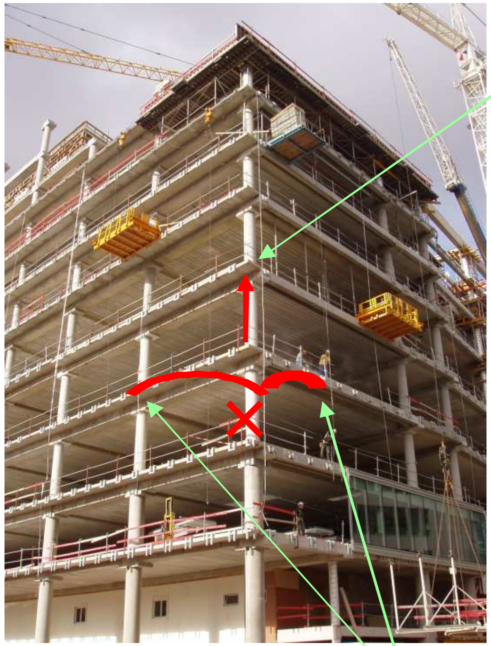
$R_H = (g_k + q_k)\, \ell^2 / 8f$ $\quad$ $f = 0.1\, \ell$

$M_A = (g_k + q_k)\, \ell^2 / 12$

Alternate load path method - example

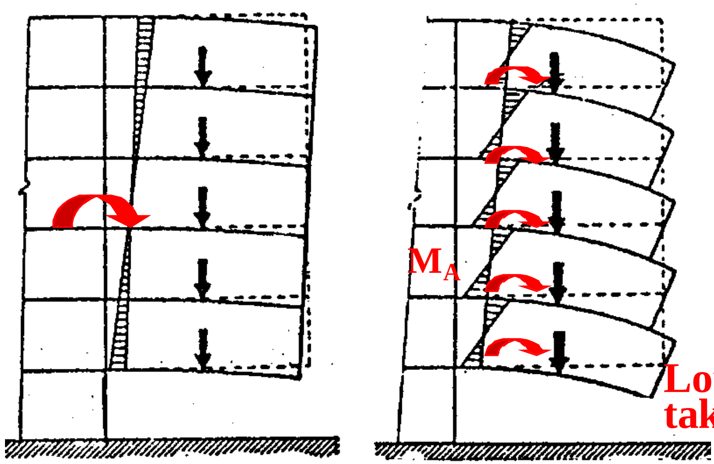
- **Failure of corner column or wall**

Suspension via column to above structure



Corner column taken away

Cantilever action of floor beams



Lower wall panel taken away

Cantilever action in wall frame structures

$M_A = (g_k+q_k)\,\ell^2/2$

c) 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 70 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. EN1991-1-7 A.8
  - 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.

d) Systematic risk assessment

EN1991-1-7 Annex B

- **Search for:**
  - A cause or threat
  - A mechanisme (sequence, or event)
  - The effects (death casualties, wounded, cost, enviromental impact …)

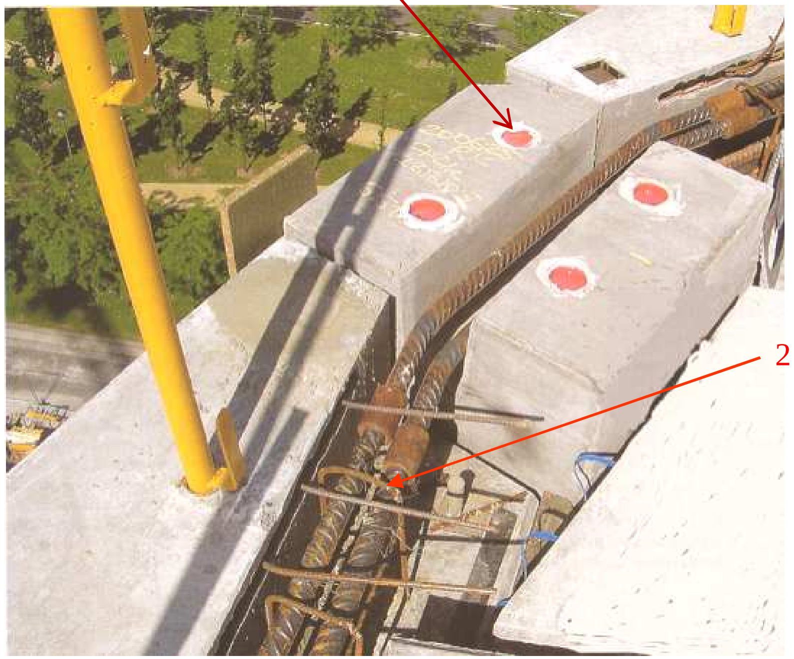
Use ALARP principle   B.5

(As Low As Reasonably Practical)

9. Detailing

- **Realisation peripheral ties**

Vertical tie connection



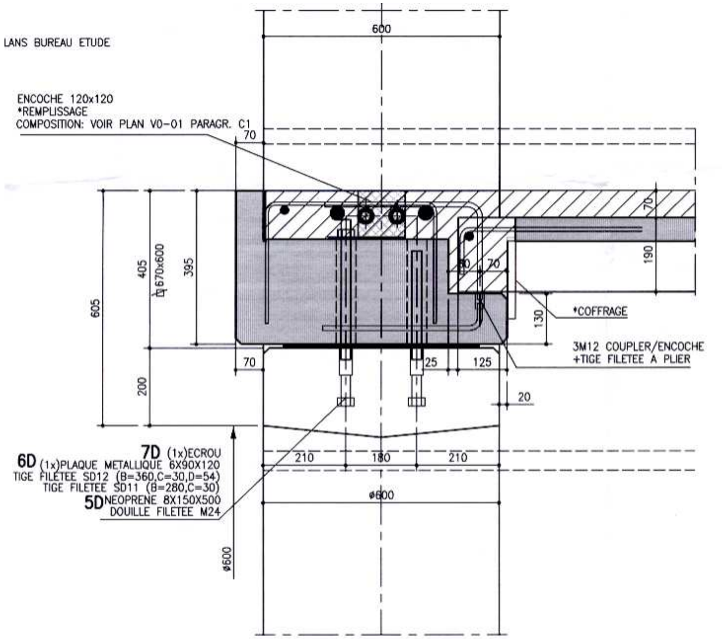
2 Ø 22

Detail tie beam

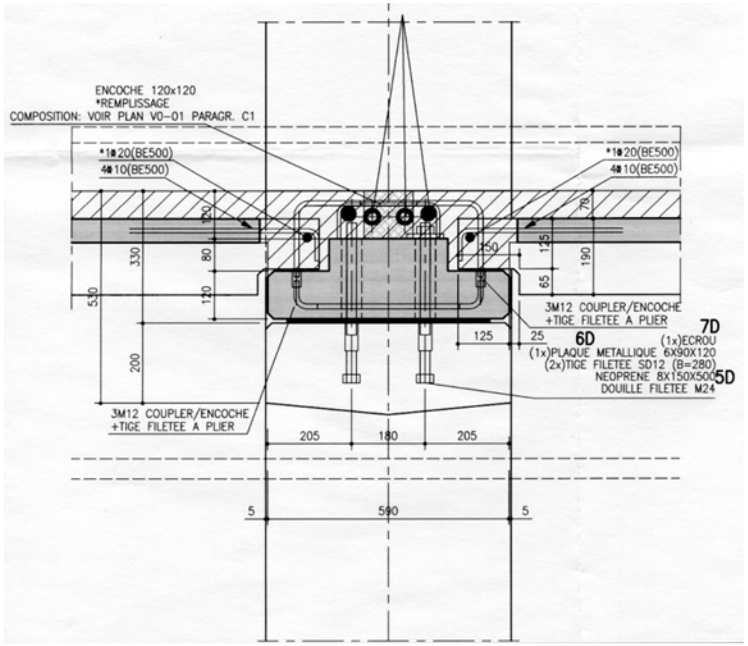
Tie provisions in skeletal tower building 26 floors

Detailing

- **Ties for catenary action**



Edge beam



Intermediate ebam

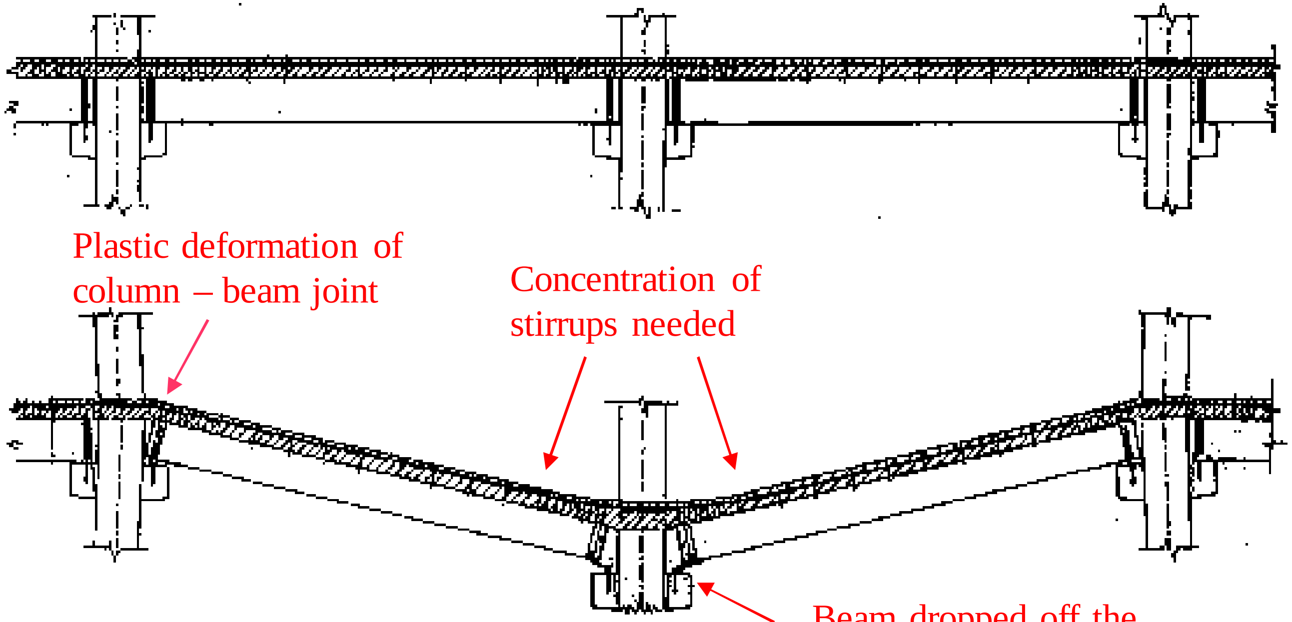
Detailing

- **Provisions for peripheral ties**

Sleeves in columns for passage of ties

Detailing

- **Bridging by catenary action**

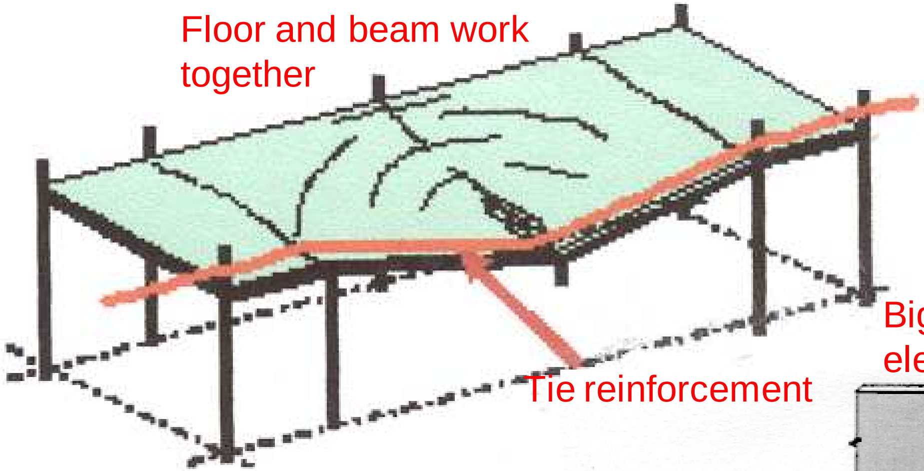


Floor beams supported by stirrups to catenary tie reinforcement

Catenary action

- **Difference between monolithic and precast**

Floor and beam work together



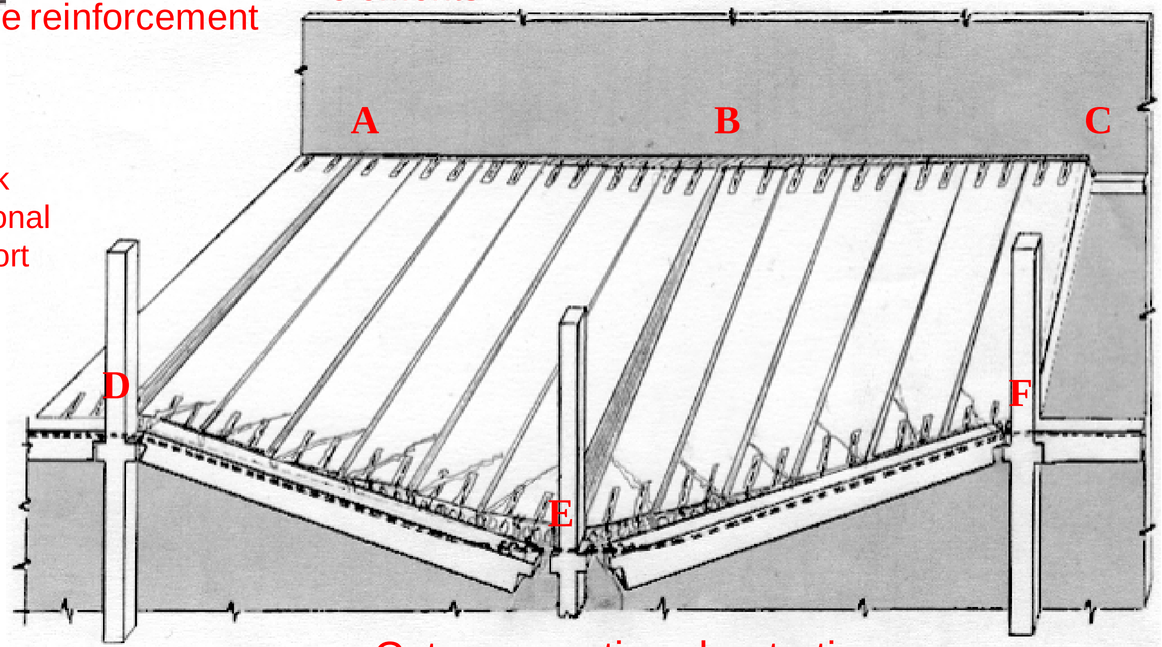
Tie reinforcement

Cast in situ

Joints between elements will break and we have torsional action at the support

Big cracks between the elements

Probably the topping will delaminate from the slab due to big deformations

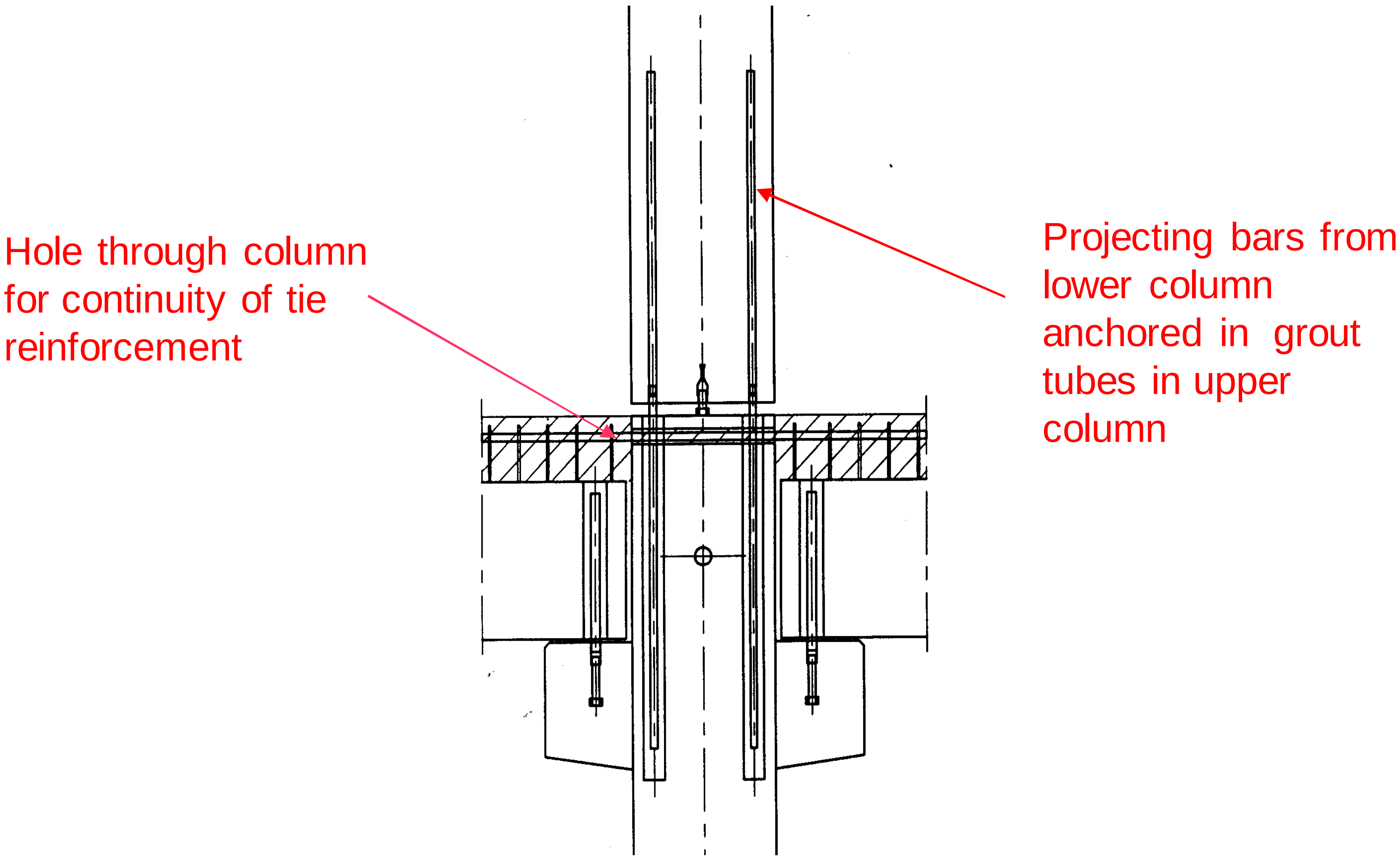


Precast with elements

Catenary action due to tie reinforcement in 2nd phase

Detailing

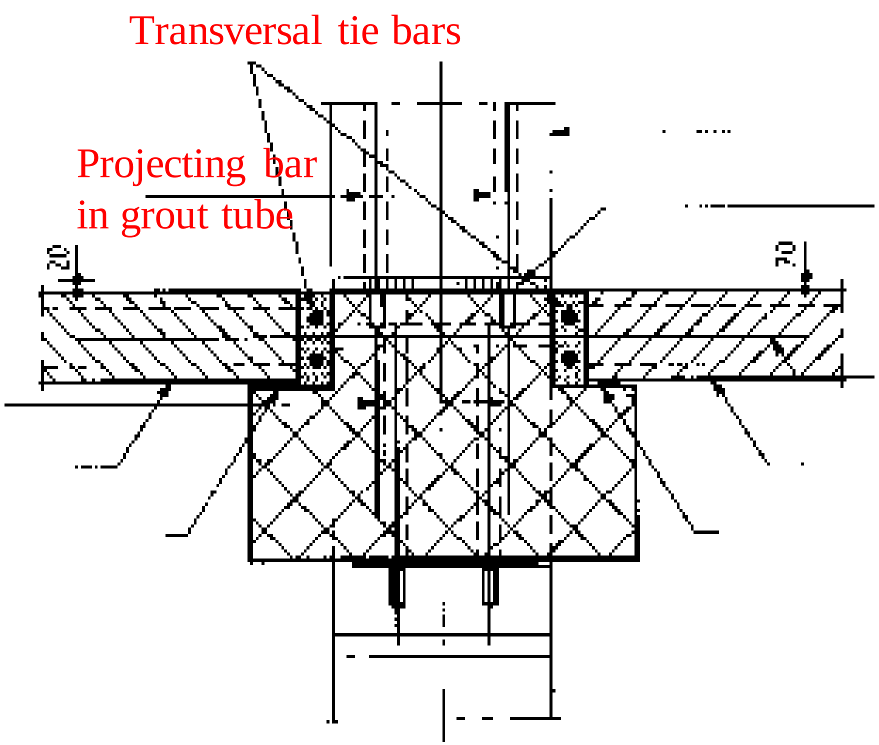
- **Column to column connections**



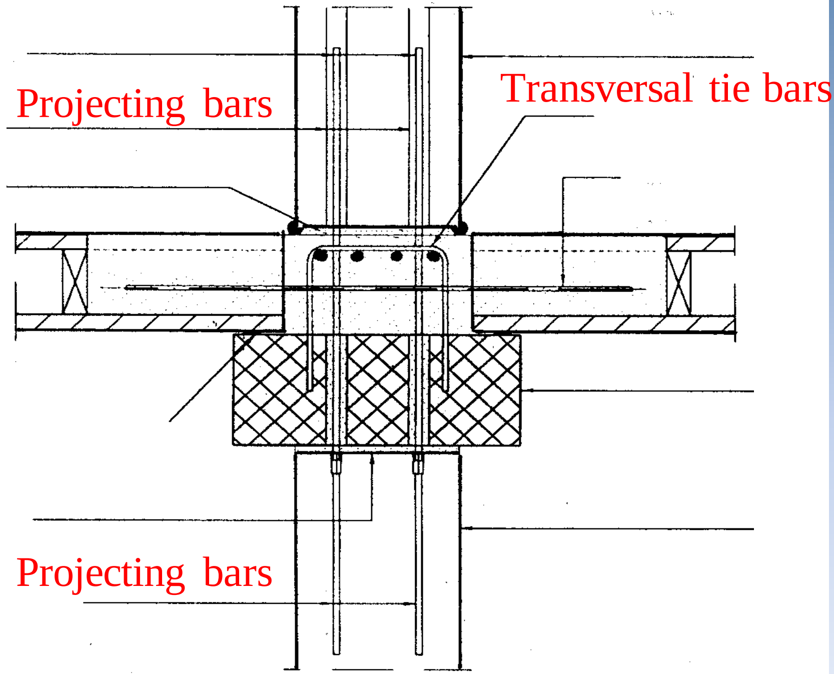
Example of column-to-column connection with good strength, anchorage and ductility characteristics to withstand abnormal loads from accidental actions

Detailing

- **Beam to floor connections**



(a) less good solution

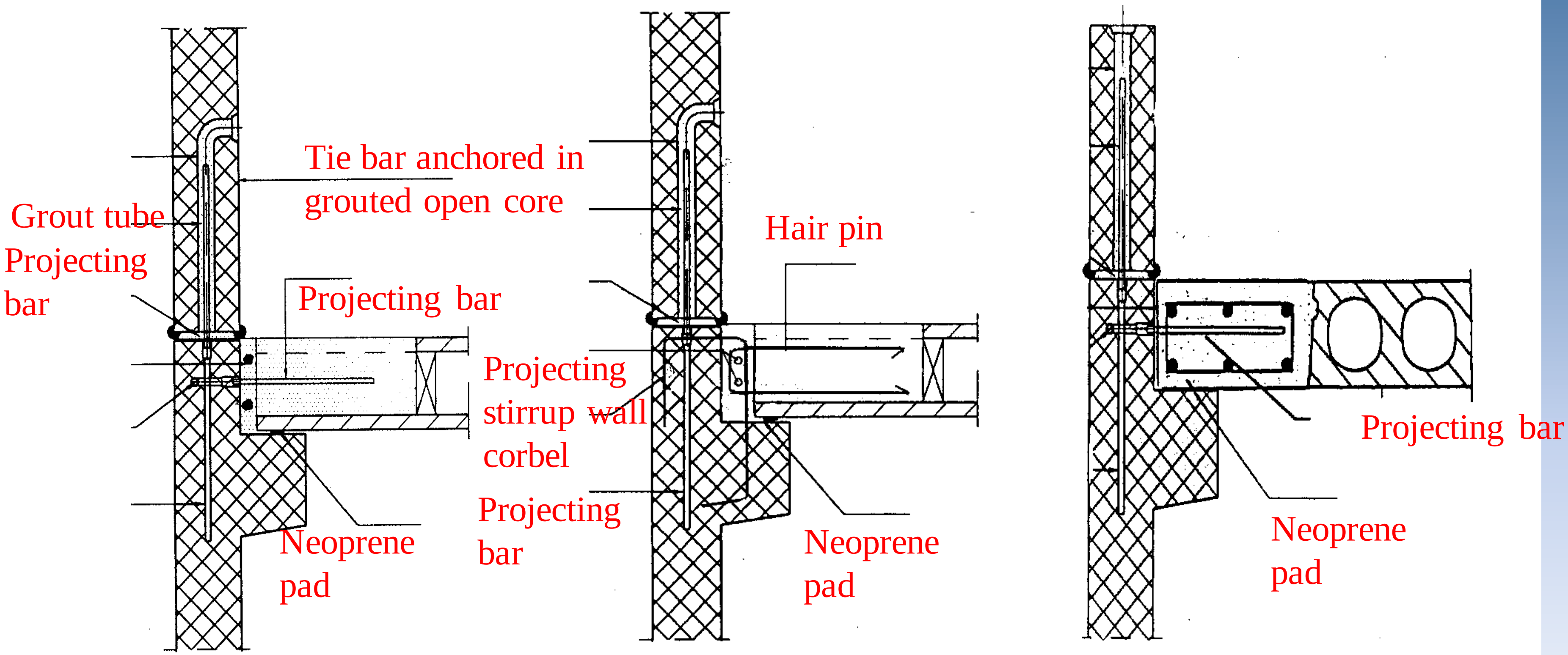


(b) good solution

Examples of transversal tie reinforcements in floor-beam connections

Detailing

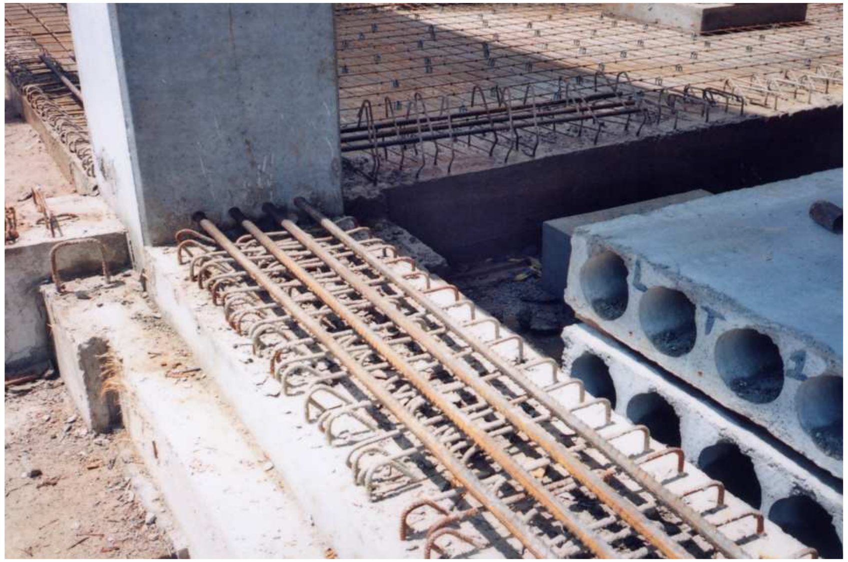
- **Wall to wall and wall to floor connections**



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

Detailing

- **Bad placement of longitudinal rebars**



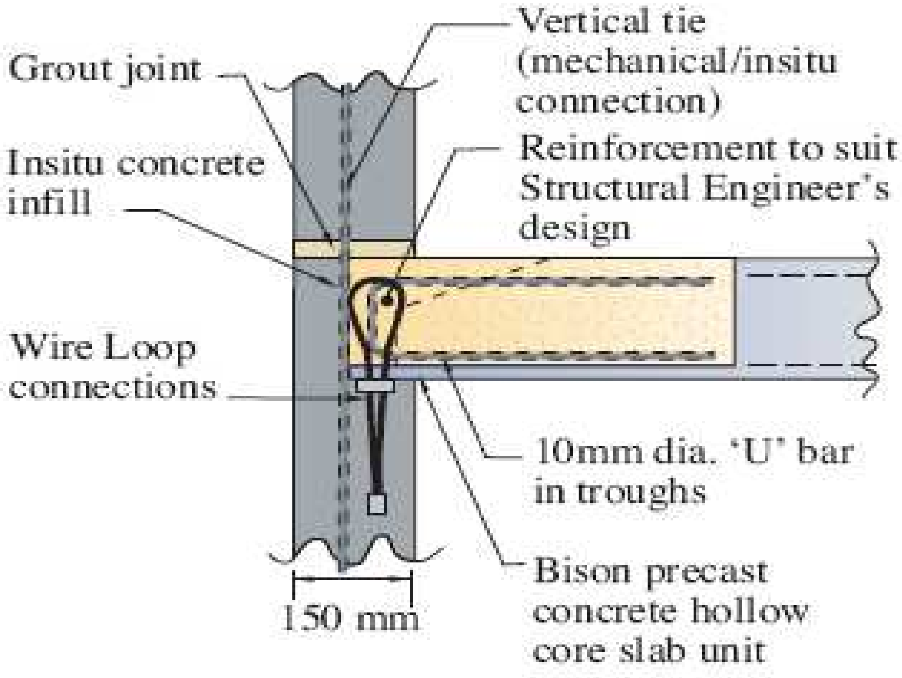

Bars should be inside the stirrups

Membrane action

After a lorry broke the beam, and because the connection between steeldeck and beam, the beam couldn’t turn away the compression and traction still did it’s work.

Detailing

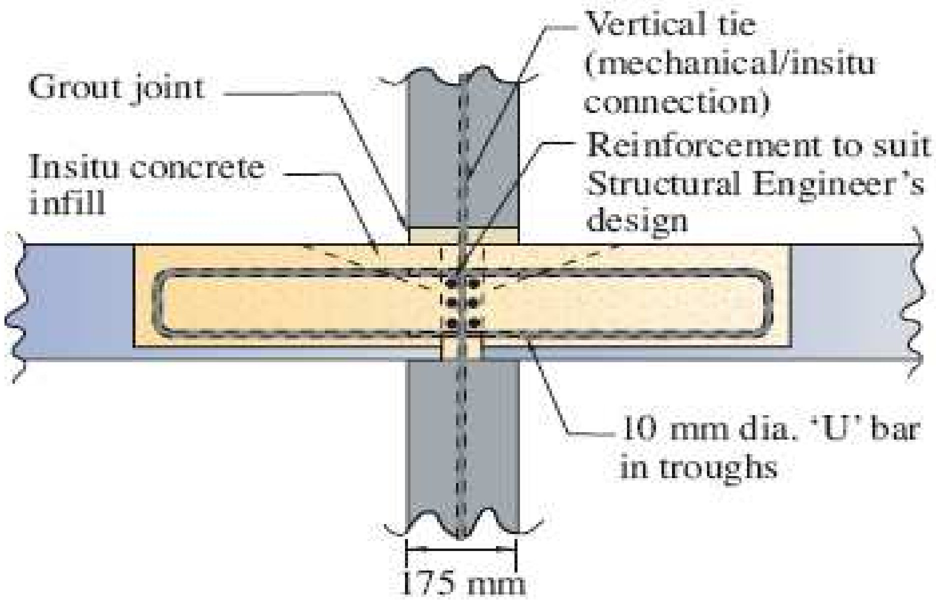
- **Wall to floor connections**



Typical section through load bearing edge wall

Detailing

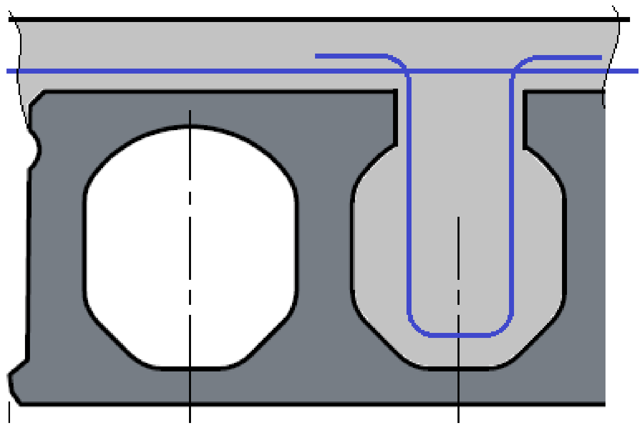
- **Wall to floor connection**

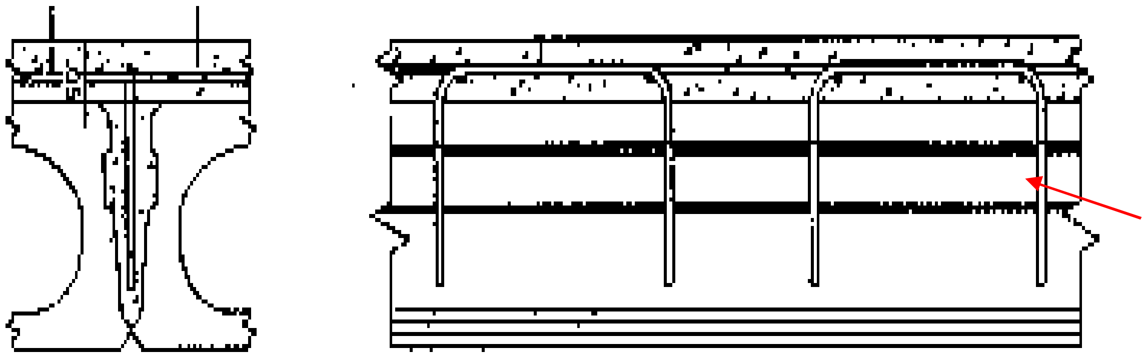


Typical section through internal load bearing wall

Detailing

- **Floor connections**

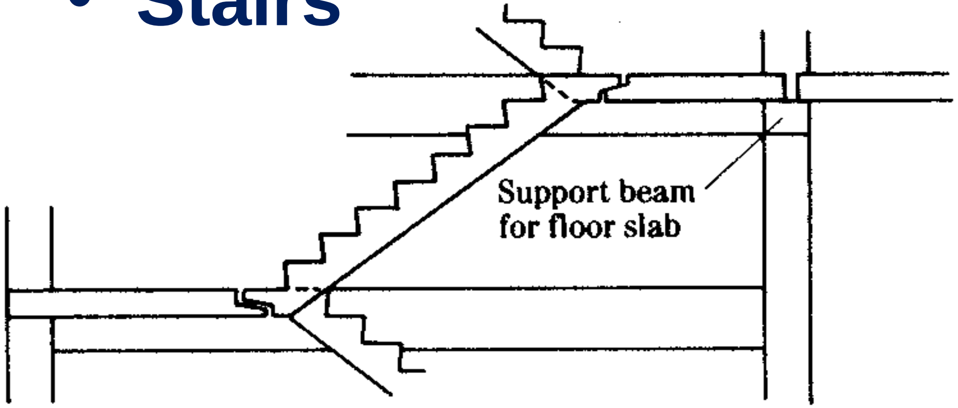


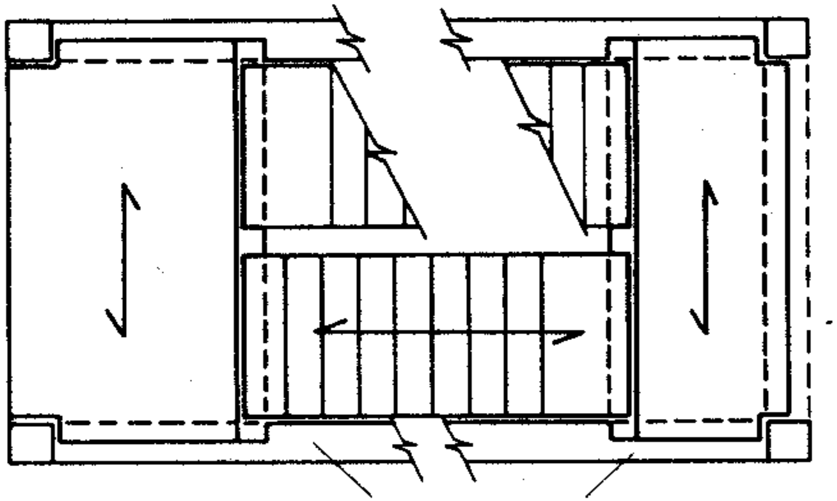


Connection between reinforcement in structural topping and hollow core floor by means of vertical stirrups anchored in the longitudinal joints or in partial opened chanal.

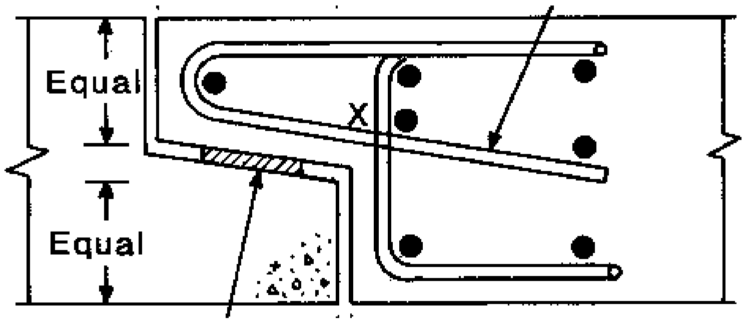
Detailing

- **Stairs**

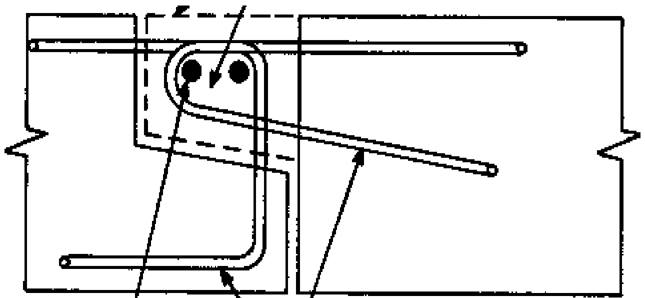




Support beams for half-landing and landing



(a) Reinforcement in stair scarf joint



(b) intermittent scarf joint

Staircase to landing joint details

Thanks for listening

Are there any questions ?