System Design Fundamentals

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Civil Engineering

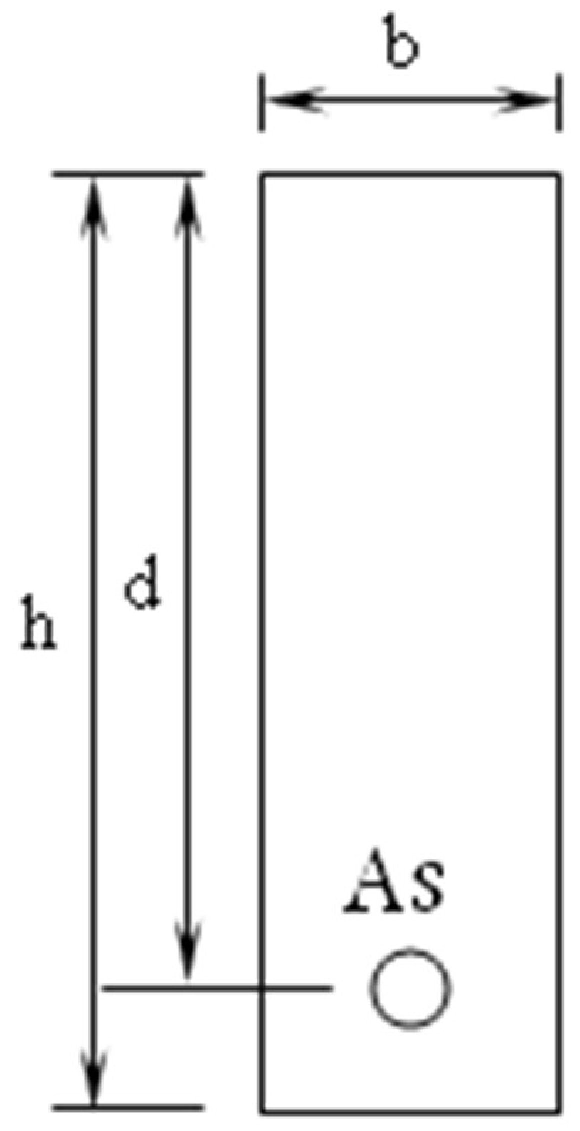
System Design Fundamentals

Objectives:

-to introduce the building construction determinant

-to analyze different systems by finite element method and analogical methods

-to build conceptual abilities in designing reinforced concrete elements.



Preface

- Most of the education and research is concentrated in analytical and anatomical skills and very little in creativity skills (analogical skills) which is fundamental in design.
- Creativity is the ability to conceive, generate design alternatives and preserve environment. It requires compositional ability.
- Compositional ability requires conceptual understanding which is based on both: “a feeling” for behavior and “approximate” analysis\design skills

Preface

- System design addresses the need for conceptual design skills.
- A design project provides opportunity for teams of students to create conceptual designs and make representations to a design "jury".
- It provides opportunity to concentrate on the structure as a whole and very little on the element behaviour.
- The conceptual design is based on a systematical approach

Chapter 1 Introduction

- Introduction to systems
- Purpose
- System determinants
- Standards versus codes
- Fundamentals of thinking

Introduction to systems:

- A system can be defined as a group of related parts that move or work together.

- A system is a necessary part of life. It occurs at any level, ranging from the molecular structure of material to laws of universe.

- As **order**, it relates all the parts of a whole reflecting some pattern of **organization**.

- Everything has system, even if we have not yet recognized it. Societies are a form of structural systems to properly function- language has system, the interrelationship of plants and animals with their **environment** represents equilibrium in nature which is a system by itself.

Purpose

- The purpose of a system is to combine global understanding with local details.
  - Discuss face of human being and how systematically it combines architectural, structural, mechanical and electrical systems
  - Analogy between a mosque and shape of human raising his hands.

System determinants:

Engineering systems must develop:

- **Support system (structure\science)**:
- It holds the structure up so that it does not collapse. A need for **strength** to achieve this.
- It prevents elements to deform or crack excessively. A need for **serviceability** to achieve this.
- It makes the structure withstands severe events (like earthquakes, wind storms, …). A **special\stable** design is needed to achieve this (**savings** in materials: smaller sections + larger strength).

System determinants

- **Faith system (facts\fashion):**

It Defines

- space configuration based on **functional** needs (social, economical),
- The capacity of adaptation based on **freedom** needs (legal, environmental)
- geometrical shape based on **form** needs (culture, esthetics)

Standards versus codes

- Standard means an approved model or level of quality
- Code means a set of rules
- Minimum standards are controlled by design codes.
- Design codes are based on model codes which often specify a particular industry standard.
- Municipal and state governments adopt the model codes (or develop their own codes) and thus provide legally enforceable laws with which the engineer must comply.
- The intent of the code is not to limit engineering creativity, but to provide minimum standards to safeguard the health and safety of the public.

Fundamentals of Design

Input: **decompose** problem into components

know **degree** of components

draw a mathematical model

Processing: **define** laws governing mechanics

provide **details** needed to solve problem

design methodology to solve problem (manual, computer)

Output: **deliver** solution in a nice way

enhance solution to values (**dean)**

develop capability to solve problems

Decomposition

- Architectural
- Structural
- Mechanical
- Electrical
- ….
- Earthquake:
  - Geology
  - Seismology
  - Geotechnical: soil+foundation
  - Structural

Degree of components

- Structure first before architectural
- Scalar, vector, stress,…., elasticity constants

draw a mathematical model

- 1D models
- 2D models
- 3D models
- ….

Define laws

- **Laws**: conceptual according to degree
  - constitutive relationships: stress-strain relationships
  - Counter-balance: equilibrium equations
  - compatibility equations: kinematics

- **Theories**:
  - Based on:
  - Assumptions based on:
  - Available knowledge is constrained with:

Details needed: definitions

- ***Conceptual is needed at first to save time:***

"what an engineer can do on a back of an envelope cannot tons of computer output do"

Design methodology for solving problems

Input
1. Problem to be solved
2. Physics of problem
3. Mathematical model

Processing
1. Propose theory
2. Formulate equations
3. Solve equations

Output
1. Verify laws
2. Build engineering sense
3. Start a new cycle

Fundamentals of thinking: Input

- Start with present worked examples (get advantage of other thoughts-how Japan builds up quickly).

1. See (a good engineer is a good observer),
2. Read (plans of others),
3. Ask (learn how to gather hidden information making sure you are satisfied with the answer, if not then argue but be careful not to go more than one round for each point (learn how to express yourself in words))

Fundamentals of thinking: Input and Processing

- Try to <u>solve the problem by</u>:

1. Study your subject first of all.
2. Get an overview about all tasks needed for solution.
3. Select members of your team based on qualifications: capability to do the work + commitment.

Choose a qualified team leader.

1. Divide the tasks between the team members.
2. Put a study plan (allocate time for each task + plan alternatives).
3. Think how to do your part of the work on paper (learn how to express yourself in writing).

Fundamentals of thinking: Processing and Output

- Systematical management of tasks

1. Survey literature of the subject (system determinants). Be careful to cover all sides of the problem.
2. Put a plan how to cover general principles before particular ones
3. Make sure to stress the important issues and basic principles (support your work by scientific proof)

Put contents of your final report

1. Unify with your team members all symbols, wording, software …etc to be used to present the final report.
2. Perform your study plan and see how well it is.
3. Get feed back from all your team members about the whole project to decide to continue or go to alternatives

End of chapter 1

Let Learning Continue

Chapter 2 Design methodology

- Limit States Design
  - Strength Limit State
  - Serviceability Limit State
  - Special Limit State
- Limit States Design
  - Design Philosophy
  - Strength Design Method
  - Safety Provisions
    - Variability in Resistance
    - Variability in Loading
    - Consequences of Failure
    - Margin of Safety

Limit State Design

Limit State:

Condition in which a structure or structural element is no longer acceptable for its intended use.

Major groups for RC structural limit states

- Strength
- Serviceability
- Special

Strength Limit State

– Structural collapse of all or part of the structure (very low probability of occurrence) and loss of life can occur (a structure will not fail as long as there is a safe load path to the foundation). Major limit states are:

(a) Loss of equilibrium of a part or all of a structure as a rigid body (tipping, sliding of structure…: reaction could not be developed).

(b) Rupture of critical components causing partial or complete collapse. (flexural, shear failure…).

Strength Limit States

(c) Progressive Collapse

- Minor local failure overloads causing adjacent members to fail until entire structure collapses.
- Structural integrity is provided by tying the structure together with correct detailing of reinforcement which provides alternative load paths to prevent localized failure.

Serviceability Limit State

- Functional use of structure is disrupted, but collapse is not expected. More often tolerated than a strength limit state since less danger of loss of life. Major limit states are:

  (a) Excessive crack width leads to leakage which causes corrosion of reinforcement resulting in gradual deterioration of structure.

  (b) Excessive deflections for normal service

  - malfunction of machinery
  - visually unacceptable
  - damage of nonstructural elements
  - changes in force distributions (no compatibility)
  - ponding on roofs leading to collapse of roof

Serviceability Limit State

(c) Undesirable vibrations

- Vertical: floors/ bridges
- Lateral\torsional: tall buildings

Special Limit State

Damage/failure caused by abnormal conditions or loading.
These could be due to:

(a) Extreme earthquakes: damage/collapse

(b) Floods: damage/collapse

(c) Effects of fire, explosions, or vehicular collisions.

(d) Effects of corrosion, deterioration

(e) Long-term physical or chemical instability

Limit States Design

- Identify all potential modes of failure.
- Determine acceptable safety levels for normal structures building codes → load combination factors.

Limit States Design

- Consider the significant limit states.
  - Members are designed for strength limit states
  - Serviceability is checked.

    Exceptions may include
    - water tanks (crack width)
    - monorails (deflection)
    - Noise in auditoriums

Design Philosophy

Two philosophies of design have long prevalent.

(a)Working stress method focusing on conditions at service loads.

(b)Strength design method focusing on conditions at loads greater than the service loads when failure may be imminent.

The strength design method is deemed conceptually more realistic to establish structural safety.

Strength Design Method

In the strength method, the service loads are increased sufficiently by factors to obtain the load at which failure is considered to be "imminent". This load is called the ***factored load*** or ***factored service load***.

$$\text{strength provided} \geq \begin{bmatrix} \text{strength required to} \\ \text{carry factored loads} \end{bmatrix}$$

Strength Design Method

Strength provided is computed in accordance with rules and assumptions of behavior prescribed by the building code and the strength required is obtained by performing a structural analysis using factored loads.

The "***strength provided***" has commonly referred to (wrongly) as "***ultimate strength***". However, it is a code defined value for strength and not necessarily "***ultimate***". The ACI Code uses a conservative definition of strength.

Safety Provisions

Structures and structural members must always be designed to carry some reserve load above what is expected under normal use.

There are three main reasons why some sorts of safety factor are necessary in structural design.

[1] Variability in resistance.

[2] Variability in loading.

[3] Consequences of failure.

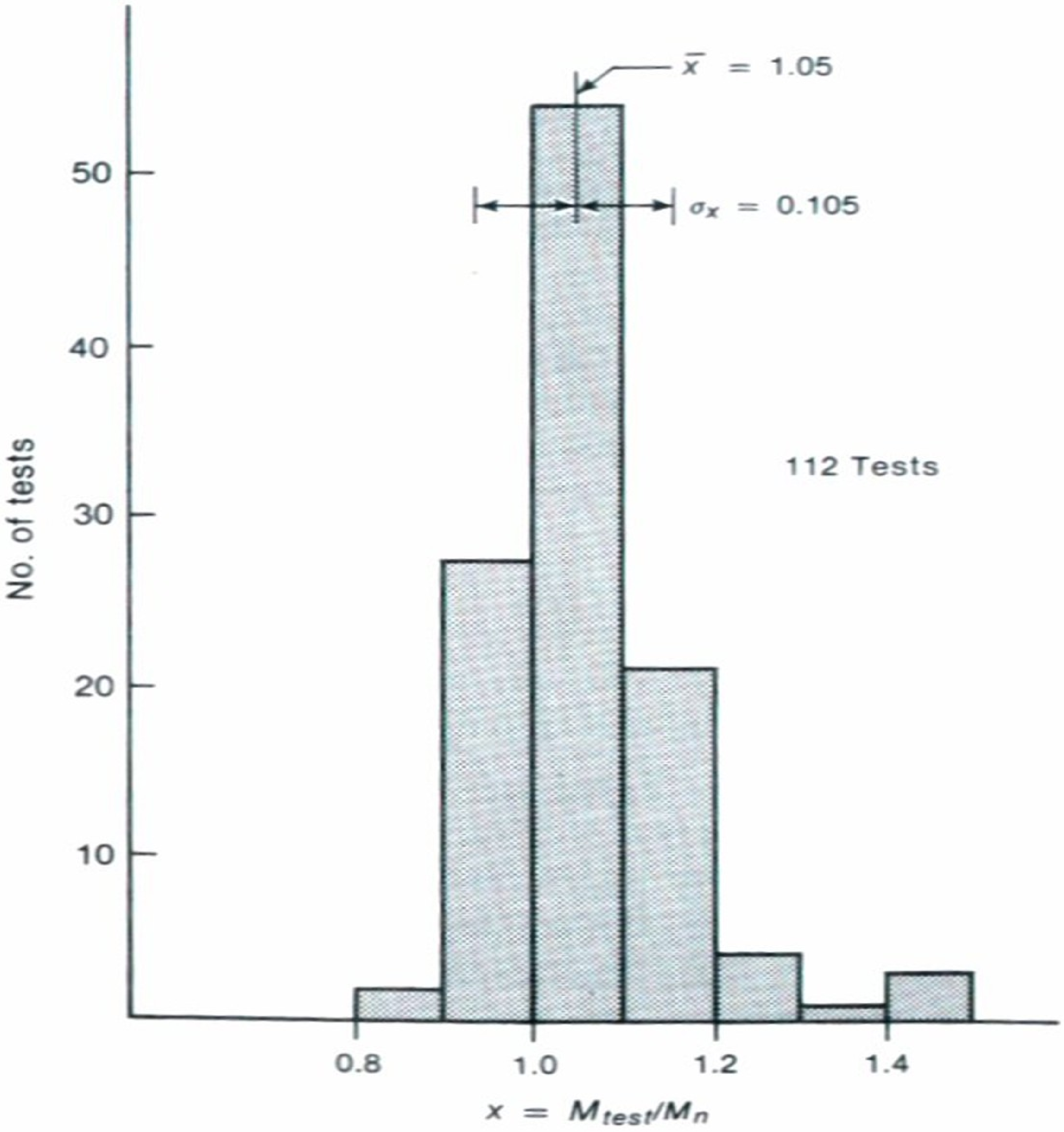
Variability in Resistance: R

- Variability of the strengths of concrete and reinforcement.
- Differences between the as-built dimensions and those found in structural drawings.
- Effects of simplification made in the derivation of the members resistance (i.e. simplifying assumptions).

Variability in Resistance: R

Comparison of measured and computed failure moments based on all data for reinforced concrete beams with $f_c > 14MPa$

The variability shown is due largely to simplifying assumptions.



Variability in sustained Loads: S

Frequency distribution of sustained component of live loads in offices.

<u>In small areas:</u>

Average=0.65kN/m^2

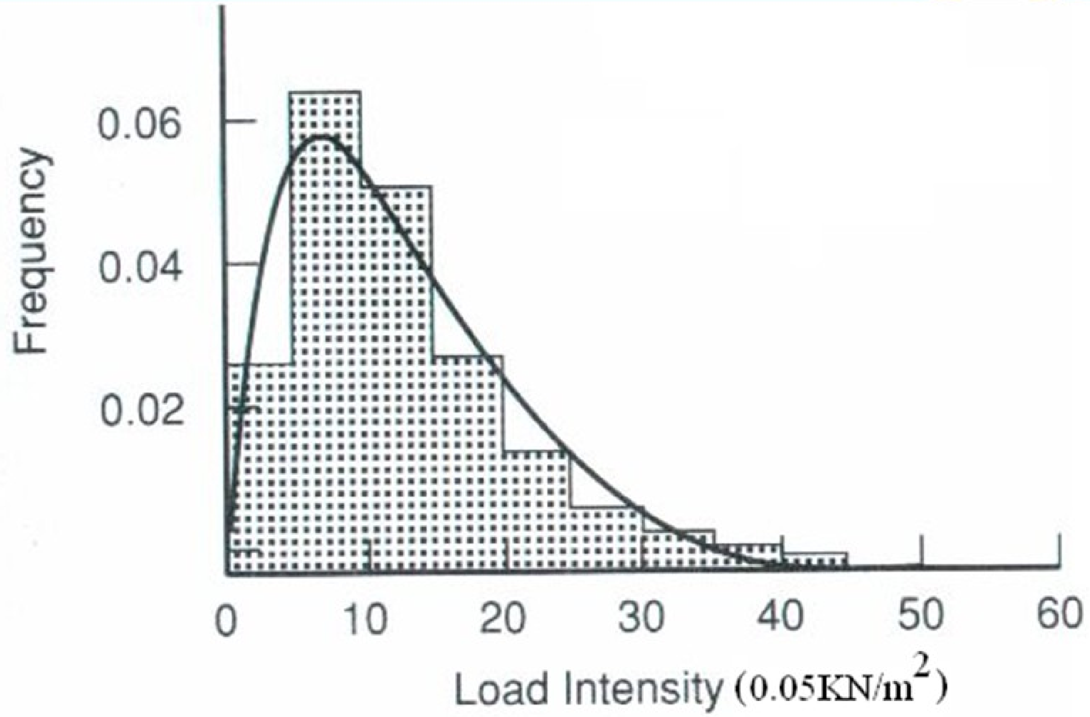
1% exceeded=2.2kN/m^2

Code use 2.5kN/m^2

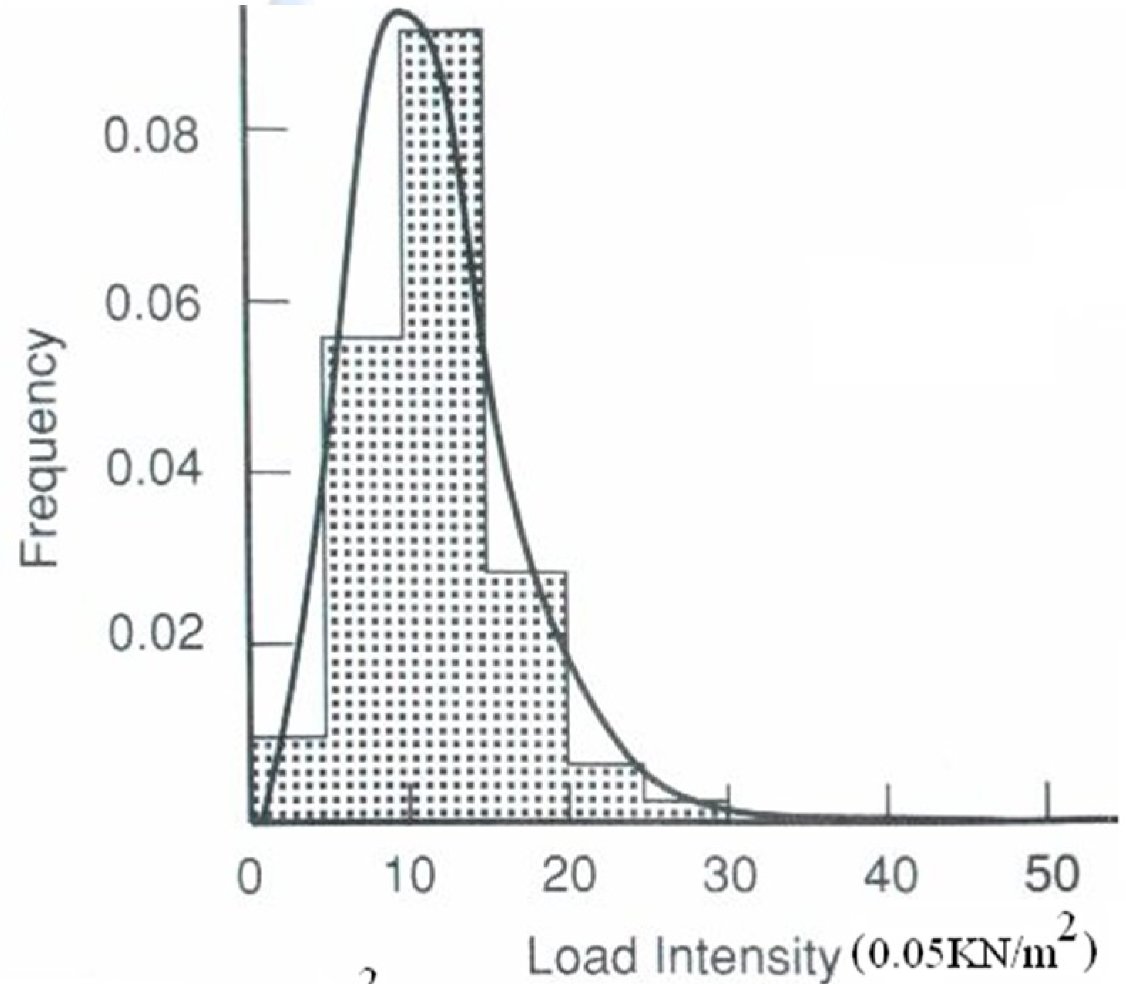
<u>In large areas:</u>

average almost the same, but variability decreases.

(notice that large areas can be used for parties, temporary storage…etc, thus larger LL is needed)



(a) Area = 14 m^2



(a) Area = 190 m^2

Consequences of Failure

A number of subjective factors must be considered in determining an acceptable level of safety.

- Potential loss of life: larger SF for auditorium than a storage building.
- Cost of clearing the debris and replacement of the structure and its contents.
- Cost to society: collapse of a major road.
- Type of failure, warning of failure, existence of alternative load paths.

Margin of Safety

The term

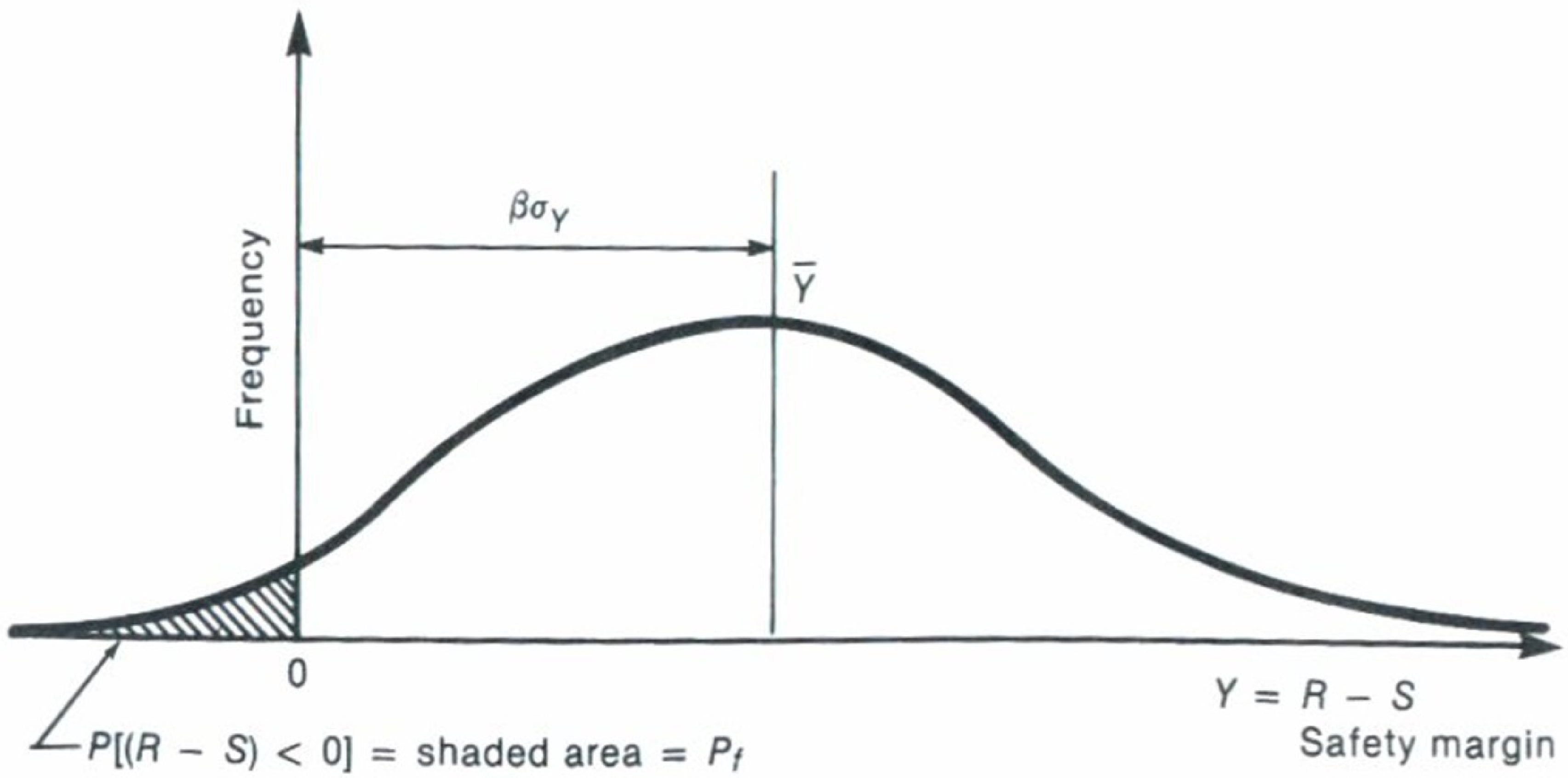
$$Y = R - S$$

is called the safety margin. The probability of failure is defined as:

$$P_f = \text{Probability of } [Y < 0]$$

and the safety index is

$$\beta = \frac{\overline{Y}}{\sigma_Y}$$



Problem set #1 Due (   )

- Types of design can be classified as:
  - Creative
  - Development
  - Copy
- Analyze previous types showing advantages and disadvantages of each type in view of what you learned from previous two chapters.

End of chapter 2

Let Learning Continue

Chapter 3 Loadings

- Loading Specifications
- Dead Loads
- Live Loads
- Environmental Loads
- Classification of Buildings for Wind, Snow and Earthquake Loads
  - Snow Loads
  - Earthquake Loads
- Roof Loads
- Construction Loads
- Load factors

Building Codes

Cities in the U.S. generally base their building code on one of the three model codes:

- Uniform Building Code
- Basic Building Code (BOCA)
- Standard Building Code

These codes have been consolidated in the 2000 *International Building Code*.

Loading Specifications

Loadings in these codes are mainly based on *ASCE Minimum Design Loads for Buildings and Other Structures* ASCE 7-10.

Dead Loads

- Weight of all permanent construction
- Constant magnitude and fixed location

Examples:

- Weight of the Structure
  (Walls, Floors, Roofs, Ceilings, Stairways)
- Fixed Service Equipment
  (HVAC, Piping Weights, Cable Tray, etc.

Live Loads

- Loads produced by use and occupancy of the structure.
- Maximum loads likely to be produced by the intended use.
- Not less than the minimum uniformly distributed load given by Code.

Live Loads

See Table 4-1 from *ASCE 7-05*

Stairs and exitways:	4.8KN/m^2.
Storage warehouses:	6KN/m^2 (light)
	12 KN/m^2 (heavy)

Minimum concentrated loads are also given in the codes.

Live Loads

ASCE 7-05 allows reduced live loads for members with influence area (K_{LL} A_T) of 38m² or more (not applied for roof):

$$L = L_o \left(0.25 + \frac{4.6}{\sqrt{K_{LL} A_T}} \right)$$

where L ≥ 0.50 L_o for members supporting one floor

≥ 0.40 L_o otherwise

K_{LL} =live load element factor (Table 4.2)

=2 for beams

=4 for columns

Environmental Loads

- Snow Loads
- Earthquake
- Wind
- Soil Pressure
- Roof Loads
- Temperature Differentials
- …etc

Classification of Buildings for Wind, Snow and Earthquake Loads

Based on Use Categories (I through IV)

I Buildings and other structures that represent a low hazard to human life in the event of a failure (such as agricultural facilities), I=1

II Buildings/structures not in categories I, III, and IV, I=1

Classification of Buildings for Wind, Snow and Earthquake Loads

III Buildings/structures that represent a substantial hazard to human life in the event of a failure (assembly halls, schools, colleges, jails, buildings containing toxic/explosive substances), I=1.25

IV Buildings/structures designated essential facilities (hospitals, fire and police stations, communication centers, power-generating stations), I=1.5

Snow Loads

Ground Snow Loads:

- Based on historical data (not always the maximum values)
- Basic equation in codes is for flat roof snow loads
- Additional equations for drifting effects, sloped roofs, etc.
- Use ACI live load factor
- No LL reduction factor allowed
- Use 1KN/m^2 as minimum snow load, multiply it by I (importance factor)

Earthquake Loads

Inertia forces caused by earthquake motion

$$F = m * a$$

- Distribution of forces can be found using equivalent static force procedure (code, not allowed for every building) or using dynamic analysis procedures (computer applications).

Roof Loads

- Ponding of rainwater
  - Roof must be able to support all rainwater that could accumulate in an area if primary drains were blocked.

  - Ponding Failure (steel structures):
    → Rain water ponds in area of maximum deflection
    → increases deflection
    → allows more accumulation of water → cycle continues…→ potential failure

- Roof loads (like storage tanks) in addition to snow loads

- Minimum loads for workers and construction materials during erection and repair

Construction Loads

- Construction materials
- Weight of formwork supporting weight of fresh concrete
- Basement walls
- Water tanks

Load factors

The loading variations are taken into consideration by using a series of "load factors" to determine the ultimate load, U.

$$U = 1.4D$$

$$U = 1.2D + 1.6L$$

$$U = 1.2D + 1.6W + 1.0L$$

$$U = 1.2D + 1.0E + 1.0L$$

$$U = 0.9D + E; \ldots \text{etc.}$$

Load factors

The equations come from ACI code 9.2

D – Dead Load   L – Live Load

E – Earthquake Load   W – Wind Load

The most general equation for the ultimate load, U (M_u) that you will see is going to be:

$$U = 1.2D + 1.6L$$

$U = 1.2D + 1.6L$

Problem set #3

- Ribbed slab construction is common in Palestine. Construct an allowable load table and an ultimate load table for common sizes of rib-construction. The table should include block (density 12KN/m^3) and eitong (density 5.5KN/m^3) of different sizes against different values of superimposed loads (1 to 4KN/m^2 in 0.5 increments).

End of chapter 3

Let Learning Continue

Element design

4.1 Short Columns

4.2 Beams:

- 4.2.1 Flexure
- 4.2.2 Serviceability
- 4.2.3 Shear
- 4.2.4 Bar development
- 4.2.5 Bar splices in tension

4.3 Footings

4.1 Short Columns

General Information

Columns: Vertical Structural members

Transmits axial compressive loads with or without moment

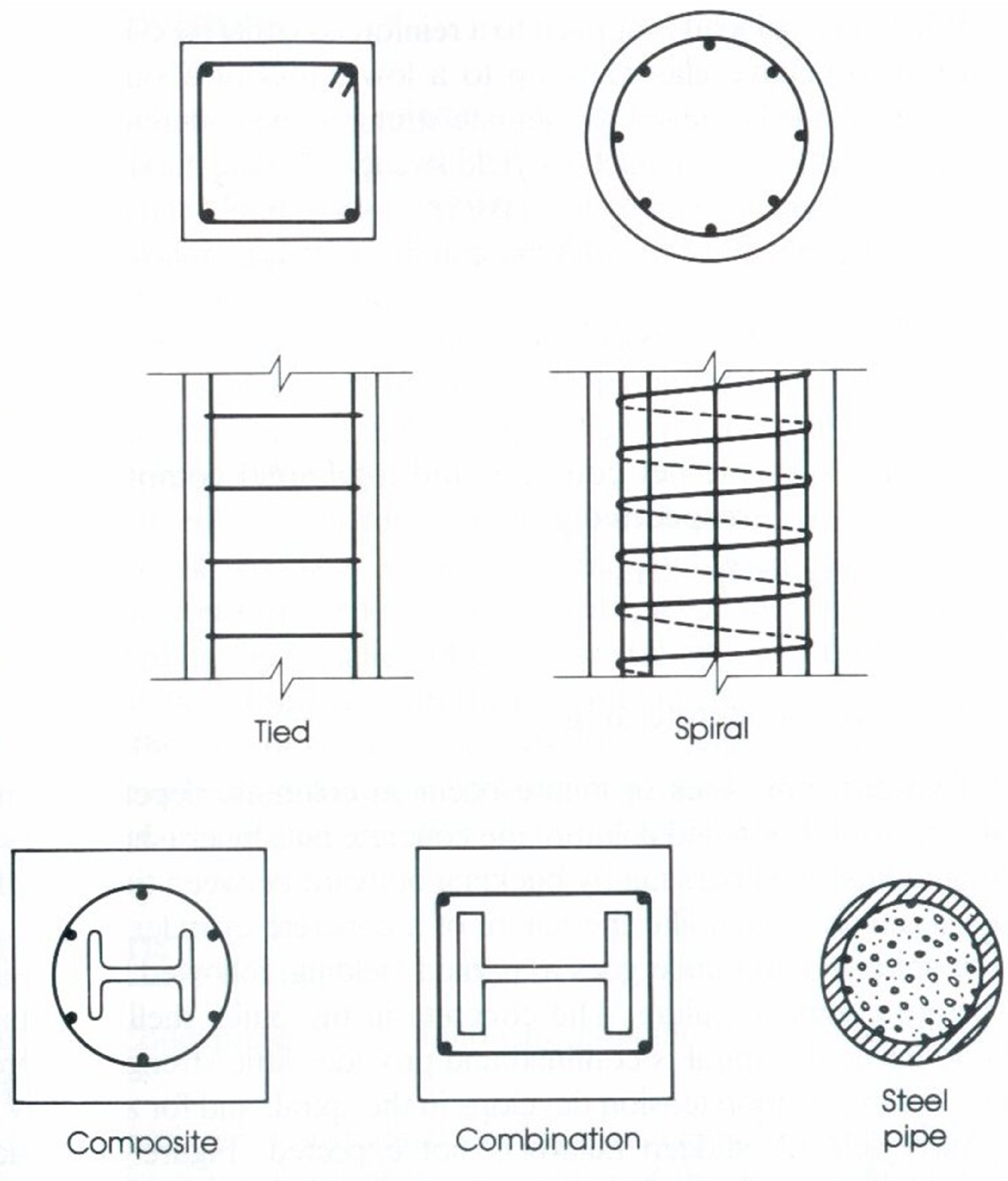
transmit loads from the floor & roof to the foundation

Short Columns: revision

General Information

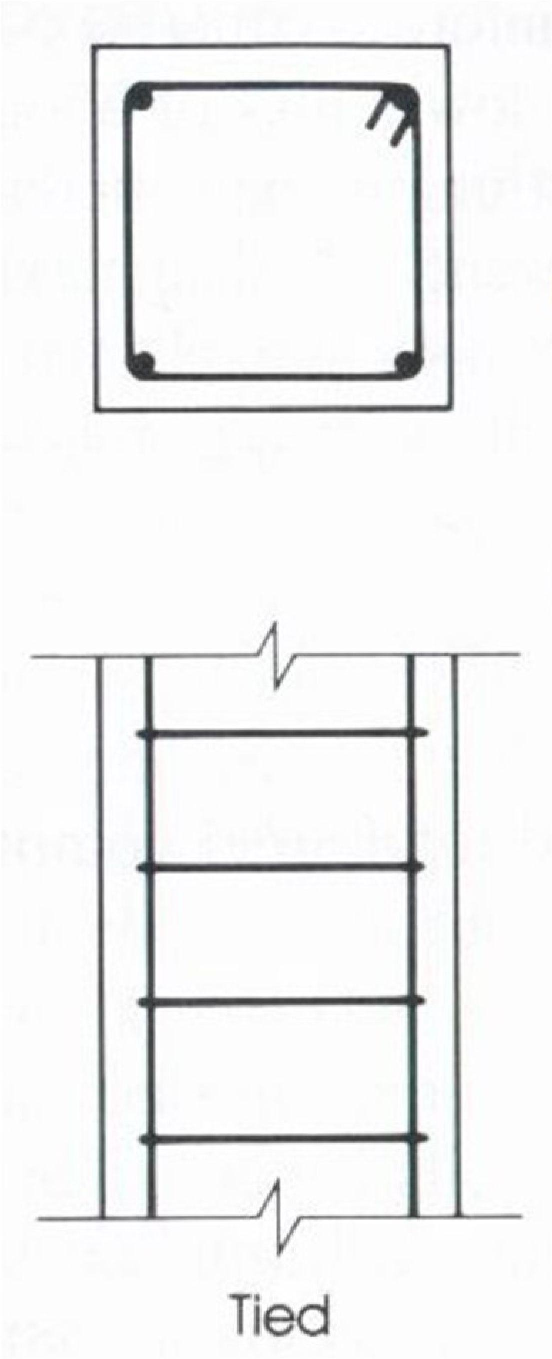
Column Types:

1. Tied
2. Spiral
3. Composite
4. Combination
5. Steel pipe



Short Columns: revision

<u>Tied Columns</u> - 95% of all columns in buildings in nonseismic regions are tied



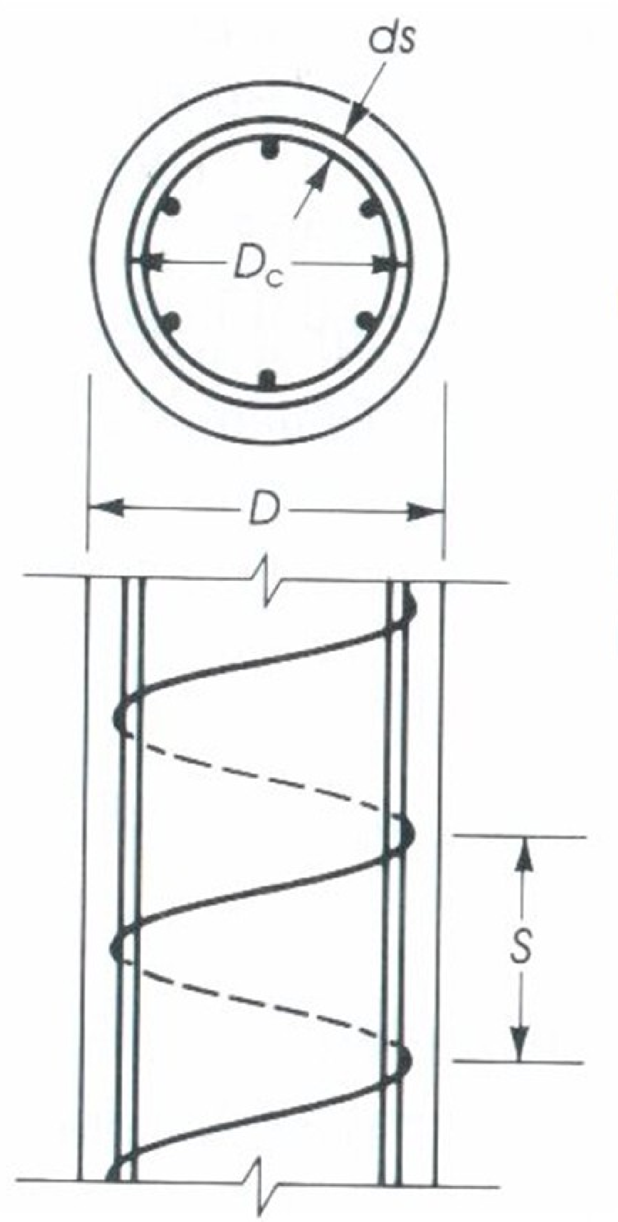
Tie spacing $\approx$ b (except for seismic)

tie supports long bars (reduces buckling)

ties provide negligible restraint to lateral expose of core

Short Columns: revision

Spiral Columns



Pitch =2.5cm to 7.5cm

spiral restrains lateral (Poisson's effect)

axial load ⟶ delays failure (ductile)

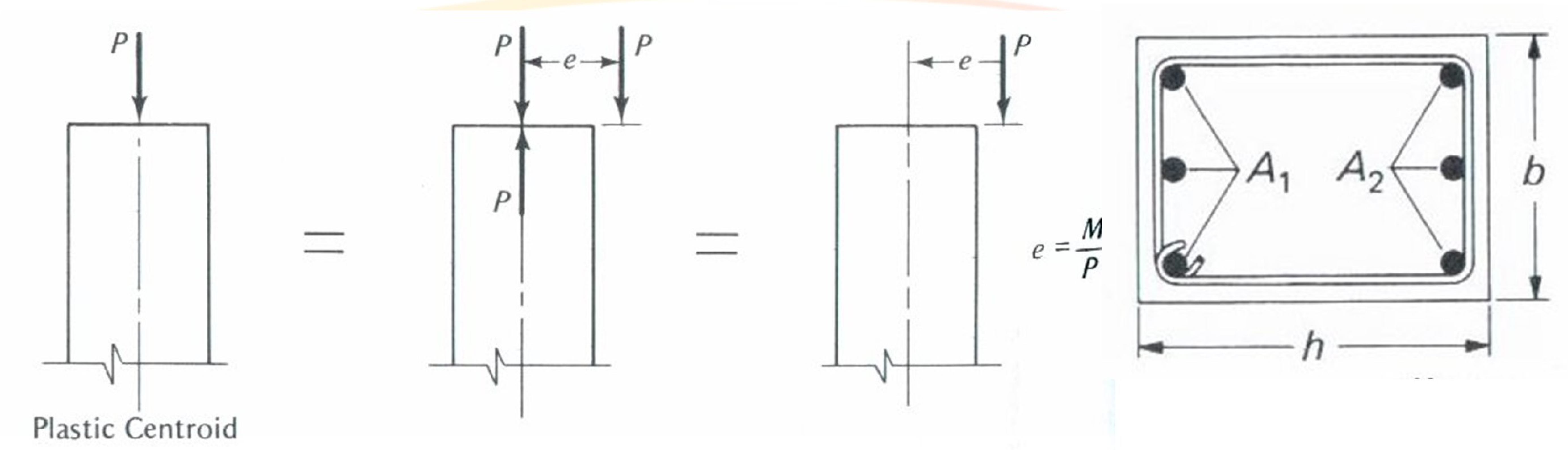
Short Columns: revision

Behavior

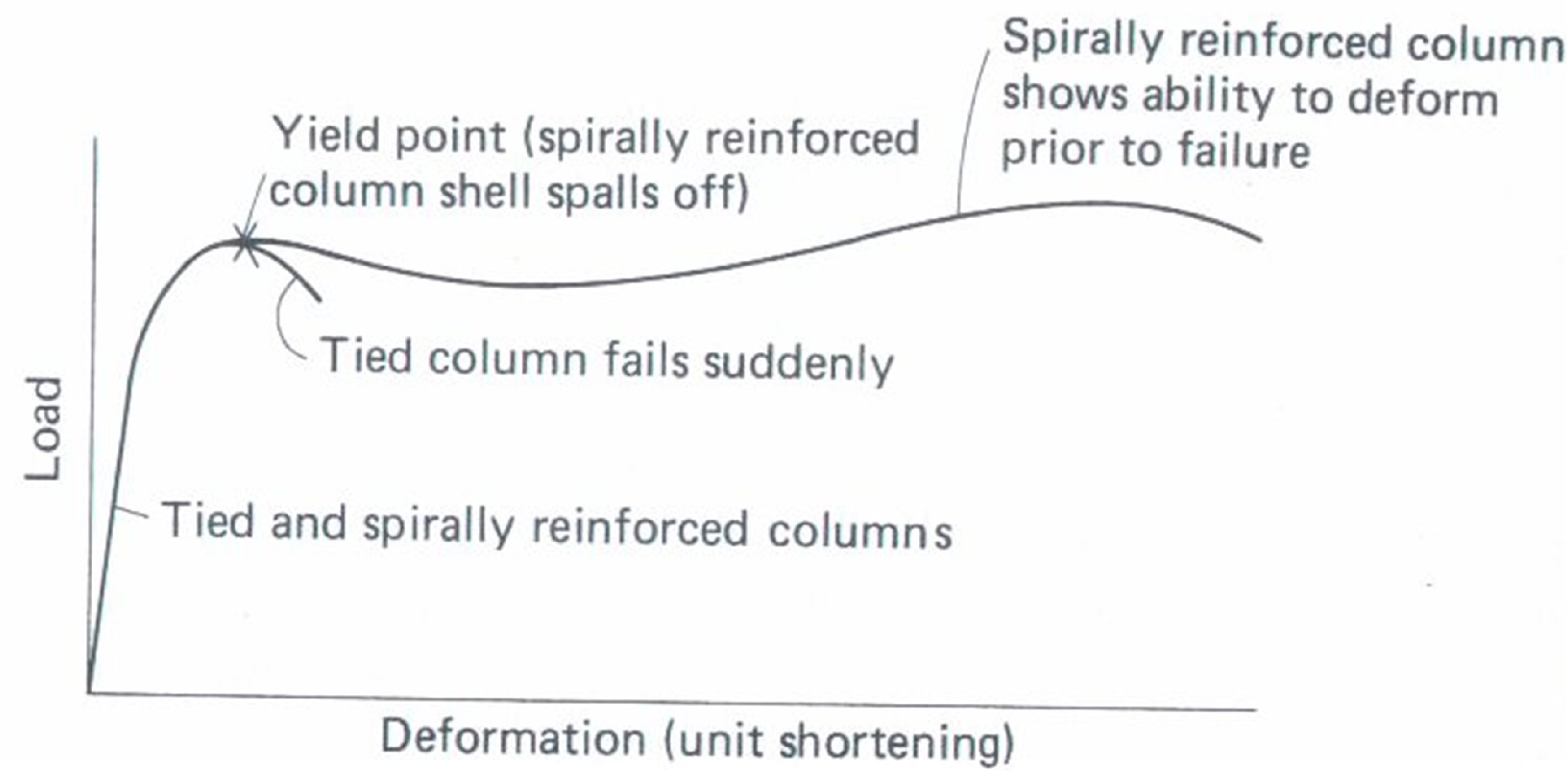
An "allowable stress" design procedure using an elastic analysis was found to be unacceptable. Reinforced concrete columns have been designed by a "strength" method since the 1940's.

Short Columns: revision

1. Initial Behavior up to Nominal Load - Tied and spiral columns.



Short Columns: revision



Approximate Analysis

- Use of tributary area: area of floor or roof which supports all of the loads whose load path leads to the column.
- Use load path: slab reactions carried by beams. Beam reactions carried by columns.

e-learning Design of Short Columns

$$P_0 = 0.85 f_c * \left(A_g - A_{st}\right) + f_y A_{st}$$

Let

A_g = Gross Area = b*h A_{st} = area of long steel

f_c = concrete compressive strength

f_y = steel yield strength

Factor due to less than ideal consolidation and curing conditions for column as compared to a cylinder. It is **not** related to ***Whitney's*** stress block.

2. Maximum Nominal Capacity for Design $P_{n\,(max)} \Rightarrow$

$$P_{n(max)} = 0.8P_0 \rightarrow tied$$

$$P_{n(max)} = 0.85P_0 \rightarrow spiral$$

ACI 10.3.6.1-2

3. Reinforcement Requirements (Longitudinal Steel A_{st})

Let $$\rho_g = \frac{A_{st}}{A_g}$$

- ACI Code requires $0.01 \le \rho_g \le 0.08$

-ACI 10.8.4 use half A_g if column section is much larger than loads.

-Minimum # of Bars (ACI Code 10.9.2): 6 in circular arrangement and 4 in rectangular arrangement

3. Reinforcement Requirements (Lateral Ties)

Vertical spacing: (ACI 7.10.5.1-3)

#10mm bars least dimension of tie

$s \leq 16\ d_b$ (d_b for longitudinal bars)

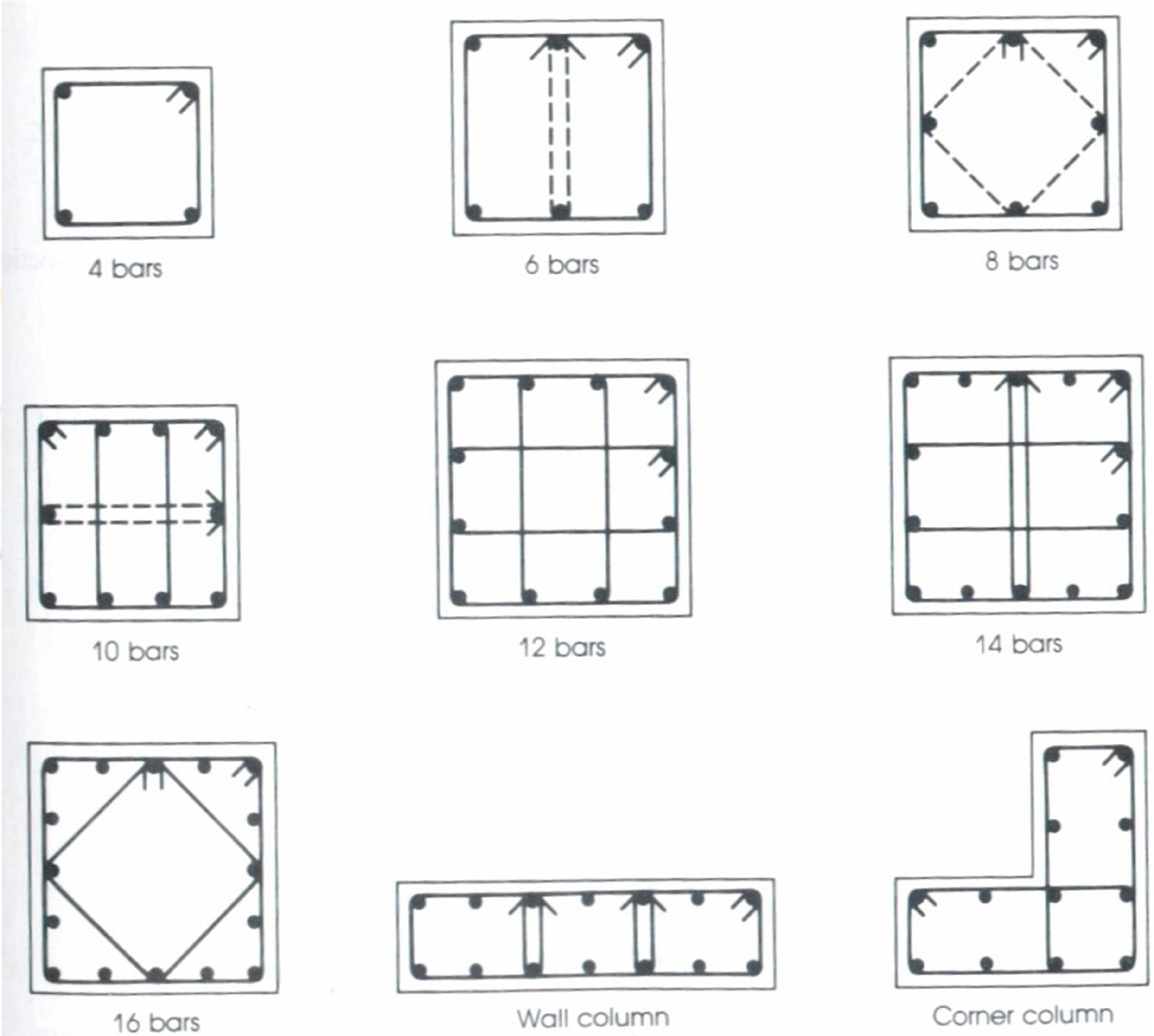
$s \leq 48\ d_b$ (d_b for tie bar)

$s \leq$ least lateral dimension of column

Every corner and alternate longitudinal bar shall have lateral support provided by the corner of a tie with an included angle not more than 135°, and no bar shall be more than 15cm clear on either side from "support" bar.

Design of Short Columns

Examples of lateral ties.



Design of Short Columns

3. Reinforcement Requirements (Spirals)

ACI Code 7.10.4

size $\geq$ 10mm " dia.

$$2.5\text{cm} \leq \begin{matrix}\text{clear spacing} \\ \text{between spirals}\end{matrix} \leq 7.5\text{cm}$$ ACI 7.10.4.3

4. Design for Concentric Axial Loads

(a) General Strength Requirement

$$\phi P_n \geq P_u$$

where, ϕ= 0.65 for tied columns

ϕ= 0.75 for spiral columns (ACI 08)

4. Design for Concentric Axial Loads

(b) Expression for Design

defined:

$$\rho_g = \frac{A_{st}}{A_g} \qquad \text{ACI Code}\left(0.01 \le \rho_g \le 0.08\right)$$

Design of Tied Short Columns

$$\phi P_n = \phi\, 0.8\left[A_g\left(0.85 f_c\right) + A_{st}\left(f_y - 0.85 f_c\right)\right] \geq P_u$$

$$\phi P_n = \phi\, 0.8\, A_g\left[0.85 f_c + \rho_g\left(f_y - 0.85 f_c\right)\right] \geq P_u$$

- The ultimate load is found using tributary area and number of stories

The design load can be approximated as follows:

Approximate Design of Short Columns

- For a tied column with 1% steel reinforcement

$$\phi P_n = 0.65 * 0.8 A_g \left[0.85 f_c + 0.01 \left(f_y - 0.85 f_c \right) \right]$$

$$\phi P_n = A_g \left[0.438 f_c + 0.0052 f_y \right] \geq P_u$$

For 20MPa concrete strength and 420MPa yield strength and representing gross area in cm^2 and column capacity in kN

$$\phi P_n = 1.1 X 10^4 (A_g X 10^{-4}) \approx A_g$$

Thus the area of column in square cm represents approximately its capacity in kN

Length to width ratio

- Condition for short columns: braced

$$\frac{KL}{r} \leq 34 - 12\frac{M_1}{M_2} = 34$$

$$0.5 \leq K \leq 1, r \approx 0.3b$$

$$\frac{KL}{0.3b} \leq 34 \rightarrow \frac{L}{b} \leq \frac{34*0.3}{K} \rightarrow \frac{L}{b} \leq 10, 20$$

- Thus if the height to width ratio is less than 15 (the mean value) the column is classified as short

Problem set # 4

- Common practice is to build four stories with 4m span dimensions. What is the size of the column needed to support a common 25cm rib construction (17cm height blocks, 15cm ribs).
- Common practice in the last 50years is to use 6#14mm bars in columns 25cmX50cm, thus a use of 0.72% instead of 1% minimum. Comment!
- In the nineties trying to build columns with 2% reinforcement using common technology at that time yields to honeycombing, comment!
- Is it wise to design columns according to minimum design requirements, comment!

End of 4.1

Let Learning Continue

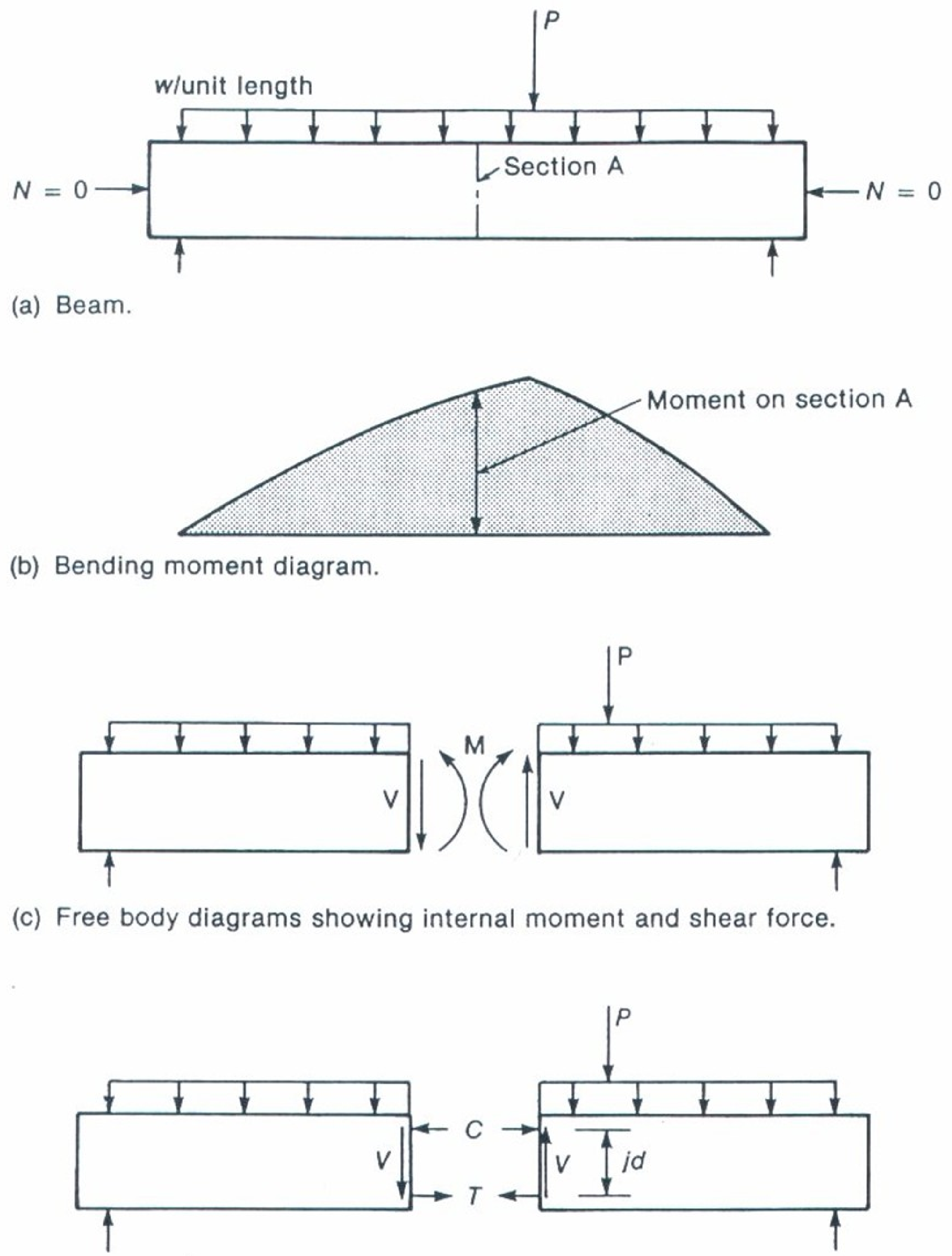
Beams: 4.2.1 Flexure

The beam is a structural member used to support the internal moments and shears. It would be called a beam-column if a compressive force existed.

$$C = T$$

$$M = C^*(jd)$$

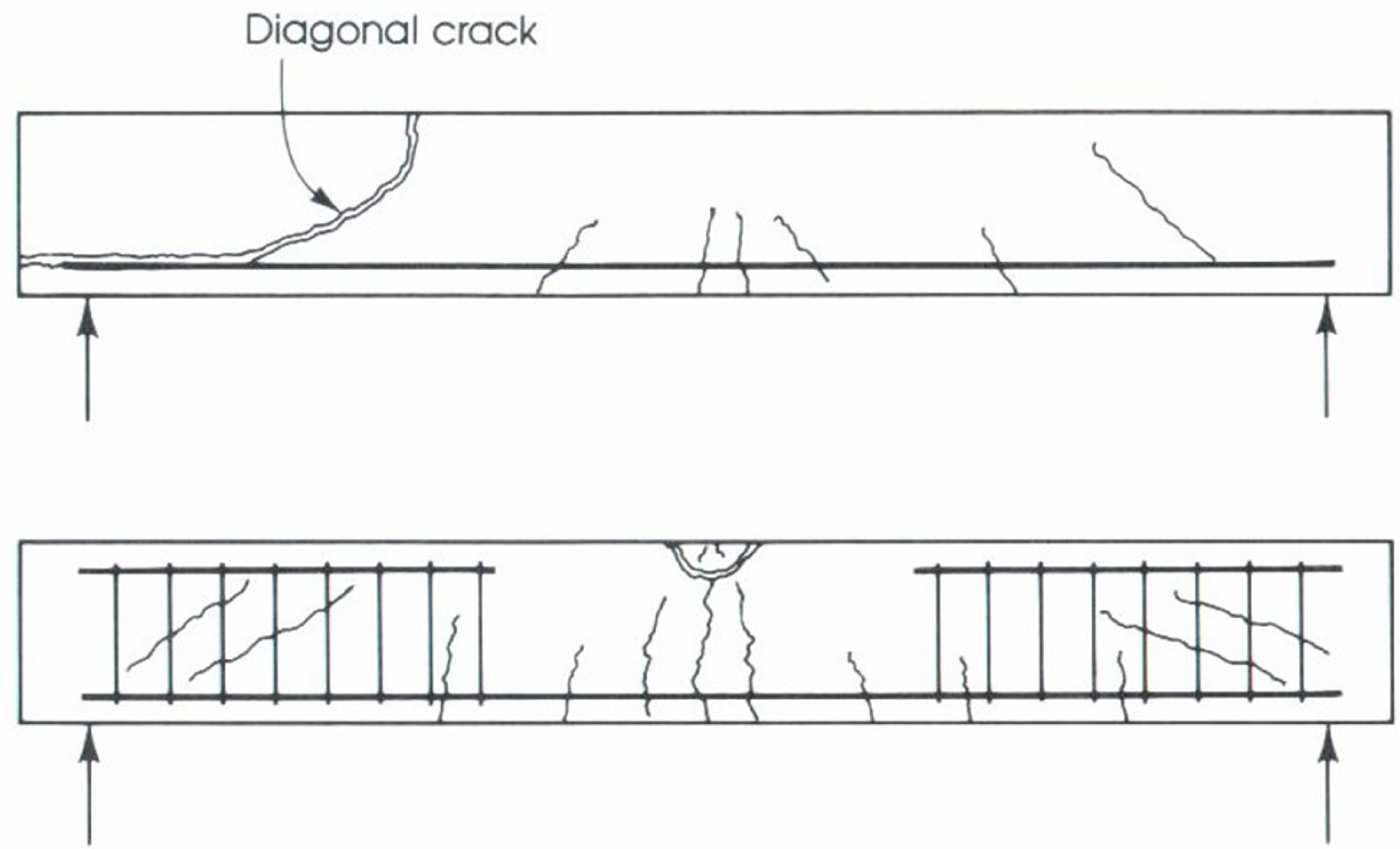
$$= T^*(jd)$$



(a) Beam.
(b) Bending moment diagram.
(c) Free body diagrams showing internal moment and shear force.
(d) Free body diagrams showing internal moment as a compression–tension force couple.

Flexure

The first beam fails in shear, the second fails in bending moment.



Approximate analysis

- Use of tributary area (area of floor or roof which supports all of the loads whose load path leads to the beam) determines the beam load.
- Perform approximate analysis through:
  - Approximate deflected shape to locate points of inflection, hence transform to determinate beam and analyze using statics.
  - Use analysis coefficients (e.g. ACI coefficients)
  - Use finite element programs

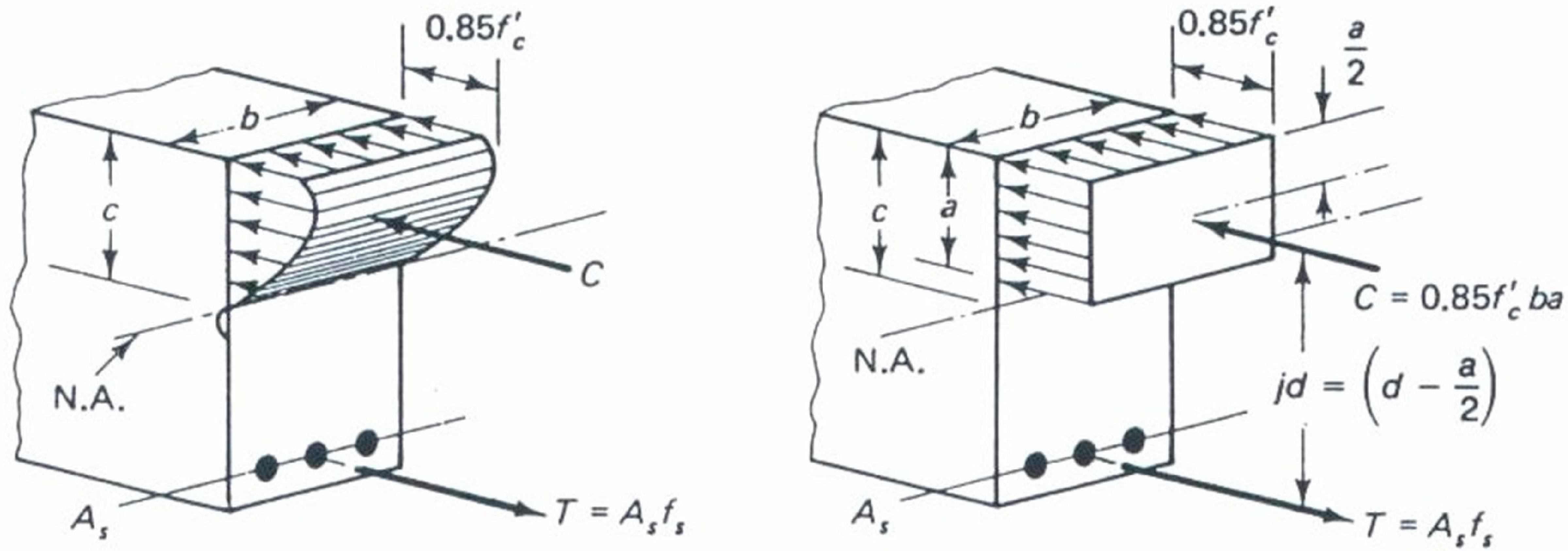
Design for Flexure: review

Basic Assumptions in Flexure Theory

- Plane sections remain plane (not true for deep beams h > 4b)
- The strain in the reinforcement is equal to the strain in the concrete at the same level, i.e. $\varepsilon_s = \varepsilon_c$.
- Stress in concrete & reinforcement may be calculated from the strains using f-ε curves for concrete & steel.
- Tensile strength of concrete is neglected.
- Concrete is assumed to fail in compression, when $\varepsilon_c = 0.003$
- Compressive f-ε relationship for concrete may be assumed to be any shape that results in an acceptable prediction of strength.

Design for Flexure: review

The compressive zone is modeled with an equivalent stress block.



Design for Flexure: review

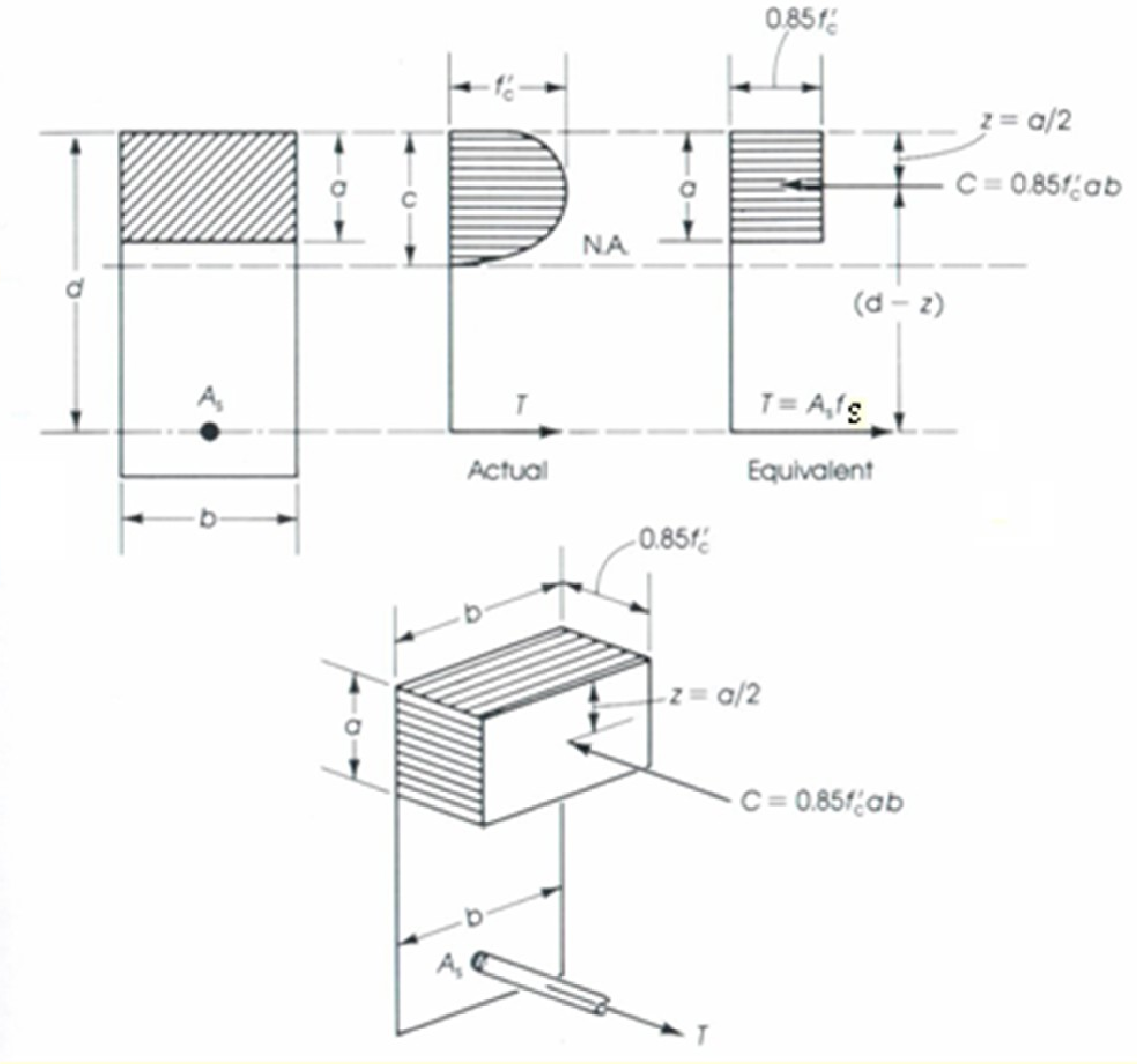
Example of rectangular reinforced concrete beam.

Setup equilibrium.

$$\sum F_x = 0 \quad \Rightarrow \quad T = C$$

$$A_s f_s = 0.85 f_c ab$$

$$\sum M = 0 \quad \Rightarrow \quad T\left(d - \frac{a}{2}\right) = M_n$$



Design for Flexure: review

The ultimate load, which is used in the design and analysis of the structural member is:

$$M_u = \phi M_n$$

M_u – Ultimate Moment

M_n – Nominal Moment

Φ – Strength Reduction Factor

The strength reduction factor, Φ, varies depending on the tensile strain in steel in tension. Three possibilities:

Compression Failure - (over-reinforced beam)

Tension Failure - (under-reinforced beam)

Balanced Failure - (balanced reinforcement)

Design for Flexure: review

Which type of failure is the most desirable?

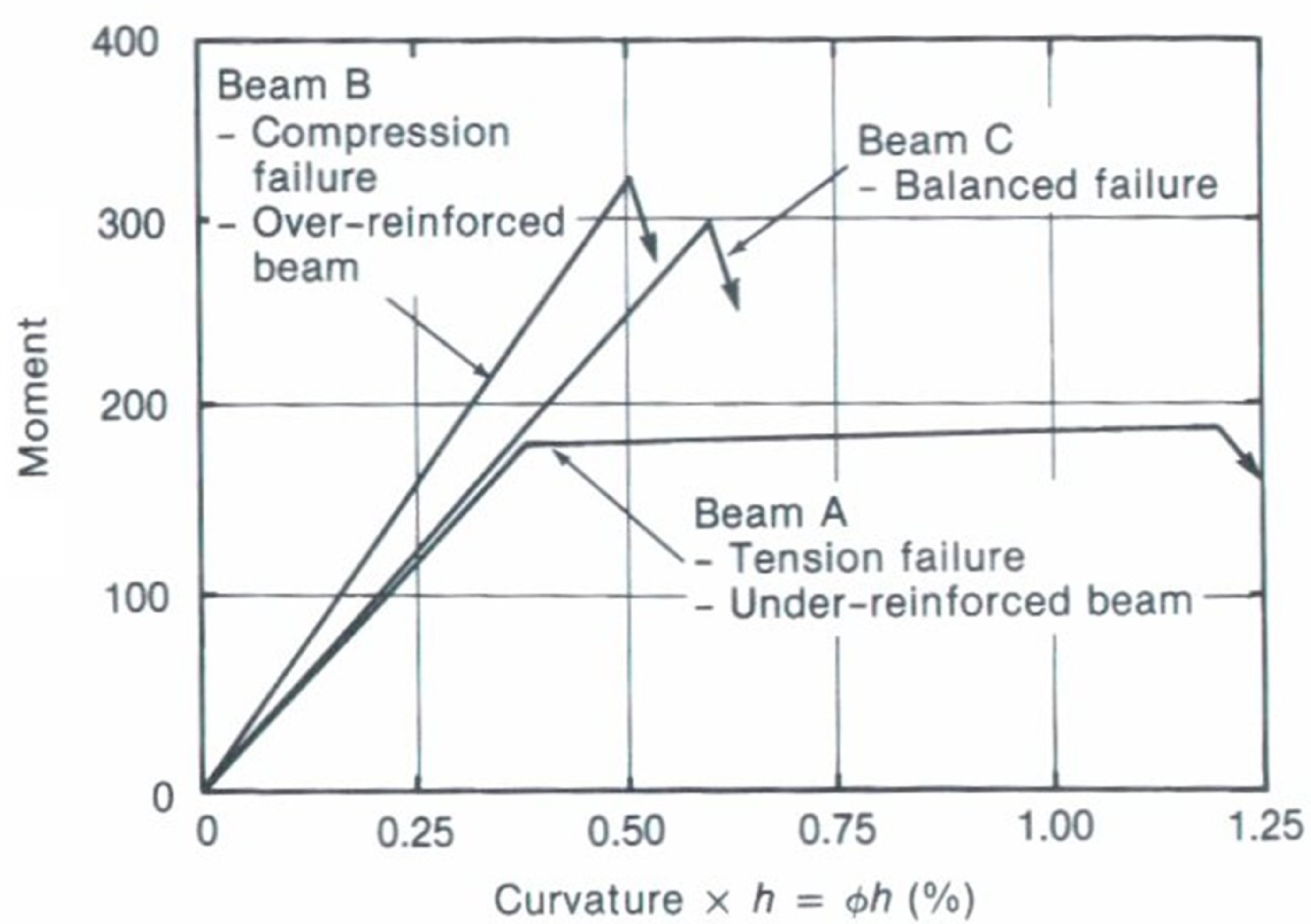
The ***under-reinforced beam*** is the most desirable.

$f_s = f_y$

$\varepsilon_s >> \varepsilon_y$

You want ductility

system deflects and still carries load.



Approximate Design for Flexure: J

For under-reinforced, the equation can be rewritten as:

$$C = T \quad \Rightarrow \quad 0.85 f_c' ba = A_s f_y$$

$$a = \frac{f_y A_s}{0.85 f_c' b}$$

$$M_n = A_s f_y d \left(1 - \frac{f_y A_s}{1.7 f_c' bd} \right)$$

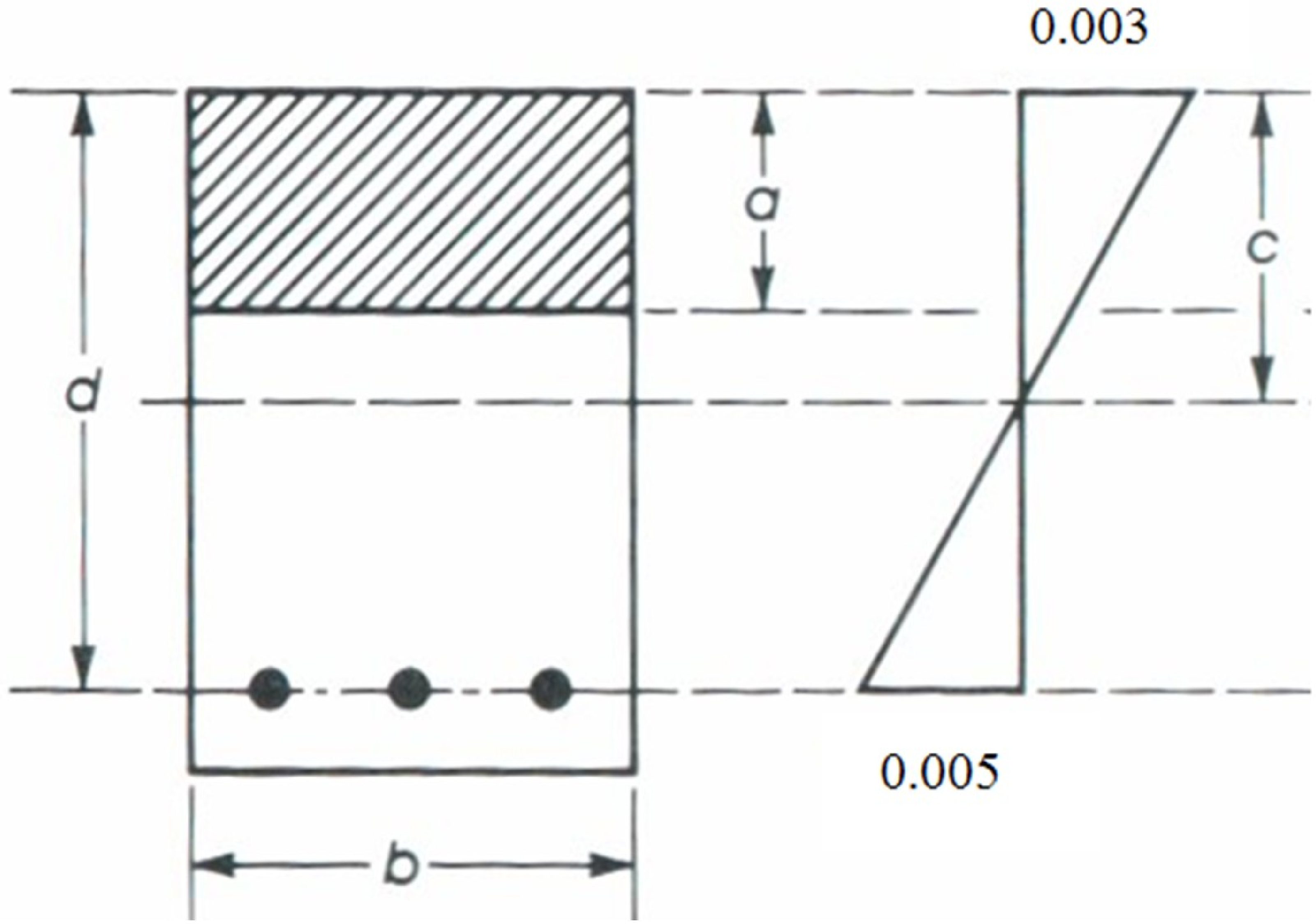
$$M_d = \phi M_n = A_s d \phi f_y \left(1 - \frac{\rho f_y}{1.7 f_c'} \right) = A_s dj$$

Approximate Design for Flexure: J

ρ_{max} = maximum ρ value recommended to get simultaneous $\varepsilon_c = 0.003$ & $\varepsilon_s = 0.005$

Use similar triangles:

$$\frac{0.003}{c} = \frac{0.005}{d-c}$$



Approximate Design for Flexure: J

For a yield stress 420MPa, the equation can be rewritten to find c as

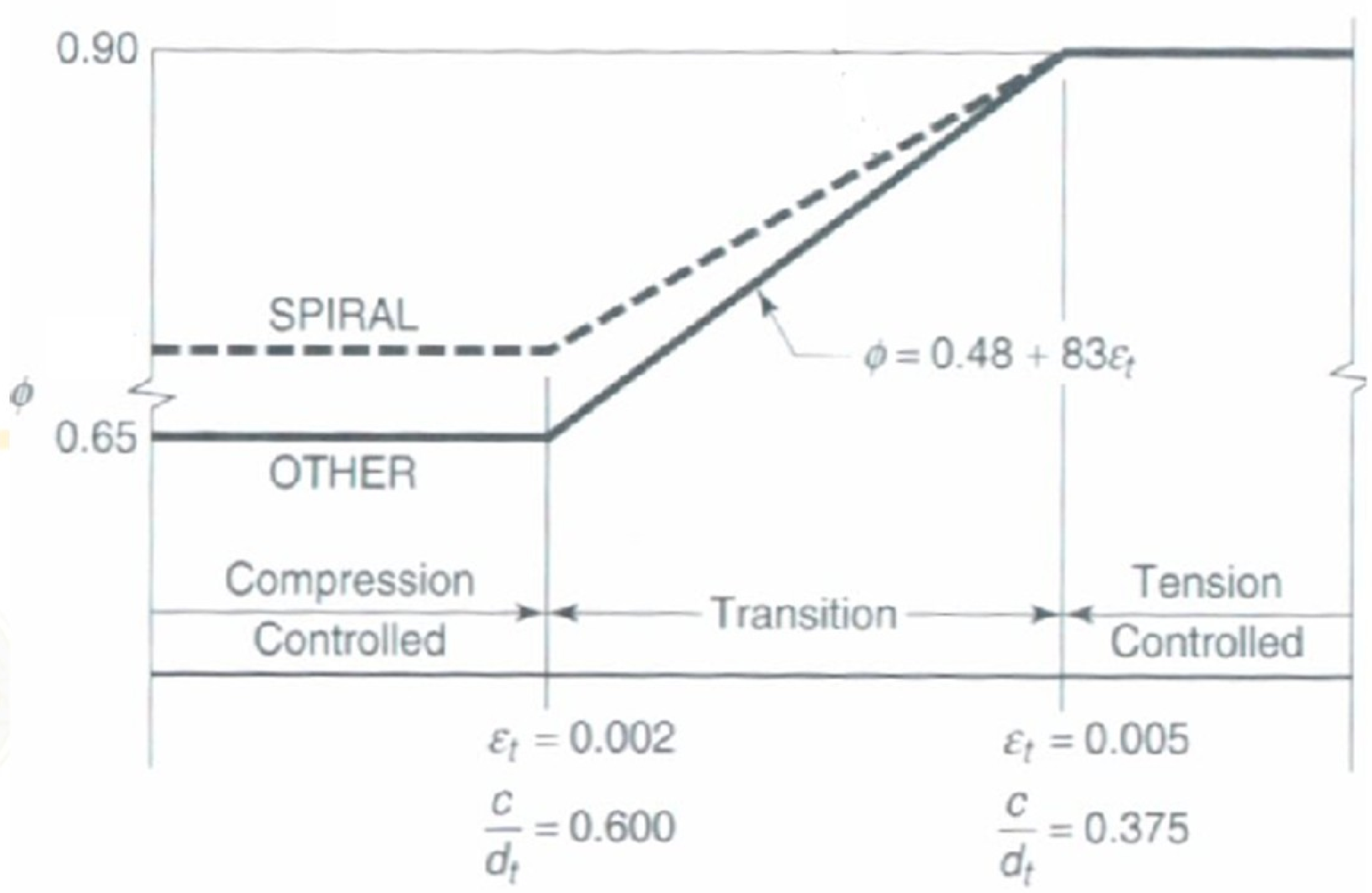
$$c = \frac{0.003d}{0.008} \quad \Rightarrow \quad c = 0.375d$$

$$a = 0.85c = 0.319d$$

$$\rho = 0.271 f_c' / f_y$$

Approximate Design for Flexure: J

The strength reduction factor, ϕ, will come into the calculation of the strength of the beam.



The factor J for large steel ratios

$$M_d = \phi M_n = A_s d \phi f_y \left(1 - \frac{\rho f_y}{1.7 f_c'}\right) = A_s dj$$

$$j = \phi f_y \left(1 - \frac{\rho f_y}{1.7 f_c'}\right)$$

- For concrete strength variation 20MPa to 42Mpa, the value of J for maximum recommended steel ratio varies is 0.317. Moment in kN.m, area of steel in square cm and depth in cm.

Limitations on Reinforcement Ratio, ρ

Lower Limit on ρ   ACI 10.5.1

ACI Eqn. (10-3)

$$A_{s(min)} = \frac{\sqrt{f'_c}}{4 f_y} * b_w d \quad \geq \quad \frac{1.4}{f_y} * b_w d$$

f_c & f_y are in MPa

Lower limit used to avoid "Piano Wire" beams.

Very small As ($M_n < M_{cr}$)

Strain in steel is huge (large deflections)

when beam cracks ($M_u/\Phi > M_{cr}$) beam fails right away because nominal capacity decreases drastically.

The factor J for minimum steel ratios

$$j = \phi f_y \left(1 - \frac{\rho \mathrm{f_y}}{1.7 f'_c} \right) = \phi f_y \left(1 - \frac{1.4}{1.7 f'_c} \right)$$

- For concrete strength variation 20MPa to 42Mpa, the value of J for minimum steel varies from 0.36 to 0.37

The factor J

- It is obvious that variation of J is not sensitive to changes in concrete strength. Thus a mean value of 0.33 is representative for all types of concrete used in Palestine (B250-B500)

$$M_d = \frac{A_s d}{3}$$

Additional Requirements for Lower Limit on ρ

Temperature & Shrinkage reinforcement in structural slabs and footings (ACI 7.12) place perpendicular to direction of flexural reinforcement.

GR 40 or GR 50 Bars: A_s (T&S) = 0.0020 A_g

GR 60 A_s (T&S) = 0.0018 A_g

A_g - Gross area of the concrete

End of 4.2.1

Let Learning Continue

4.2.2 Beams: serviceability

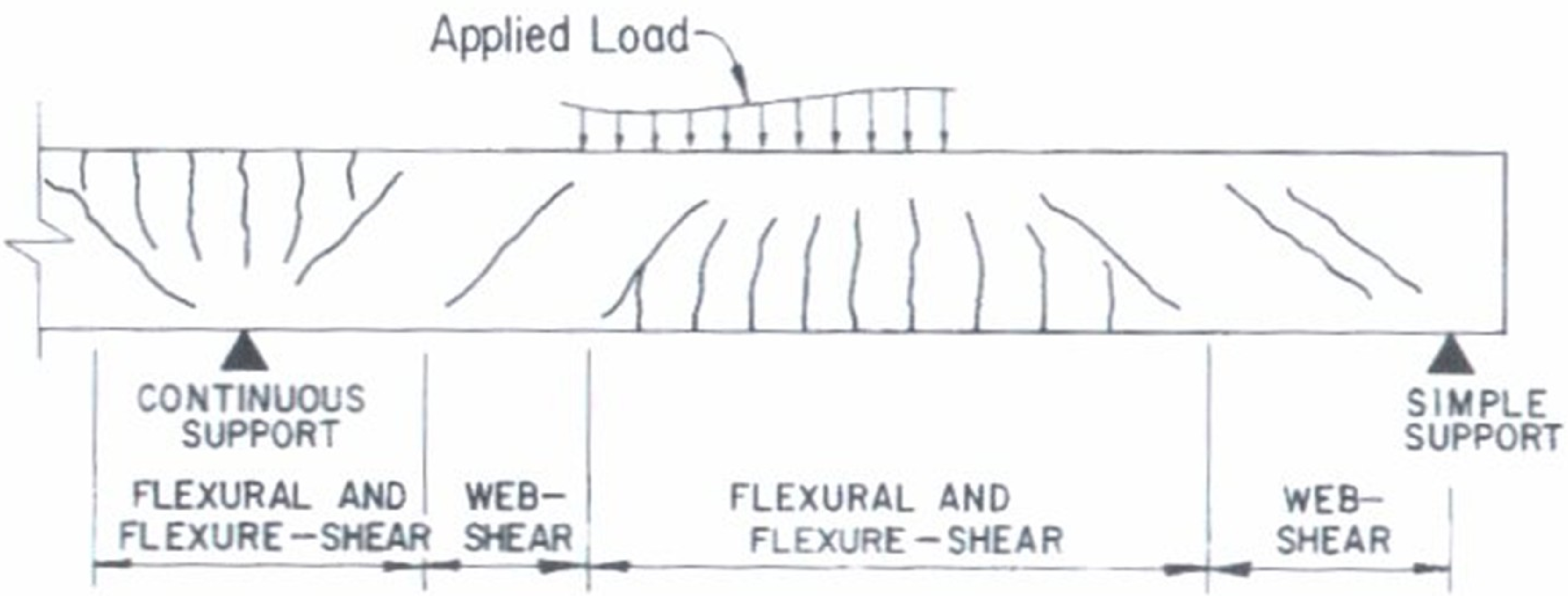
Beam Depths

• ACI 318 - Table 9.5(a) min. h based on span (slab & beams)

•Design for max. moment over a support to set depth of a continuous beam.

4.2.3 Shear

Typical Crack Patterns for a deep beam.



Shear Design: review

Shear Strength (ACI 318 Sec 11.1)

$\phi V_n \geq V_u$

capacity $\geq$ demand

V_u = factored shear force at section

V_n = Nominal Shear Strength

ϕ = 0.75 (shear) – strength reduction factor

$$V_n = V_c + V_s$$

$V_c = \dfrac{\sqrt{f_c'}}{6} b_w d$ = Nominal shear resistance provided by concrete

V_s = Nominal shear resistance provided by the shear reinforcement

Shear Design: review\ Minimum Shear Reinforcement

11.4.6.1 — A minimum area of shear reinforcement, $A_{v,min}$, shall be provided in all reinforced concrete flexural members (prestressed and nonprestressed) where V_u exceeds $0.5\phi V_c$, except in members satisfying one or more of (a) through (f):

(a) Footings and solid slabs;

(c) Concrete joist construction defined by 8.13;

(d) Beams with h not greater than 250 mm;

(e) Beam integral with slabs with h not greater than 600 mm and not greater than the larger of 2.5 times thickness of flange, and 0.5 times width of web;

Approximate design for shear

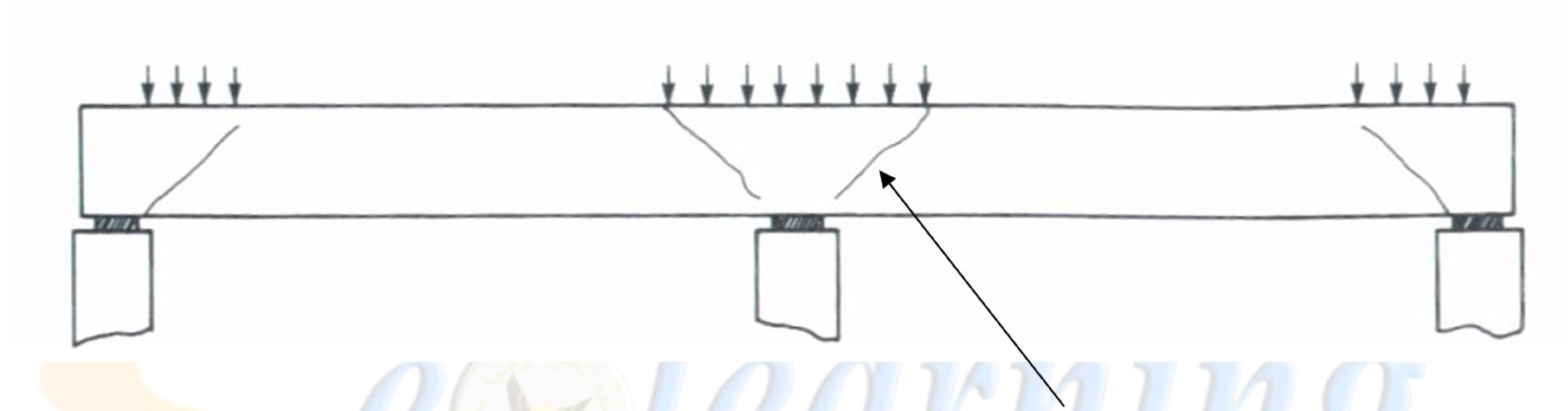
- Better to use

$$V_u < 0.5\phi\sqrt{f_c'}\ b_w d$$

- Hence

$$s_{\max} \le \frac{d}{2} \le 60cm$$

Shear Design: review/ max shear



Non-pre-stressed members:

Sections located less than a distance d from face of support may be designed for same shear, V_u, as the computed at a distance d.

Shear Design: review/ max shear

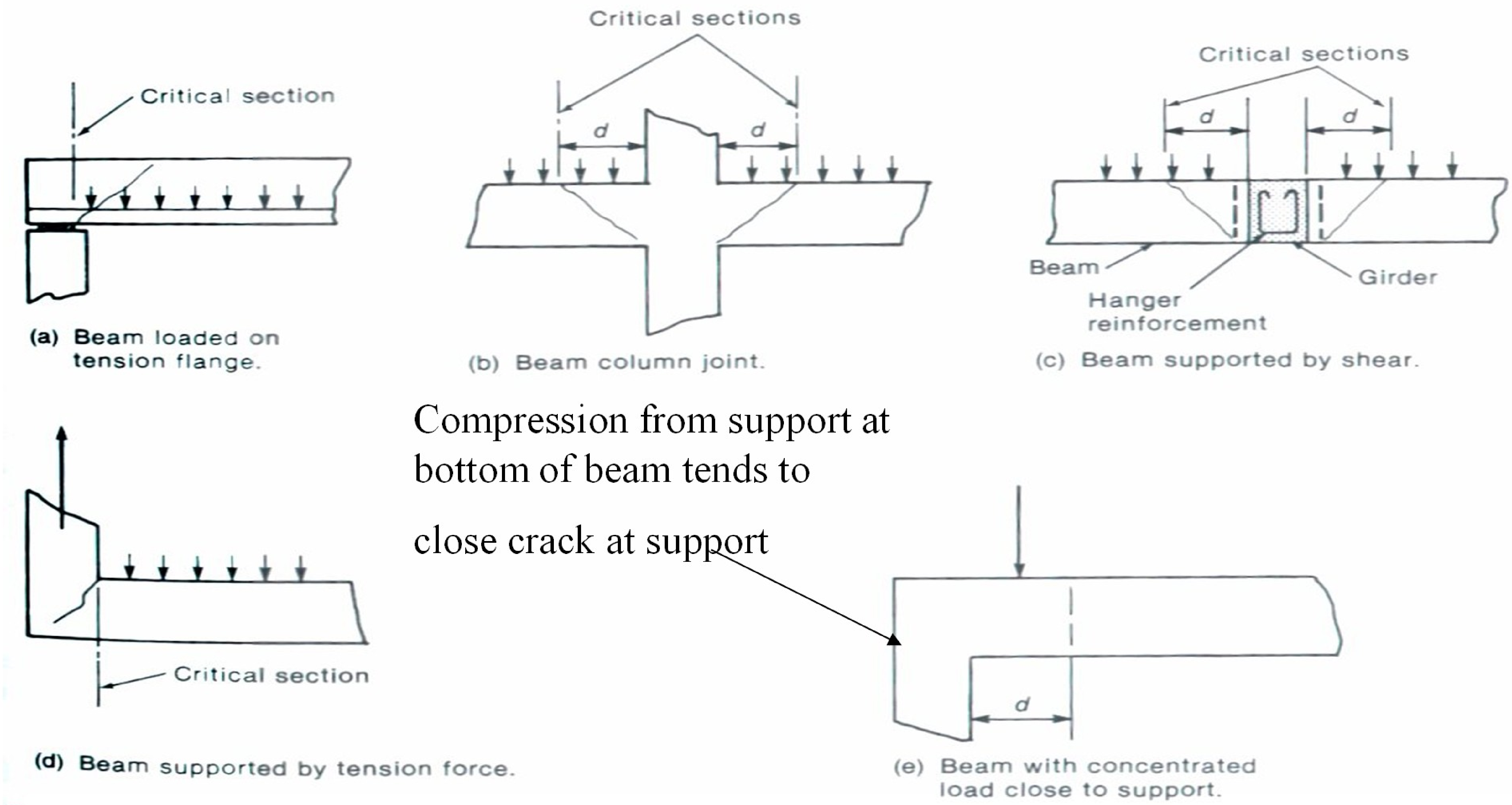
When:

1. The support reaction introduces compression into the end regions of the member.

2. The loads are applied at or near the top of the beam.

3. No concentrated load occurs with in d from face of support .

Shear Design: review/ max hear



4.2.4 Development Length

12.2.1 — Development length for deformed bars and deformed wire in tension, ℓ_d, shall be determined from either 12.2.2 or 12.2.3 and applicable modification factors of 12.2.4 and 12.2.5, but ℓ_d shall not be less than 300 mm.

12.2.2 — For deformed bars or deformed wire, ℓ_d shall be as follows:

Spacing and cover	No. 19 and smaller bars and deformed wires	No. 22 and larger bars
Clear spacing of bars or wires being developed or spliced not less than d_b, clear cover not less than d_b, and stirrups or ties throughout ℓ_d not less than the Code minimum or Clear spacing of bars or wires being developed or spliced not less than $2d_b$ and clear cover not less than d_b	$\left(\frac{f_y \psi_t \psi_e}{2.1\lambda\sqrt{f'_c}}\right) d_b$	$\left(\frac{f_y \psi_t \psi_e}{1.7\lambda\sqrt{f'_c}}\right) d_b$
Other cases	$\left(\frac{f_y \psi_t \psi_e}{1.4\lambda\sqrt{f'_c}}\right) d_b$	$\left(\frac{f_y \psi_t \psi_e}{1.1\lambda\sqrt{f'_c}}\right) d_b$

12.2.3 — For deformed bars or deformed wire, ℓ_d shall be

$$\ell_d = \left(\frac{f_y}{1.1\lambda\sqrt{f'_c}} \frac{\psi_t \psi_e \psi_s}{\left(\frac{c_b + K_{tr}}{d_b}\right)}\right) d_b \qquad (12\text{-}1)$$

in which the confinement term $(c_b + K_{tr})/d_b$ shall not be taken greater than 2.5, and

$$K_{tr} = \frac{40A_{tr}}{sn} \qquad (12\text{-}2)$$

where n is the number of bars or wires being spliced or developed along the plane of splitting. It shall be permitted to use $K_{tr} = 0$ as a design simplification

(a) Where horizontal reinforcement is placed such that more than 300 mm of fresh concrete is cast below the development length or splice, $\psi_t = 1.3$. For other situations, $\psi_t = 1.0$.

(c) For No. 19 and smaller bars and deformed wires, $\psi_s = 0.8$. For No. 22 and larger bars, $\psi_s = 1.0$.

4.2.5 Bar Splices in tension

Why do we need bar splices? -- for long spans

Types of Splices

1. Butted & Welded
2. Mechanical Connectors
3. Lab Splices

Must develop 125% of yield strength (applies to 1 and 2)

Types of Splices

Class A Splice (ACI 12.15.2)

When $\dfrac{A_{s(\text{provided})}}{A_{s(\text{req'd})}} \geq 2$ over entire splice length.

and 1/2 or less of total reinforcement is spliced within the req'd lap length.

Types of Splices

Class B Splice (ACI 12.15.2)

All tension lab splices not meeting requirements of Class A Splices

Tension Lap Splice (ACI 12.15)

As,prov/As,req'd	%As Spliced	Splice Class	Lap, req'd	Notes
≥ 2.0	≤ 50	A	l_d	Desirable
	> 50	B	$1.3\ l_d$	ok
< 2.0	≤ 50	B	$1.3\ l_d$	ok
	> 50	B	$1.3\ l_d$	Avoid

where $A_{s\ (req'd)}$ = determined for bending

l_d = development length for bars (not allowed to use excess reinforcement modification factor)

l_d must be greater than or equal to 30cm

Lab Splices should be placed in away from regions of high tensile stresses -locate near points of inflection (ACI R12.15.2)

End of 4.2.2-5

Let Learning Continue

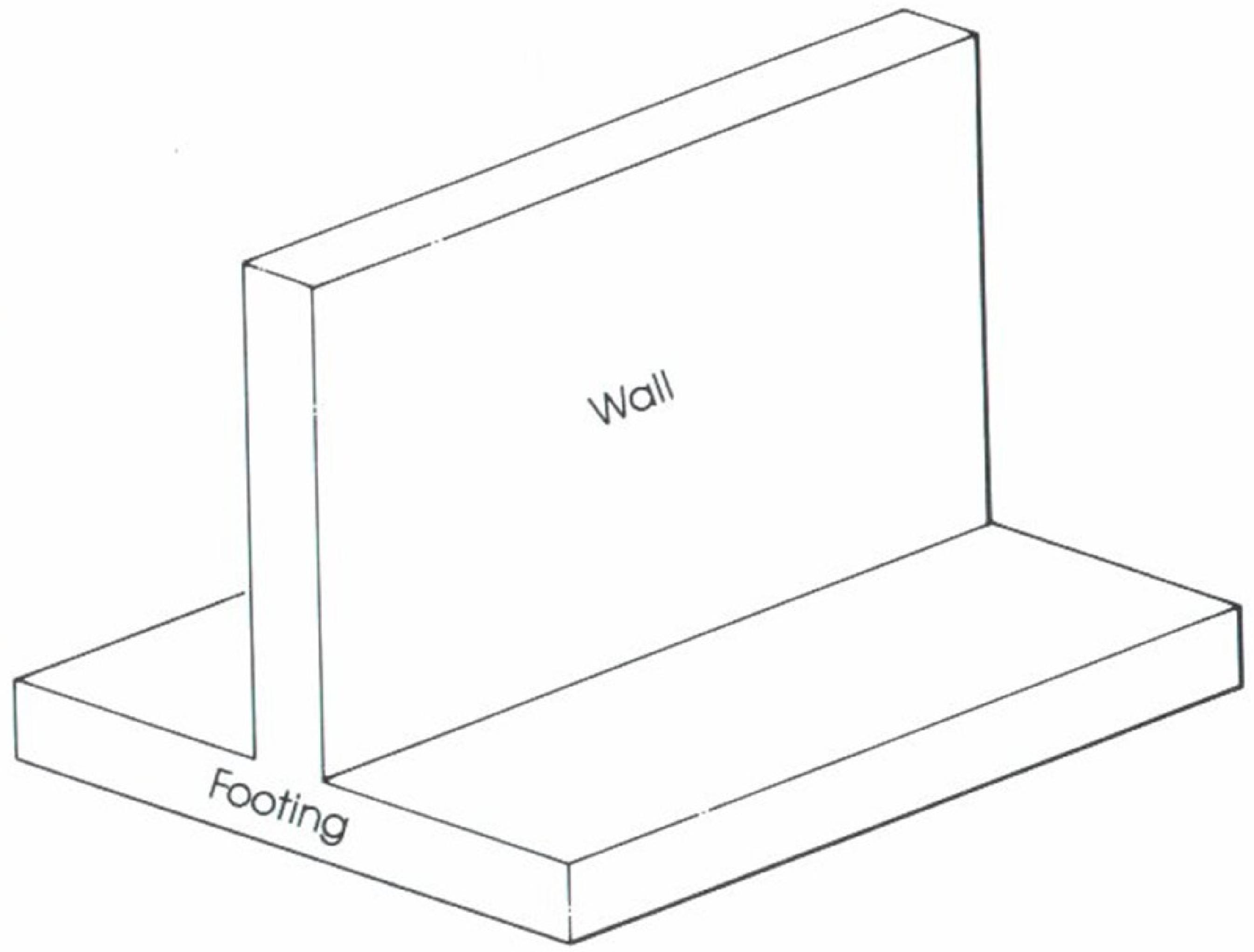
4.3 Footings

Definition

Footings are structural members used to support columns and walls and to transmit and distribute their loads to the soil in such a way that the load bearing capacity of the soil is not exceeded, excessive settlement, differential settlement,or rotation are prevented and adequate safety against overturning or sliding is maintained.

Types of Footings

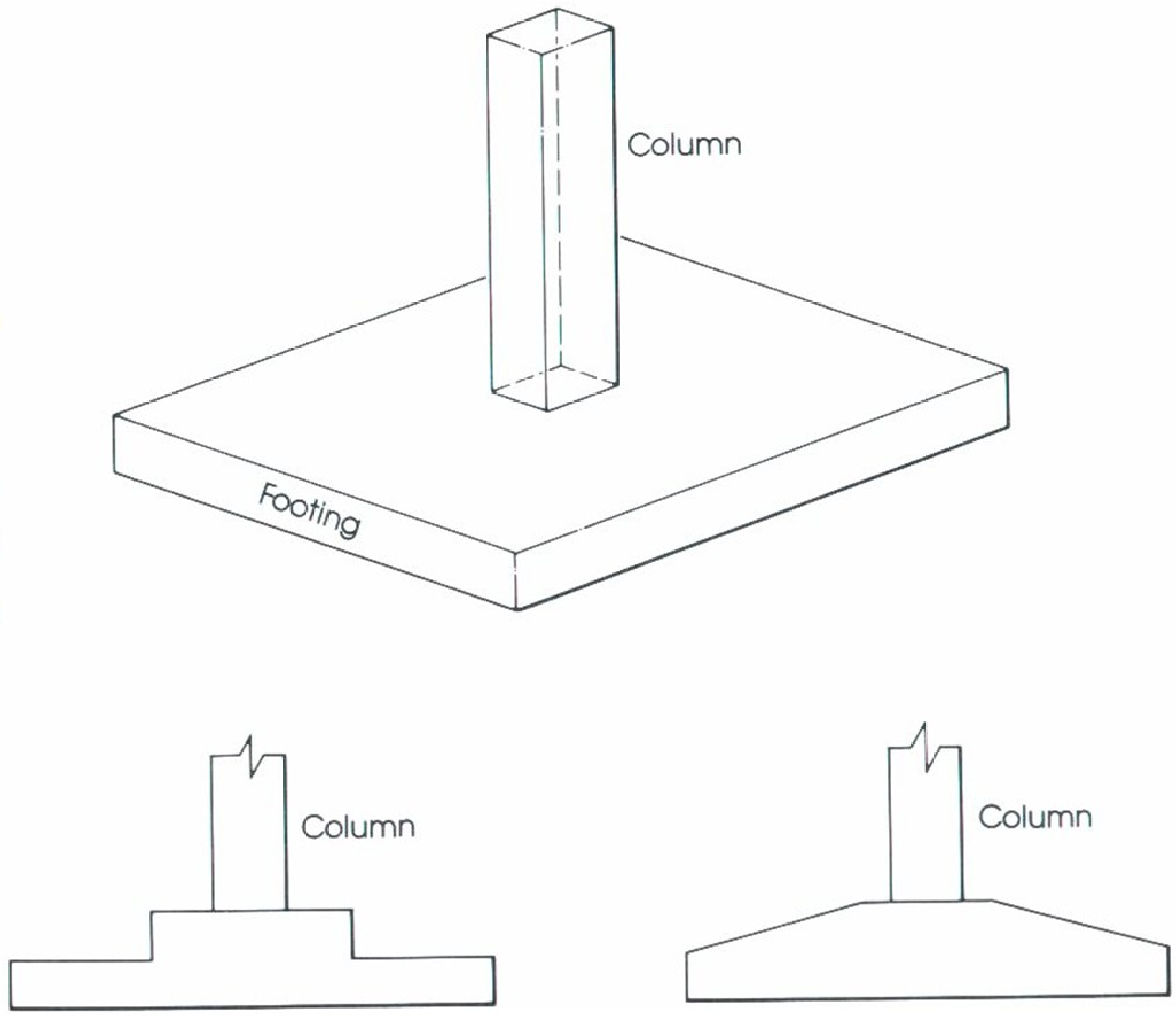
Wall footings are used to support structural walls that carry loads for other floors or to support nonstructural walls.



Wall footing.

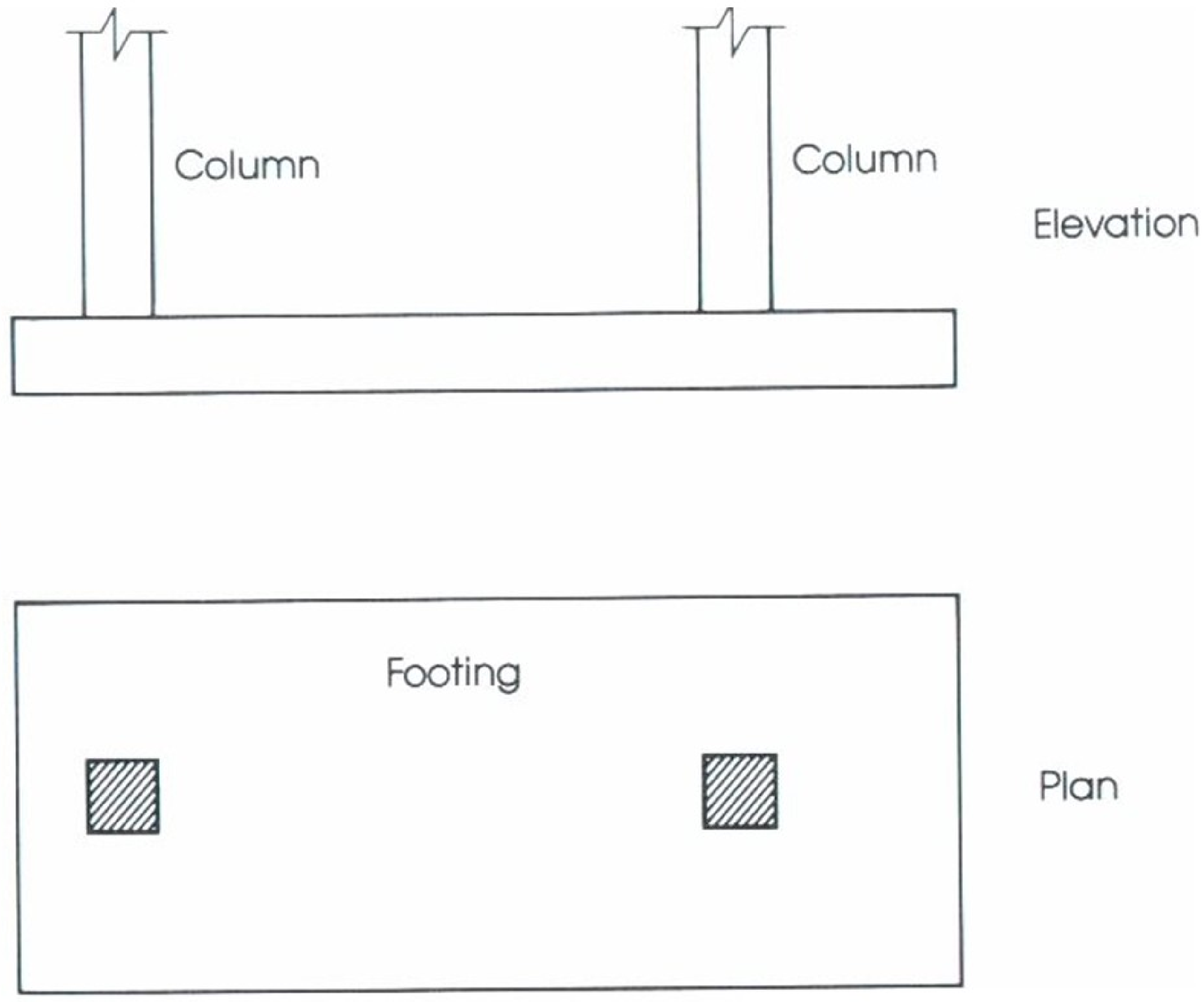
Types of Footings

Isolated or single footings are used to support single columns. This is one of the most economical types of footings and is used when columns are spaced at relatively long distances.



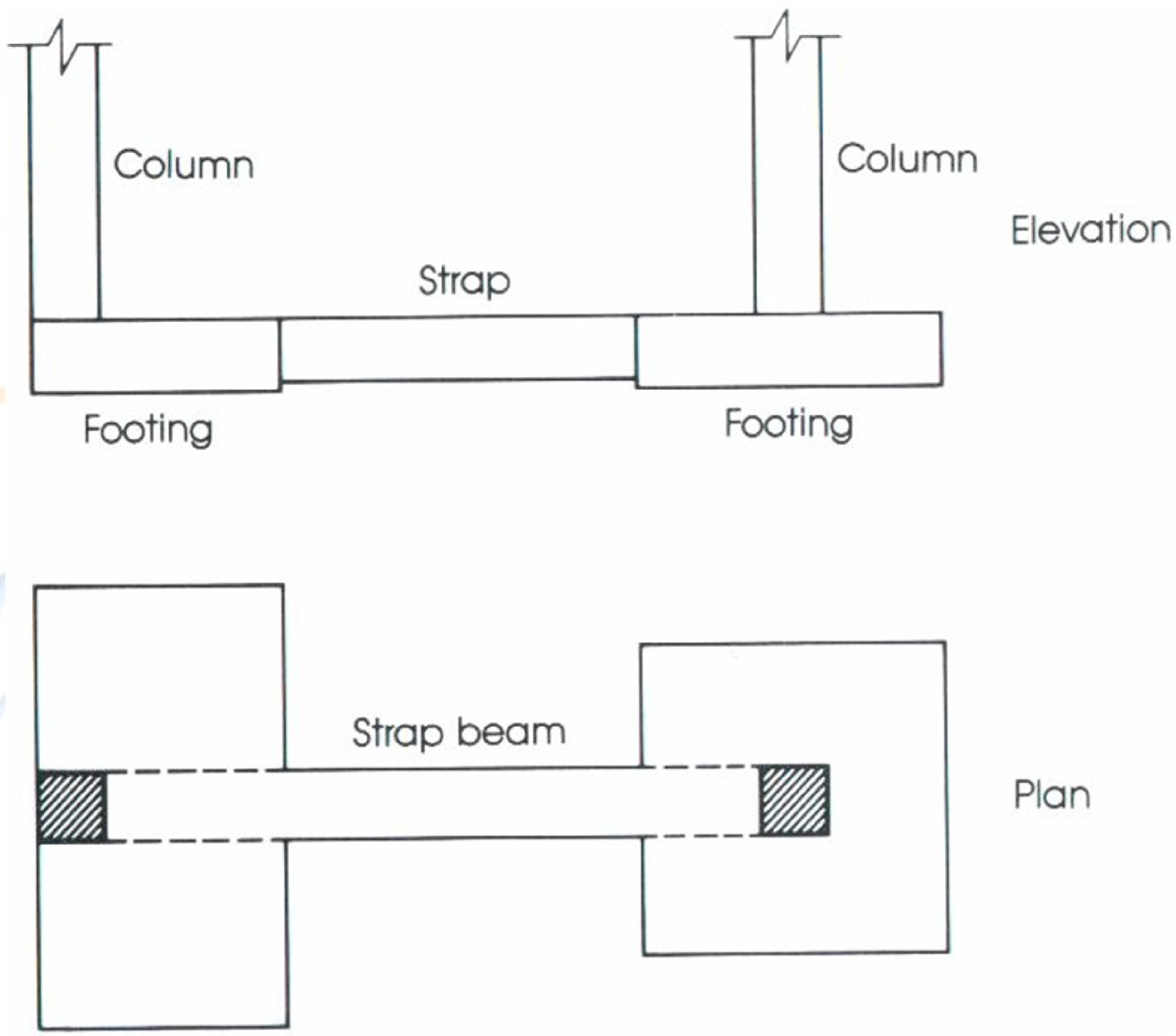
Types of Footings

Combined footings usually support two columns, or three columns not in a row. Combined footings are used when two columns are so close that single footings cannot be used or when one column is located at or near a property line.



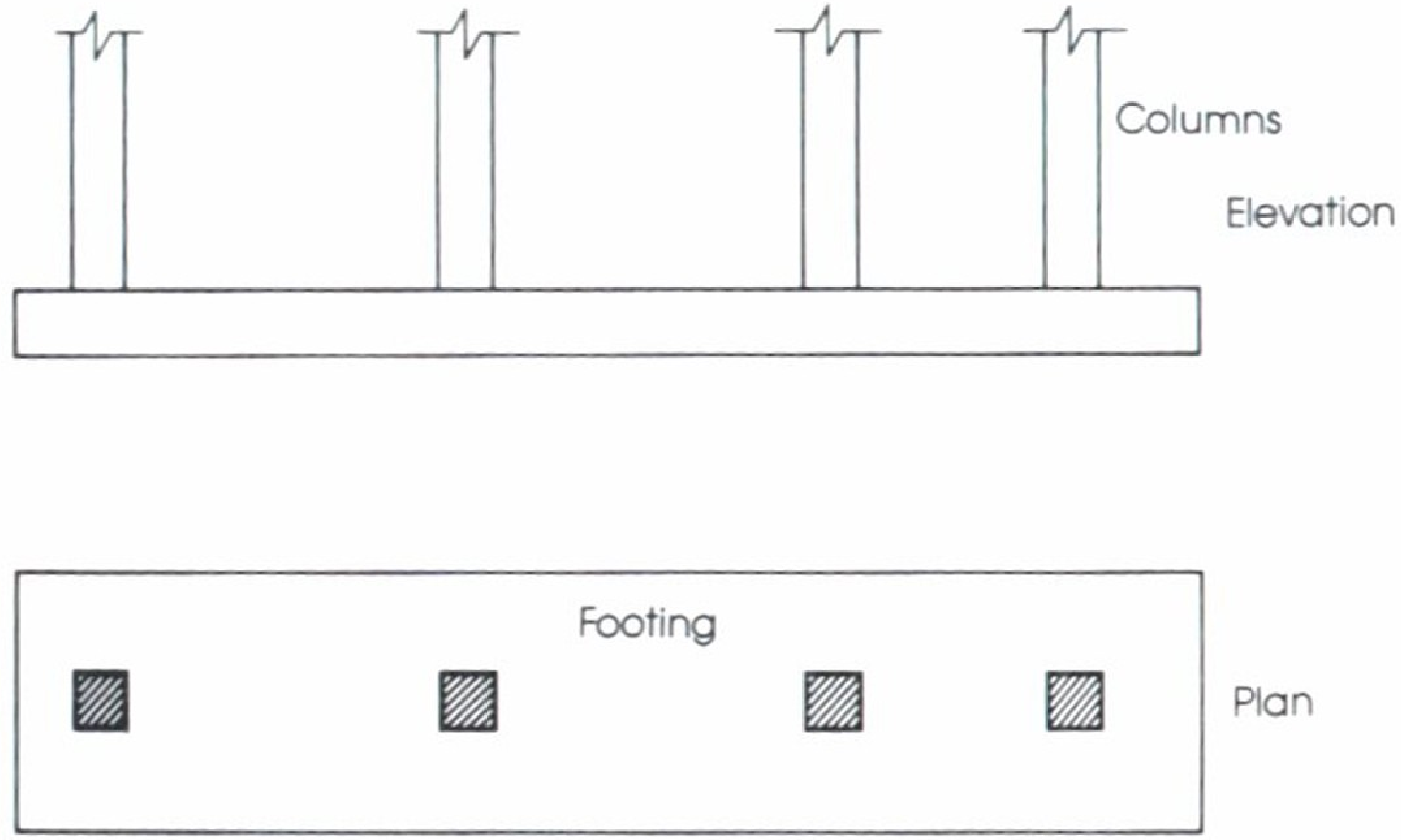
Types of Footings

Cantilever or strap footings consist of two single footings connected with a beam or a strap and support two single columns. This type replaces a combined footing and is more economical.



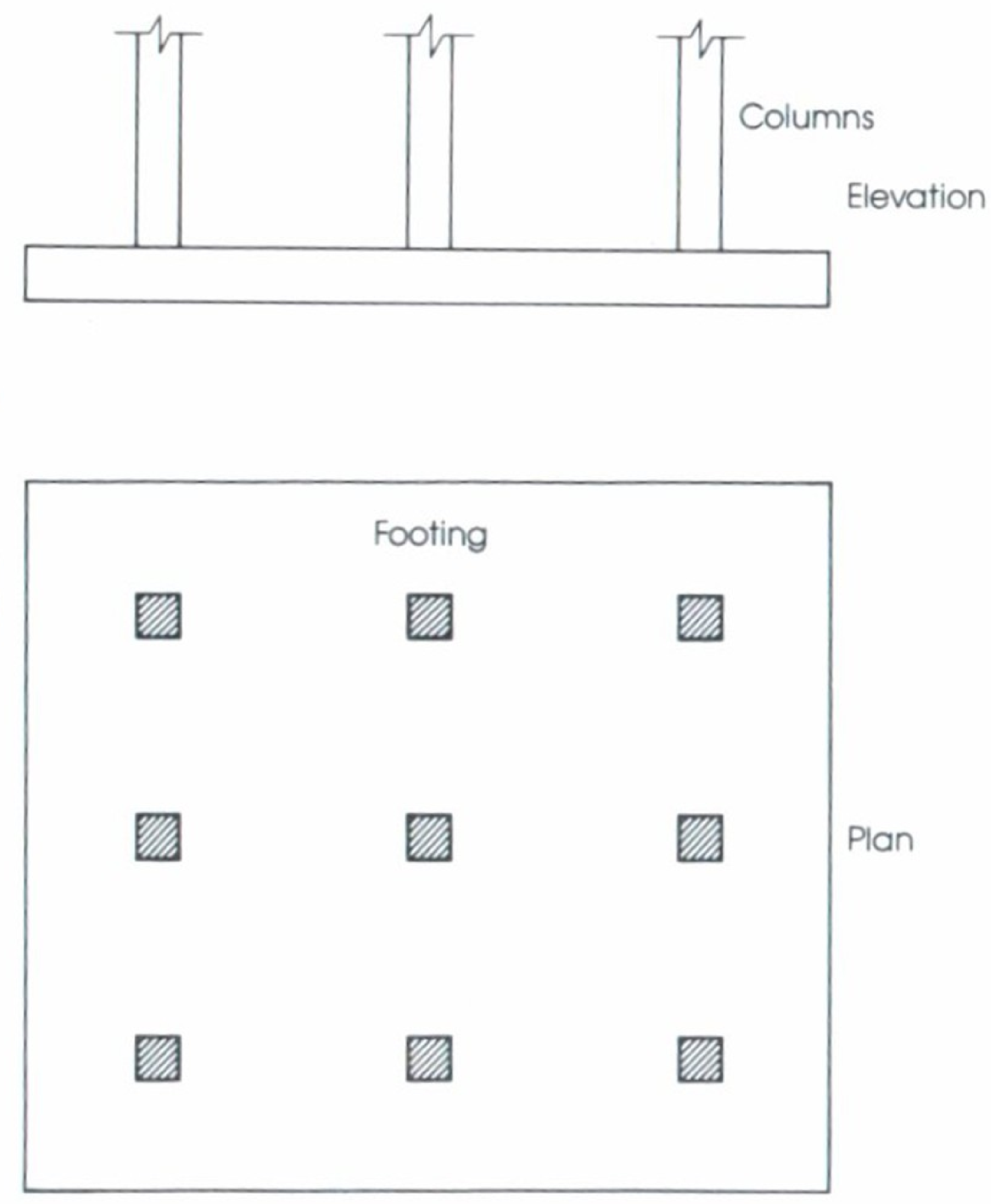
Types of Footings

Continuous footings support a row of three or more columns. They have limited width and continue under all columns.



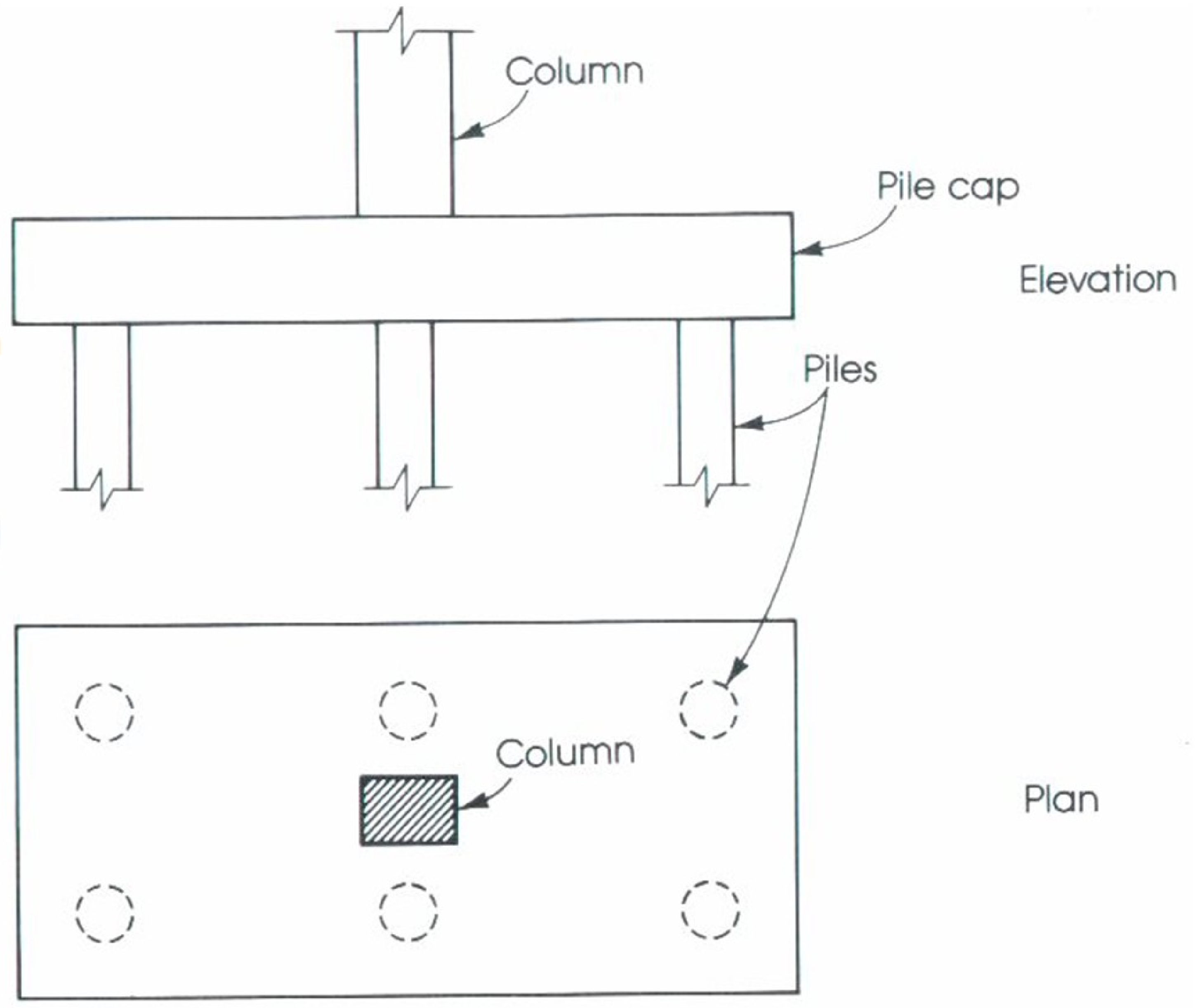
Types of Footings

Rafted or mat foundation consists of one footing usually placed under the entire building area. They are used, when soil bearing capacity is low, column loads are heavy, single footings cannot be used, piles are not used and differential settlement must be reduced.



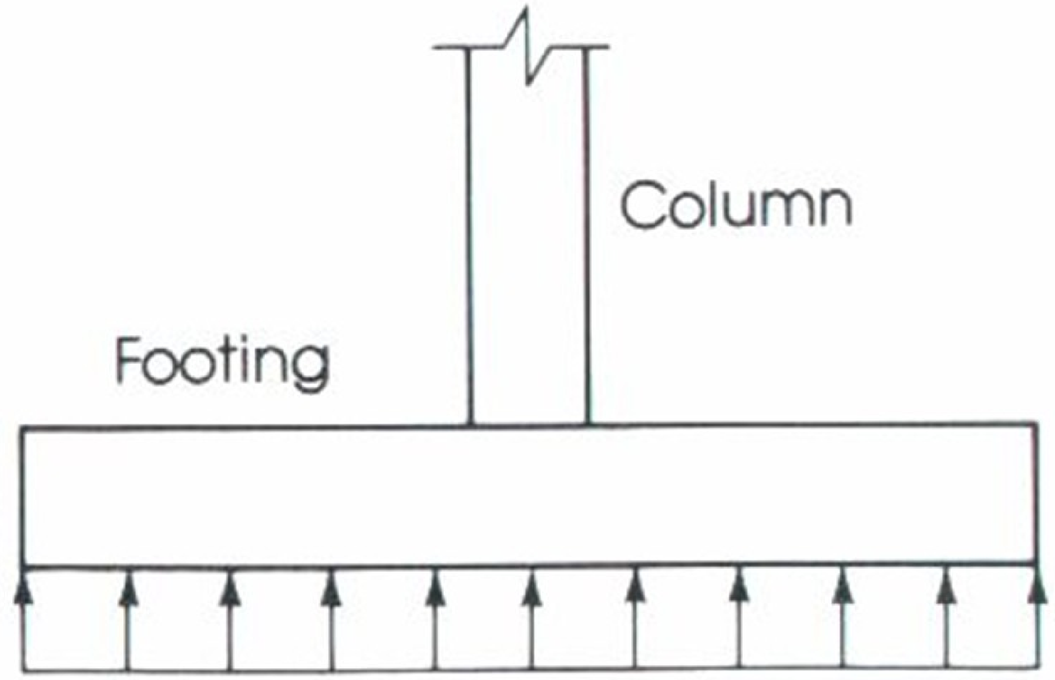
Types of Footings

Pile caps are thick slabs used to tie a group of piles together to support and transmit column loads to the piles.



Distribution of Soil Pressure

When the column load P is applied on the centroid of the footing, a uniform pressure is assumed to develop on the soil surface below the footing area.



However the actual distribution of the soil is not uniform, but depends on many factors especially the composition of the soil and degree of flexibility of the footing.

Design Considerations

Footings must be designed to carry the column loads and transmit them to the soil safely while satisfying code limitations.

1. The area of the footing based on the allowable bearing soil capacity
2. Two-way shear or punch out shear.
3. One-way wide beam shear
4. Bending moment and steel reinforcement required

Size of Footings

The area of footing can be determined from the actual external loads such that the allowable soil pressure is not exceeded.

$$\text{Area of footing} = \frac{\text{Total load (including self - weight)}}{\text{allowable soil pressure}}$$

Strength design requirements

$$q_{\mathrm{u}} = \frac{P_{\mathrm{u}}}{\text{area of footing}}$$

Two-Way Shear (Punching Shear)

For two-way shear in slabs (& footings) V_c is smallest of

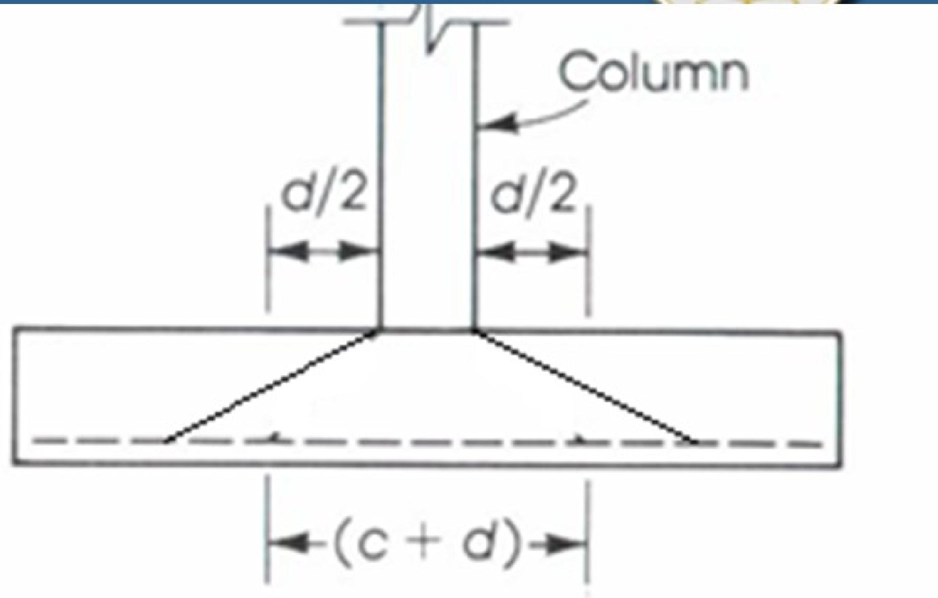
$$V_c = \left(1 + \frac{2}{\beta_c}\right)\frac{\sqrt{f_c}}{6}\, b_0 d \qquad \text{ACI 11-31}$$

where, β_c = long side/short side of column concentrated load or reaction area < 2

b_0 = length of critical perimeter around the column

When β_c > 2 the allowable V_c is reduced.

Design of two-way shear



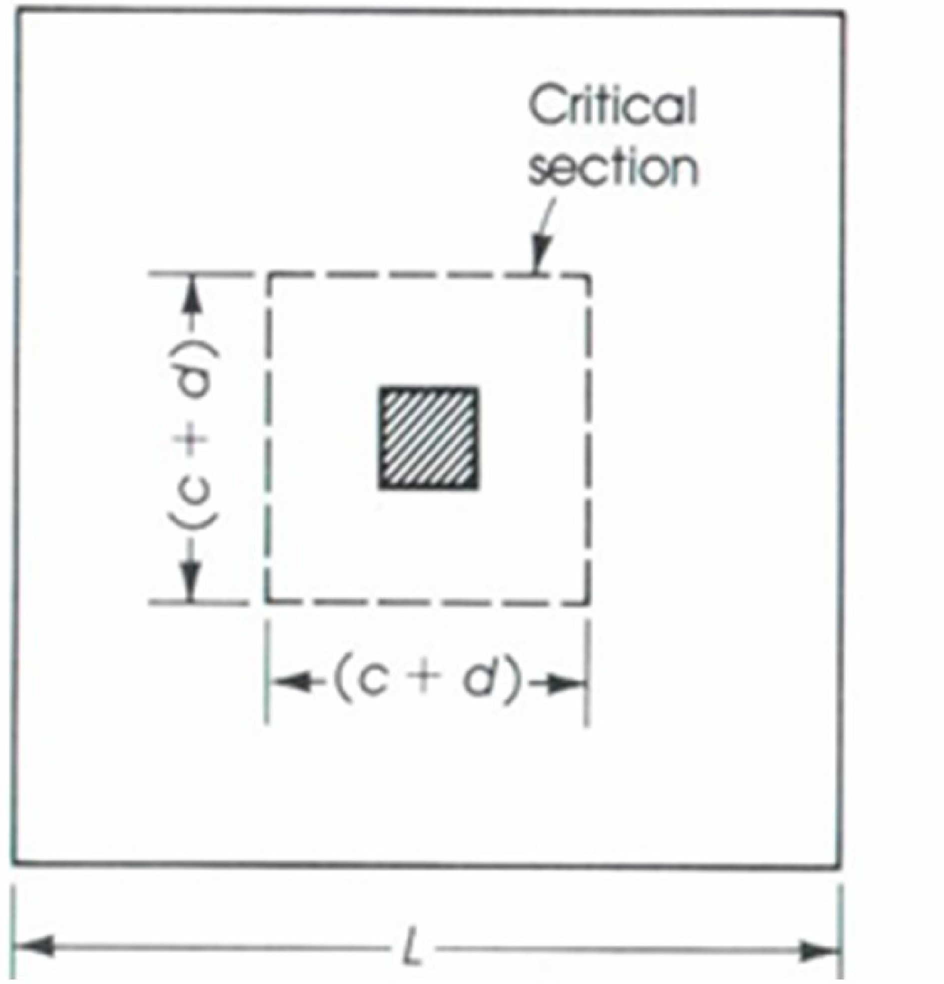
1. Assume d.
2. Determine b_0.

$b_0 = 4(c+d)$

for square columns where one side = c

$b_0 = 2(c_1+d) +2(c_2+d)$

for rectangular columns of sides c_1 and c_2.

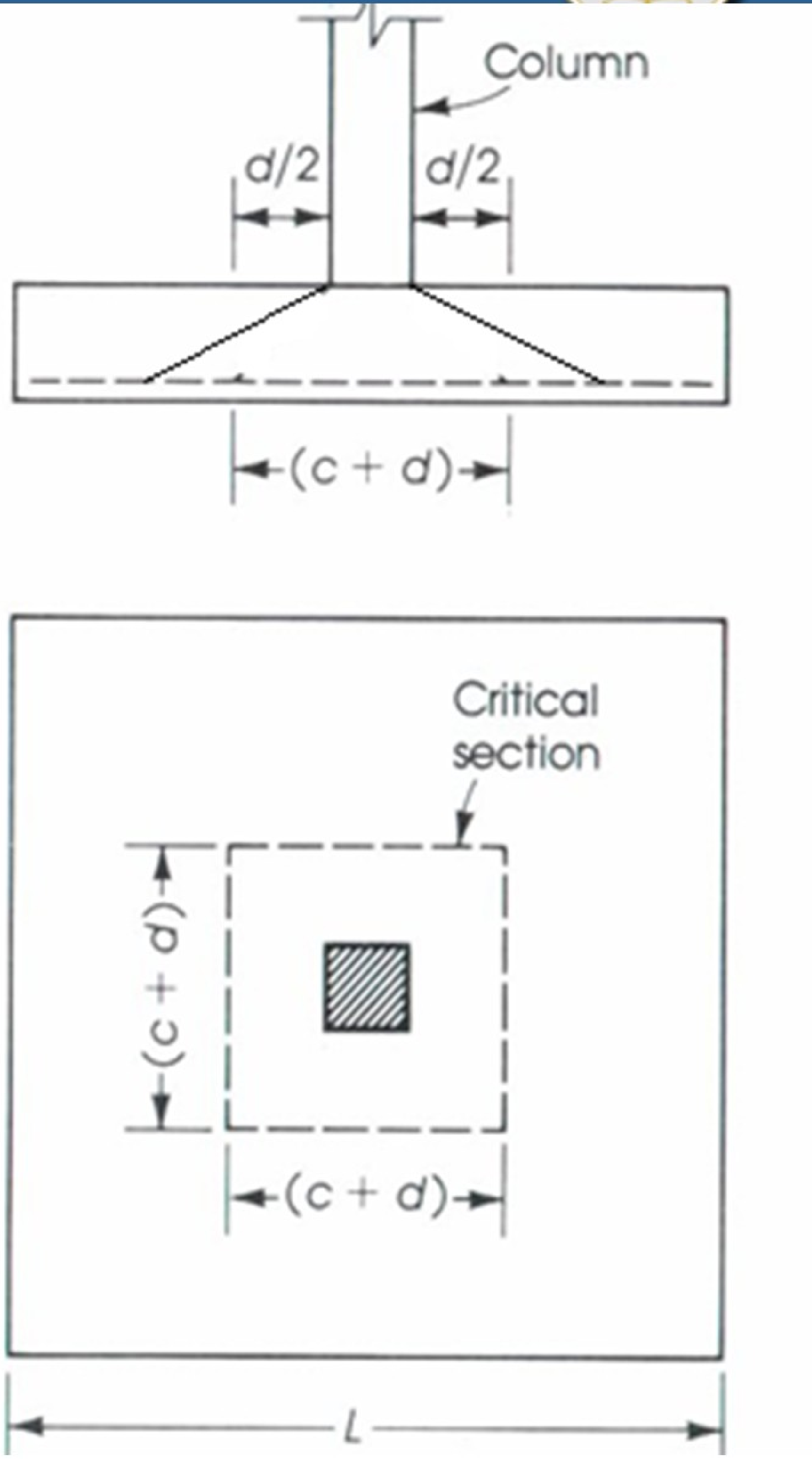


Design of two-way shear

3. The shear force V_u acts at a section that has a length $b_0 = 4(c+d)$ or $2(c_1+d) + 2(c_2+d)$ and a depth d; the section is subjected to a vertical downward load P_u and vertical upward pressure q_u.

$$V_u = P_u - q_u(c+d)^2 \quad \text{for square columns}$$

$$V_u = P_u - q_u(c_1+d)(c_2+d) \quad \text{for rectangular columns}$$



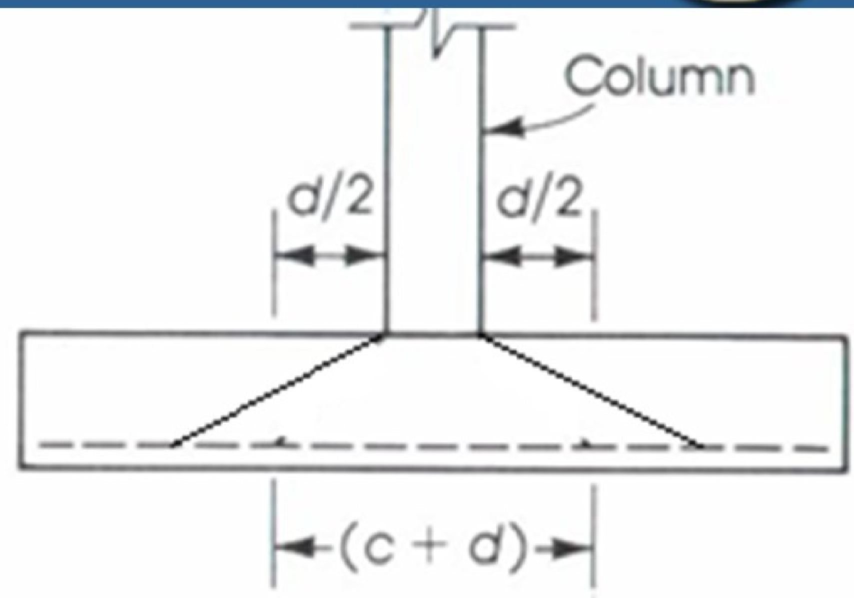
Design of two-way shear

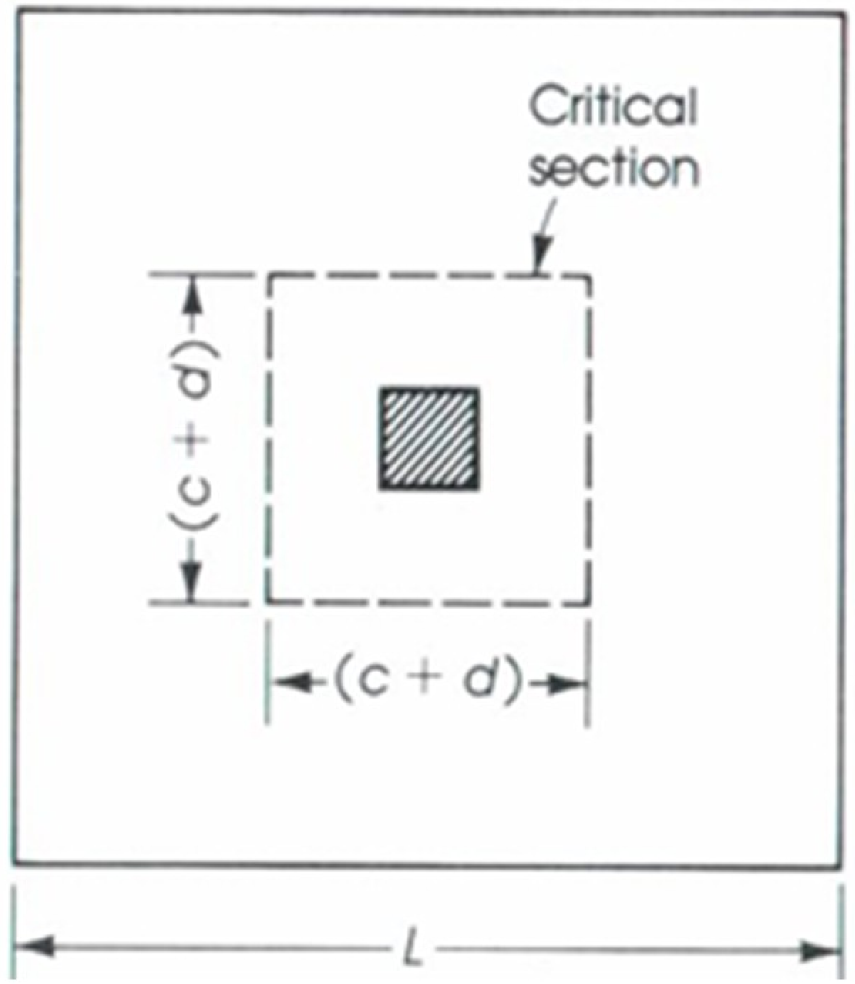
4. Allowable $\phi V_c = \phi \frac{\sqrt{f_c}}{3} b_0 d$

Let $V_u = \phi V_c$

$$d = \frac{3V_u}{\phi \sqrt{f_c} b_0}$$

If d is not close to the assumed d, revise your assumptions

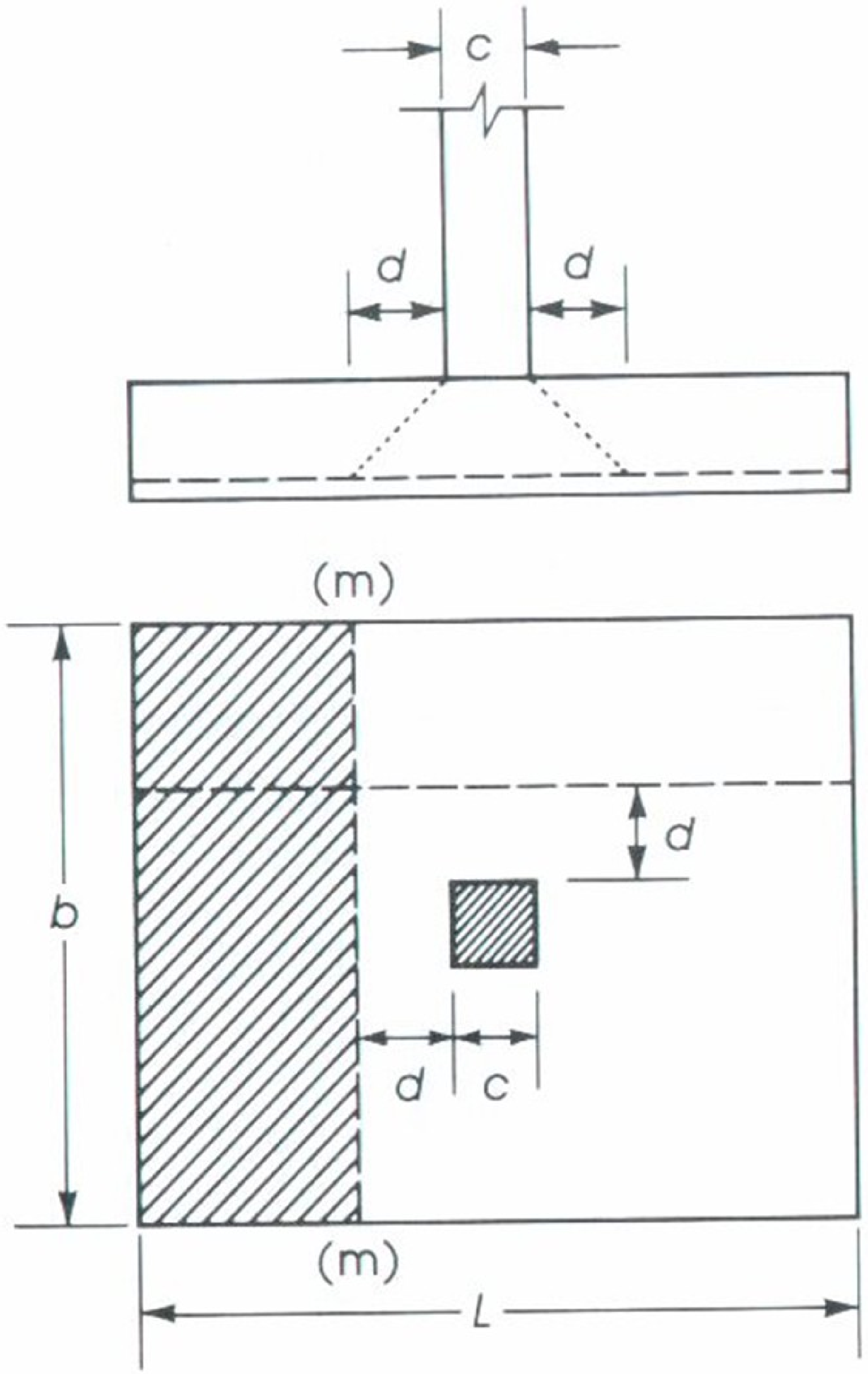




Design of one-way shear

For footings with bending action in one direction the critical section is located a distance d from face of column

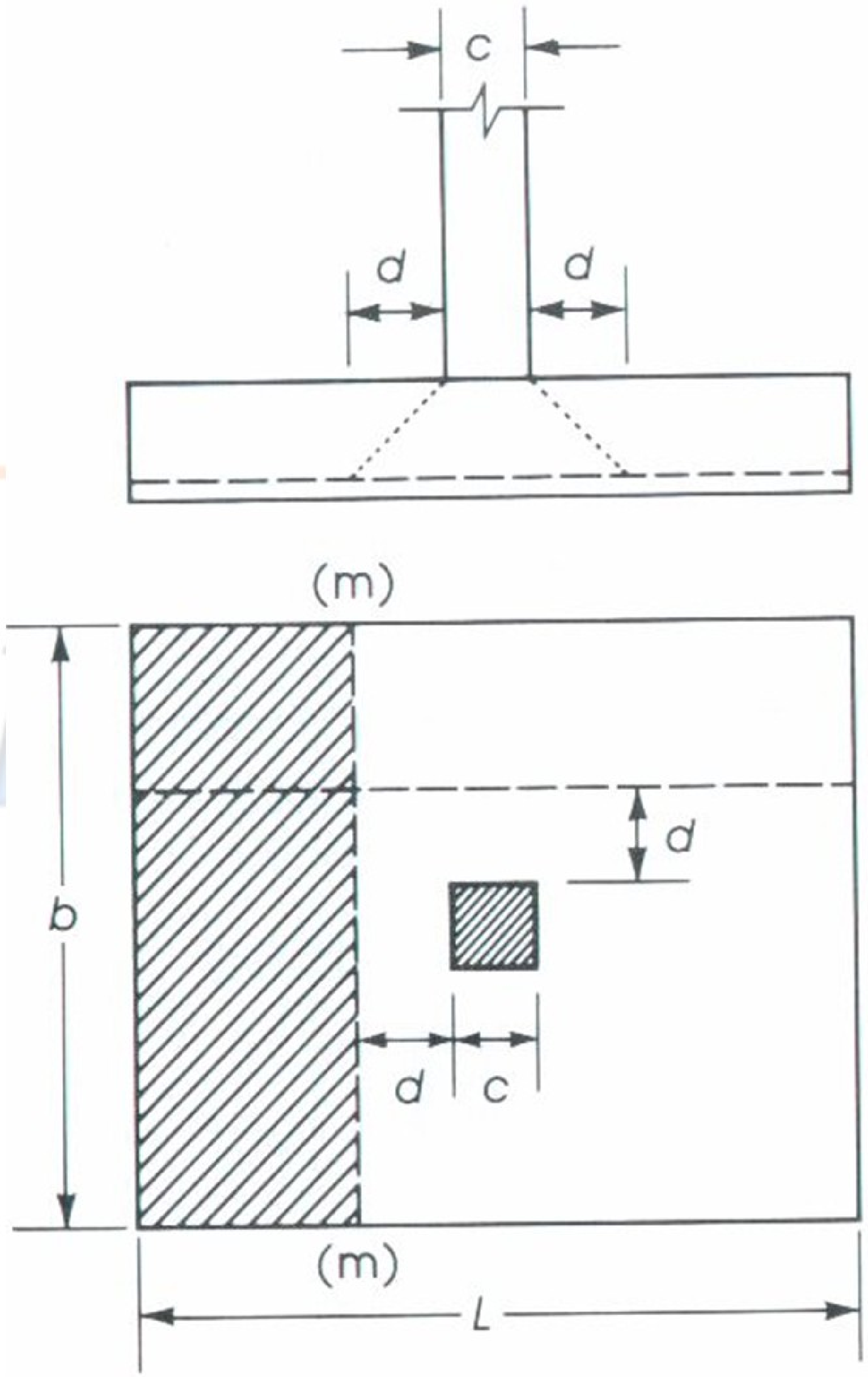
$$\phi V_c = \phi \frac{\sqrt{f_c}}{6} bd$$



Design of one-way shear

The ultimate shearing force at section m-m can be calculated

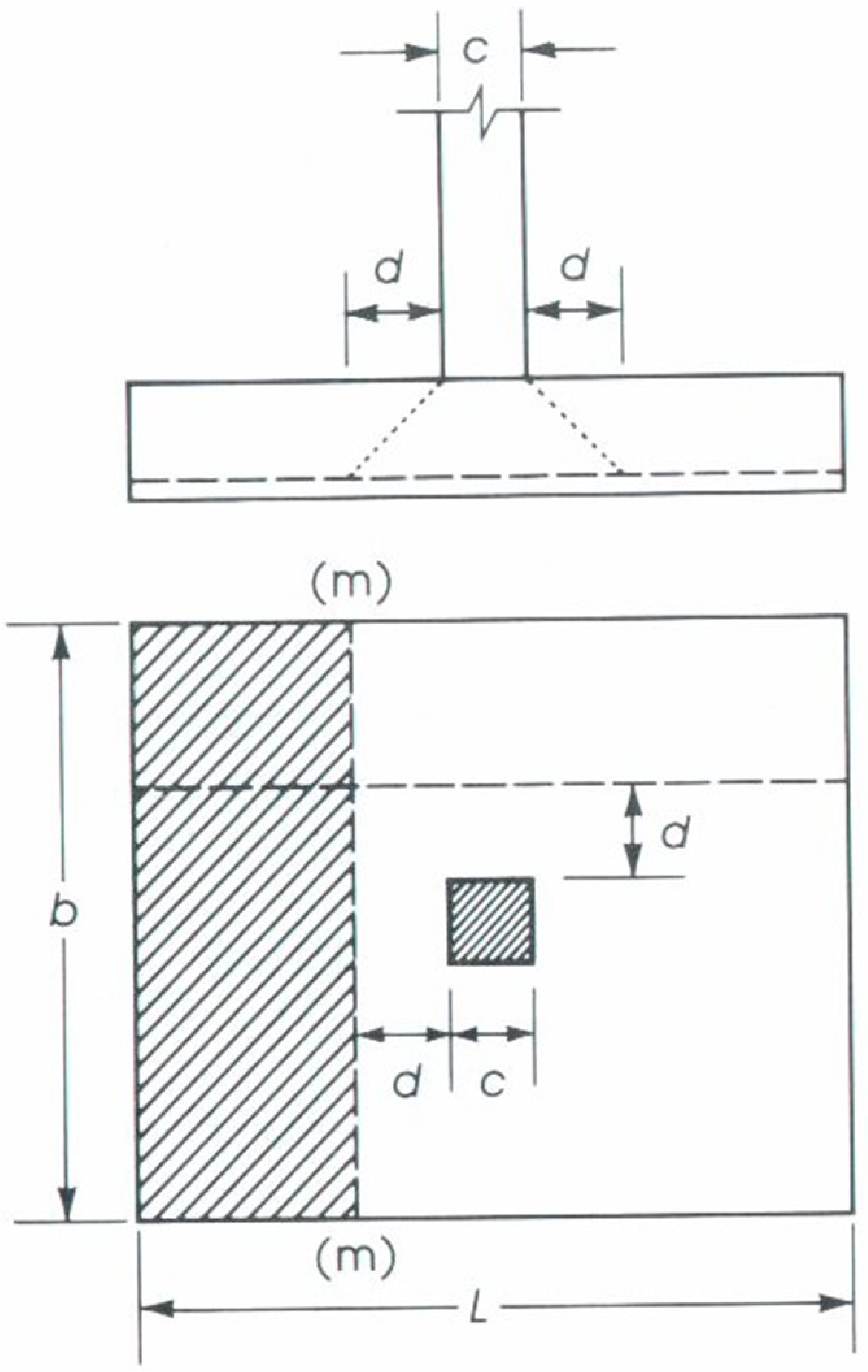
$$V_u = q_u\, b\left(\frac{L}{2} - \frac{c}{2} - d\right)$$



Design of one-way shear

If no shear reinforcement is to be used, then d can be checked, assuming $V_u = \phi V_c$

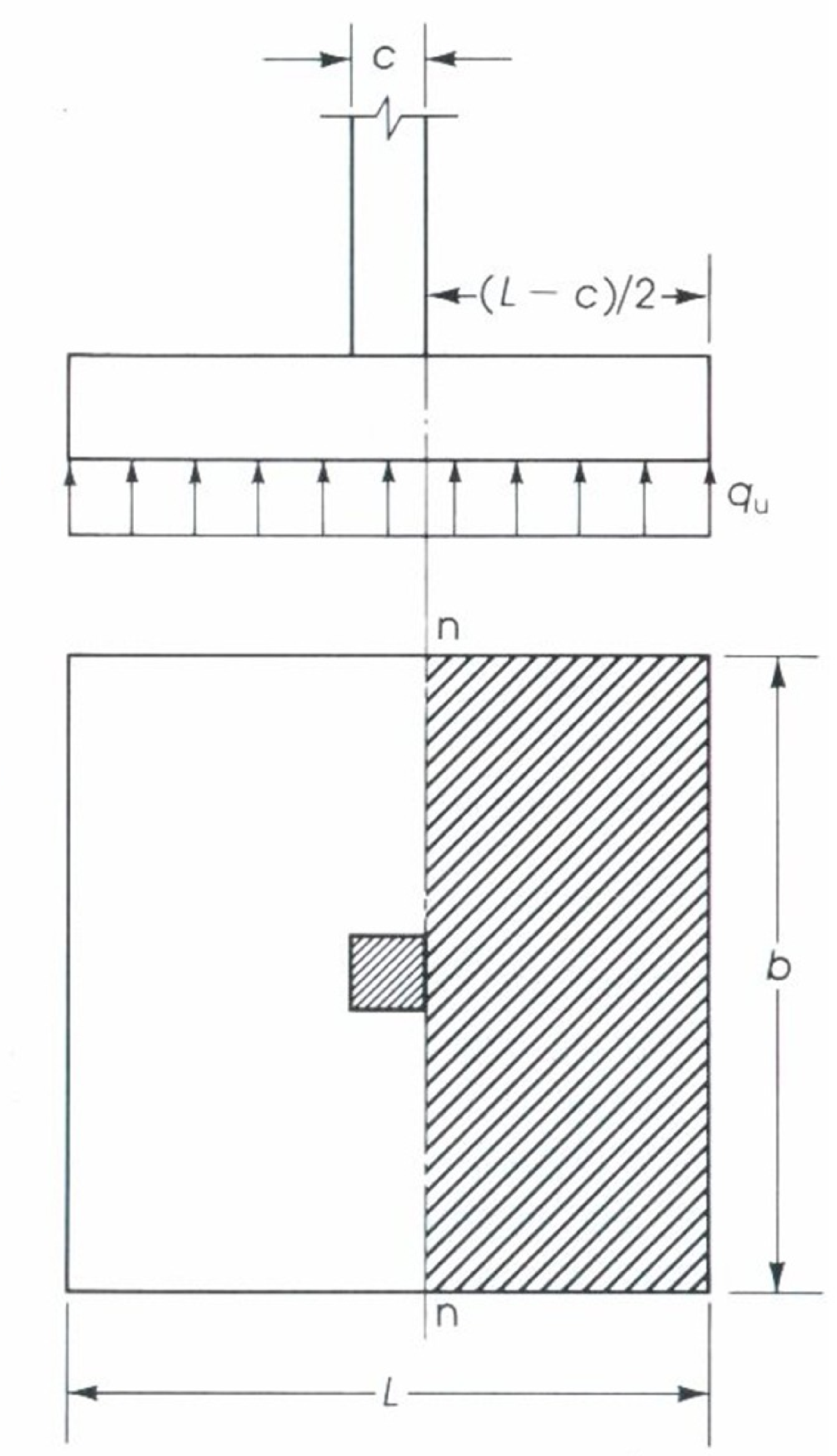
$$d = \frac{6V_u}{\phi\sqrt{f_c}\, b}$$



Approximate Flexural Strength and Footing reinforcement

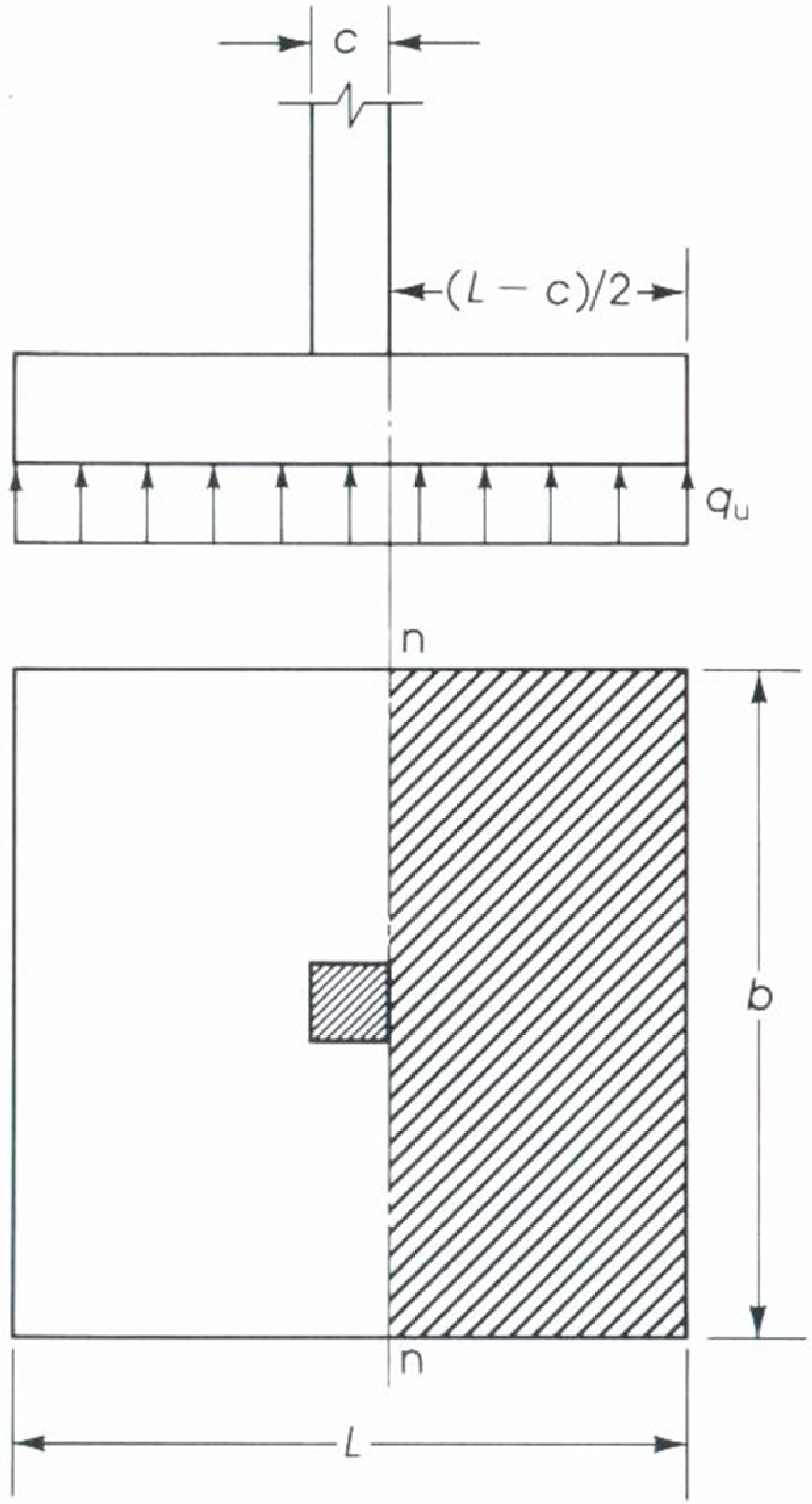
The bending moment in each direction of the footing must be checked and the appropriate reinforcement must be provided.

$$A_s = \frac{3M_u}{d}$$



Flexural Strength and Footing reinforcement

The minimum steel percentage required shall be as required for shrinkage temperature reinforcement.



Problem set #5

- Design a panel 4m by 5m supported on four columns.
  - Design the slab as one-way rib in the 4m direction. The superimposed load is $3kN/m^2$, the live load is $3kN/m^2$
  - Design the beam, column and isolated footing to support four stories, concrete is B250 .
  - Soil allowable bearing capacity is $350kN/m^2$

End of chapter 4

Let Learning Continue

System analysis and design

5.1. Regular systems

5.2. Ribbed slab systems

5.3. Two way slab systems

If time permits

5.4. Systems without vertical continuity

5.5. General shape building systems

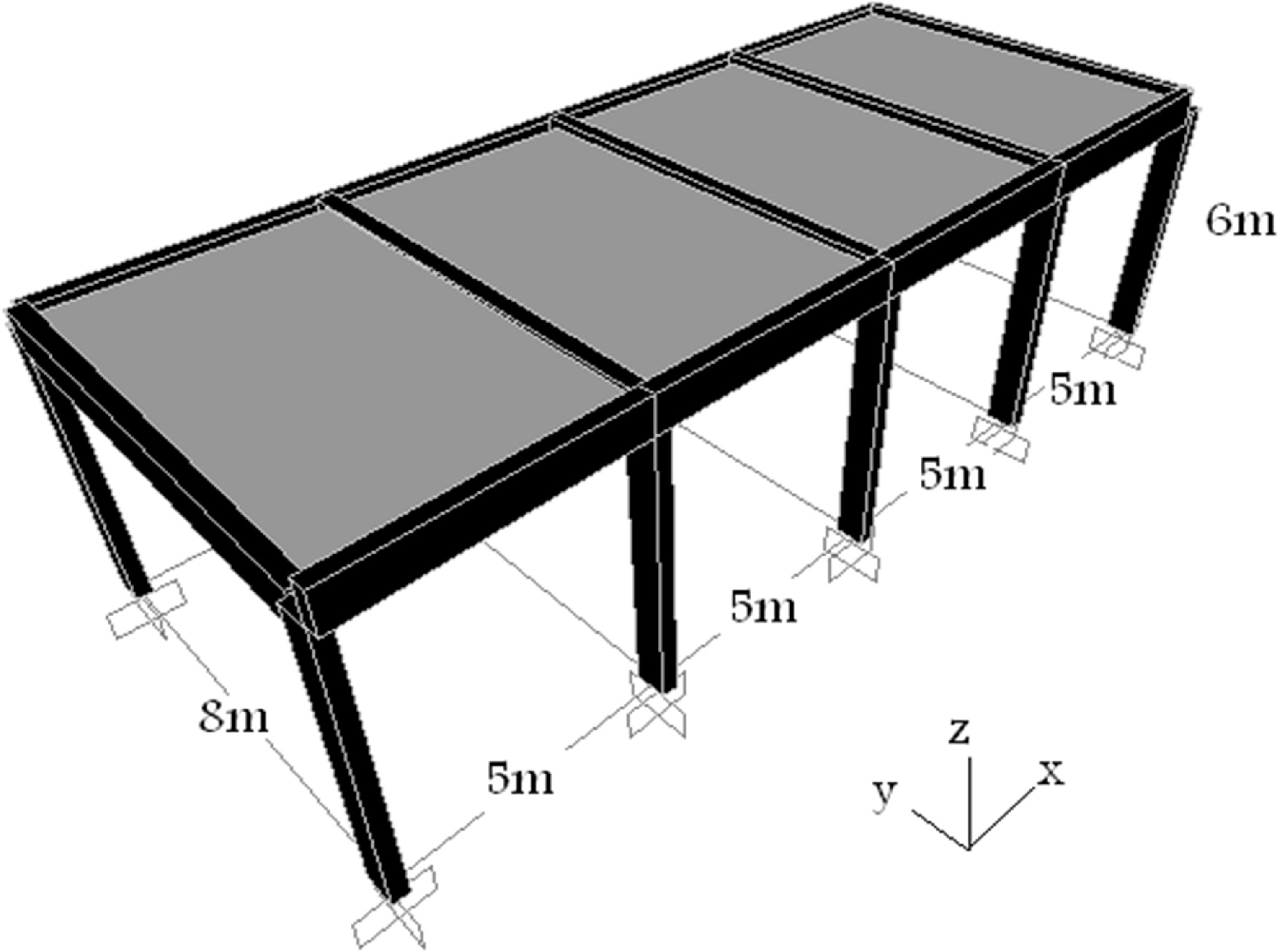
5.1 Regular systems

Regular systems are those which have one way solid slab and vertical continuity; i.e. load of slab is transferred to beams, from beams to columns and then to footings.

Analysis of all systems are done using either 1D, 2D or 3D modeling.

Regular systems: example

- 1-storey RC slab-beam factory structure shown next slide
- Fixed foundations, 4 spans 5m bays in x and a single 8m span in y, 6m elevation
- E=24GPa, μ=0.2, ρ=2.5t/m^3
- Cylinder concrete strength=25MPa, steel yield=420MPa
- superimposed loads=5kN/m^2, live load=9kN/m^2


6m
5m
5m
5m
8m
5m
z
y
x

Regular systems: example

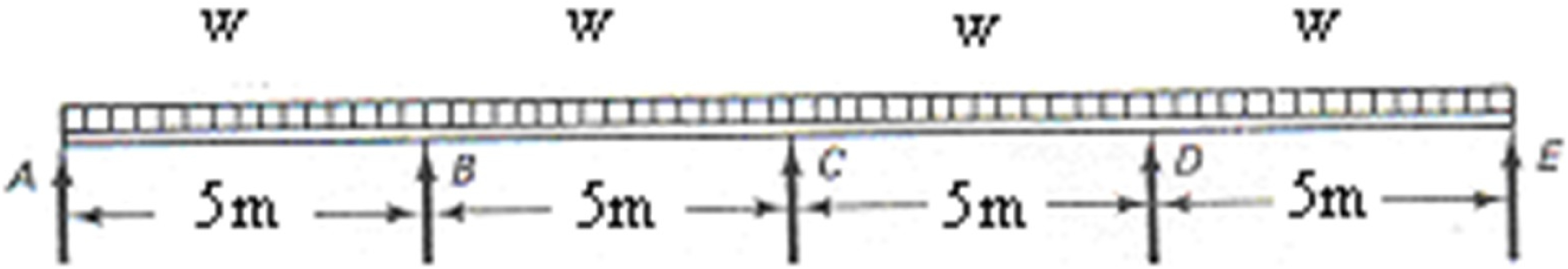
- Due to cracking of elements, use the following modifiers for gross inertia for 3D analysis (ACI R10.11.1):
  - Beam 0.35
  - Column 0.7
  - One way slab (0.35, 0.035)

Preliminary dimensioning

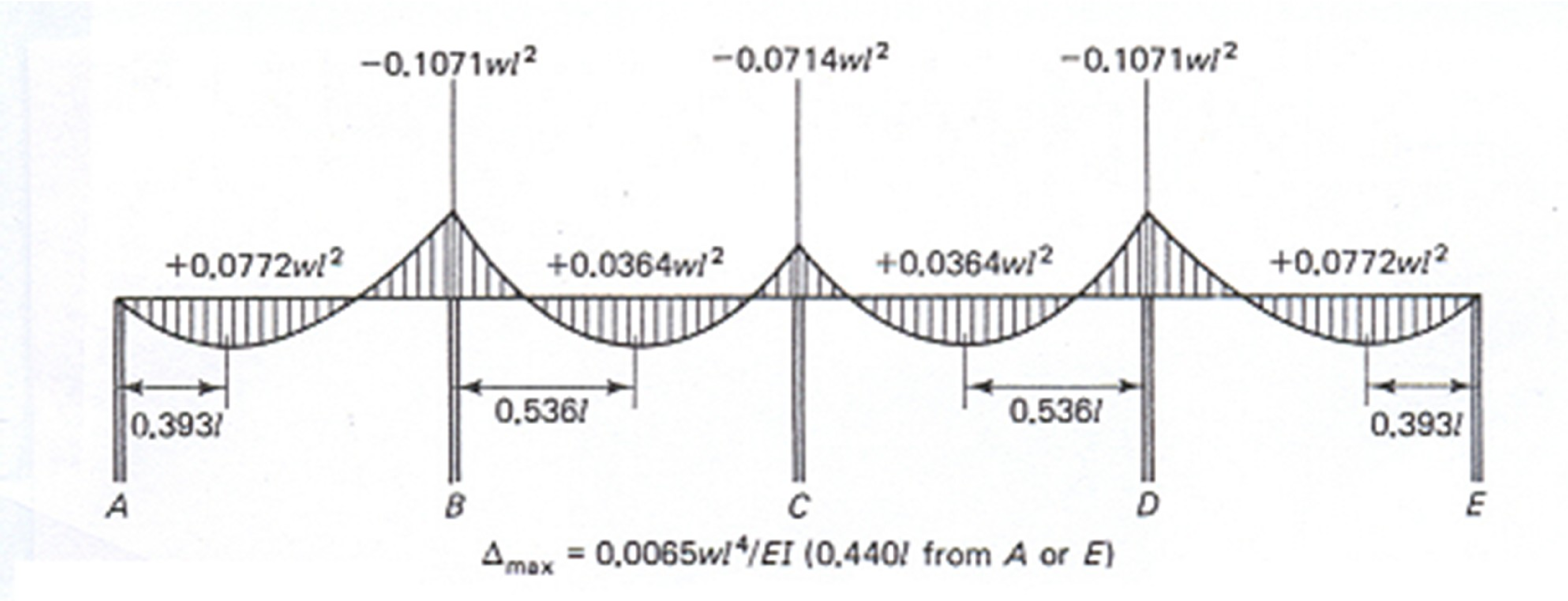
- Slab: According to ACI 9.5.2 thickness of slab=500/24=20.83cm, but considering that concentrated loads might be placed at middle of slab, use 25cm thickness
- Beam: 800/16=50cm, however beams fail by strength and not deflection, and because it is a factory use: drop beams 30cmX80cm (6cm cover)
- Columns: use 30X60cm reinforced on two faces (cover 4cm).

1D analysis and design: slab model

-



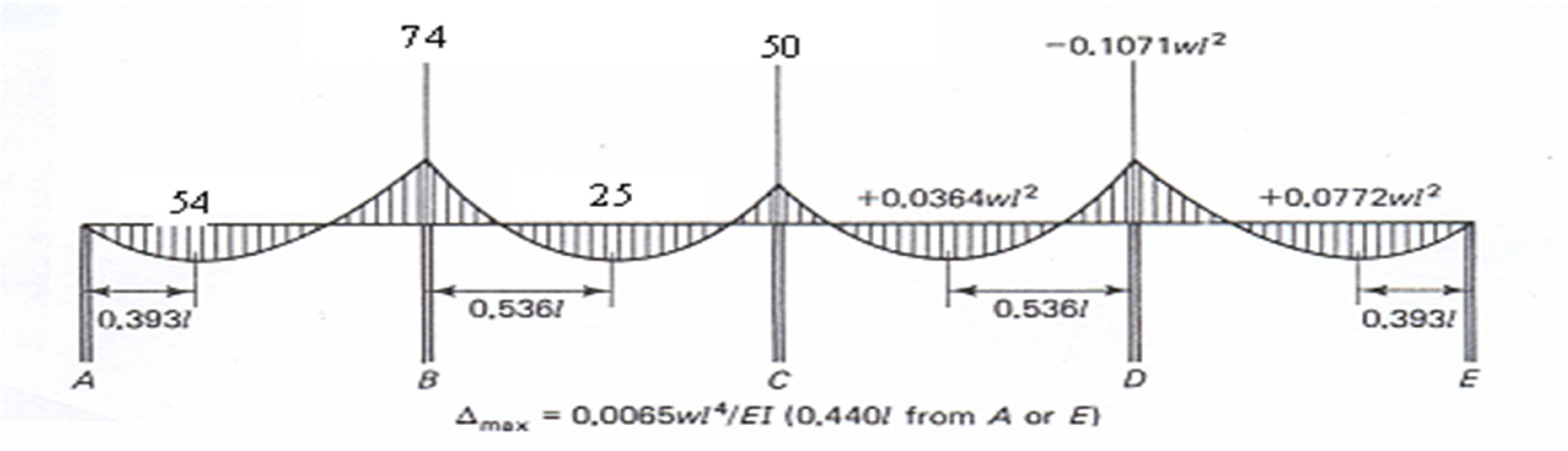
1D analysis and design: slab analysis

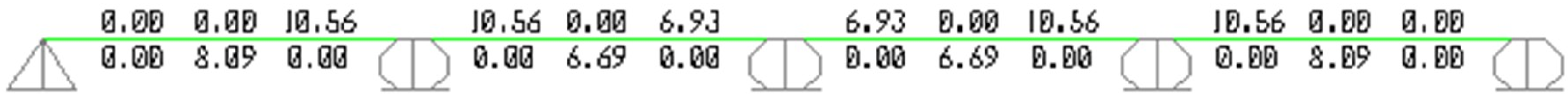


1D analysis and design: slab analysis

- w_d=(.25*24.5+5)=11.125KN/m
- w_l=9KN/m
- w_u=1.2*11.125+1.6*9=27.75KN/m

1D analysis and design: slab analysis, BM in KN.m, As in square cm

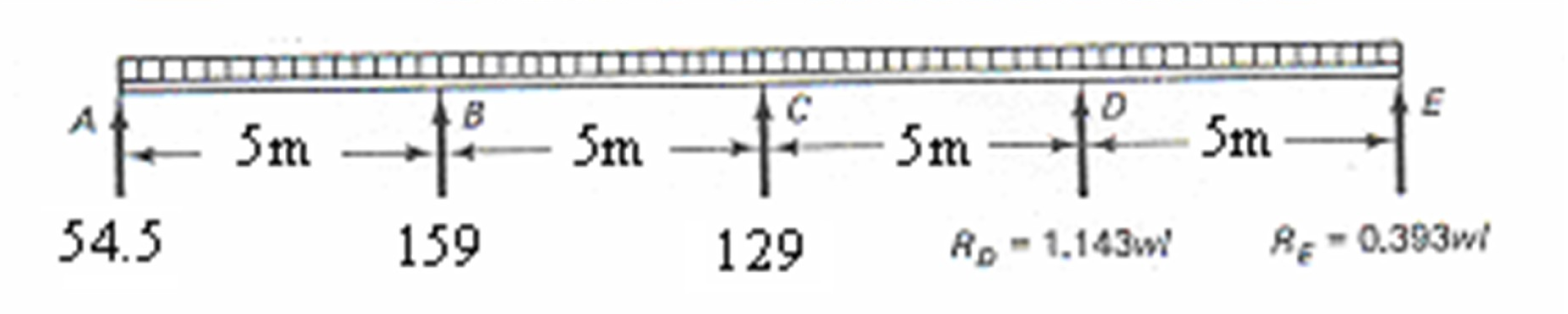




$$A_s \approx \frac{3M_u}{20} = 0.15M_u \geq \frac{1.4}{420}(100*20) = 6.67$$

1D analysis and design: slab analysis, values of reactions in KN

- Note: for slabs and footings of uniform thickness the minimum steel is that for temperature and shrinkage but with maximum spacing three times the thickness or 450mm. (ACI10.5.4)



1D analysis and design: beam analysis

- Assume simply supported beam:
- Beam C, M_u=(129+1.2*0.3*.8*24.5)*8^2 /8=1088
- Beam B, M_u=(159+1.2*0.3*.8*24.5)*8^2 /8=1328
- Beam A, M_u=(54.5+1.2*0.3*.8*24.5)*8^2 /8=492

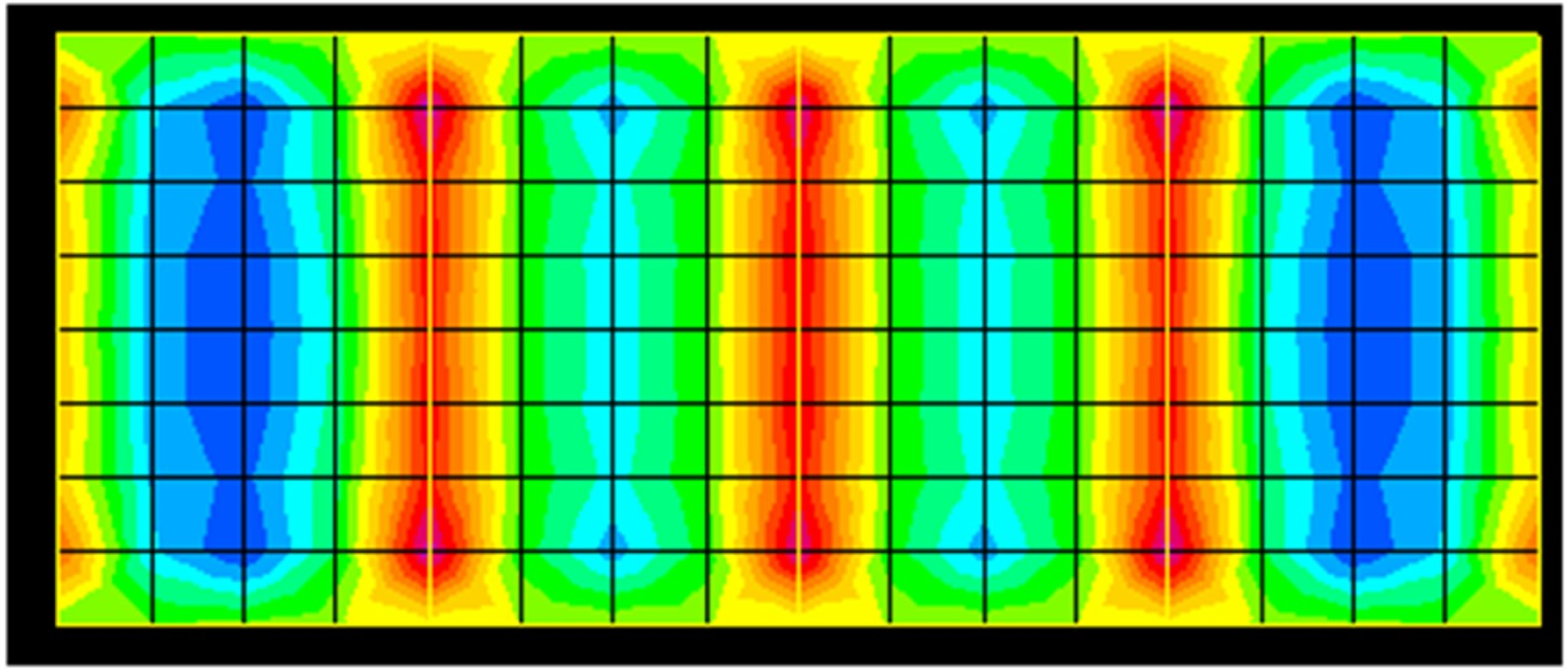
3D SAP: Gravity equilibrium checks

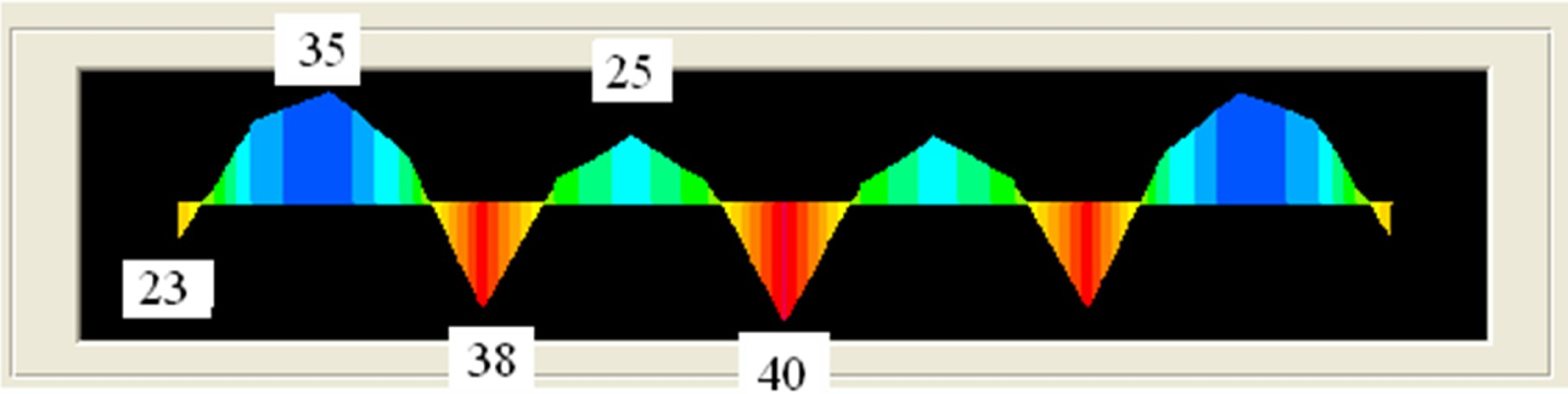
- D:
  - Slab=20X8X(0.25X24.5+5)=1780KN
  - Beams=(5X8+2X20)X.8X.3X24.5=470KN
  - Columns=10X6X.3X.6X24.5=264.6KN
  - Sum=2514.6KN
- L:
  - R =20X8X9=1440KN

Gravity equilibrium checks

- SAP results:

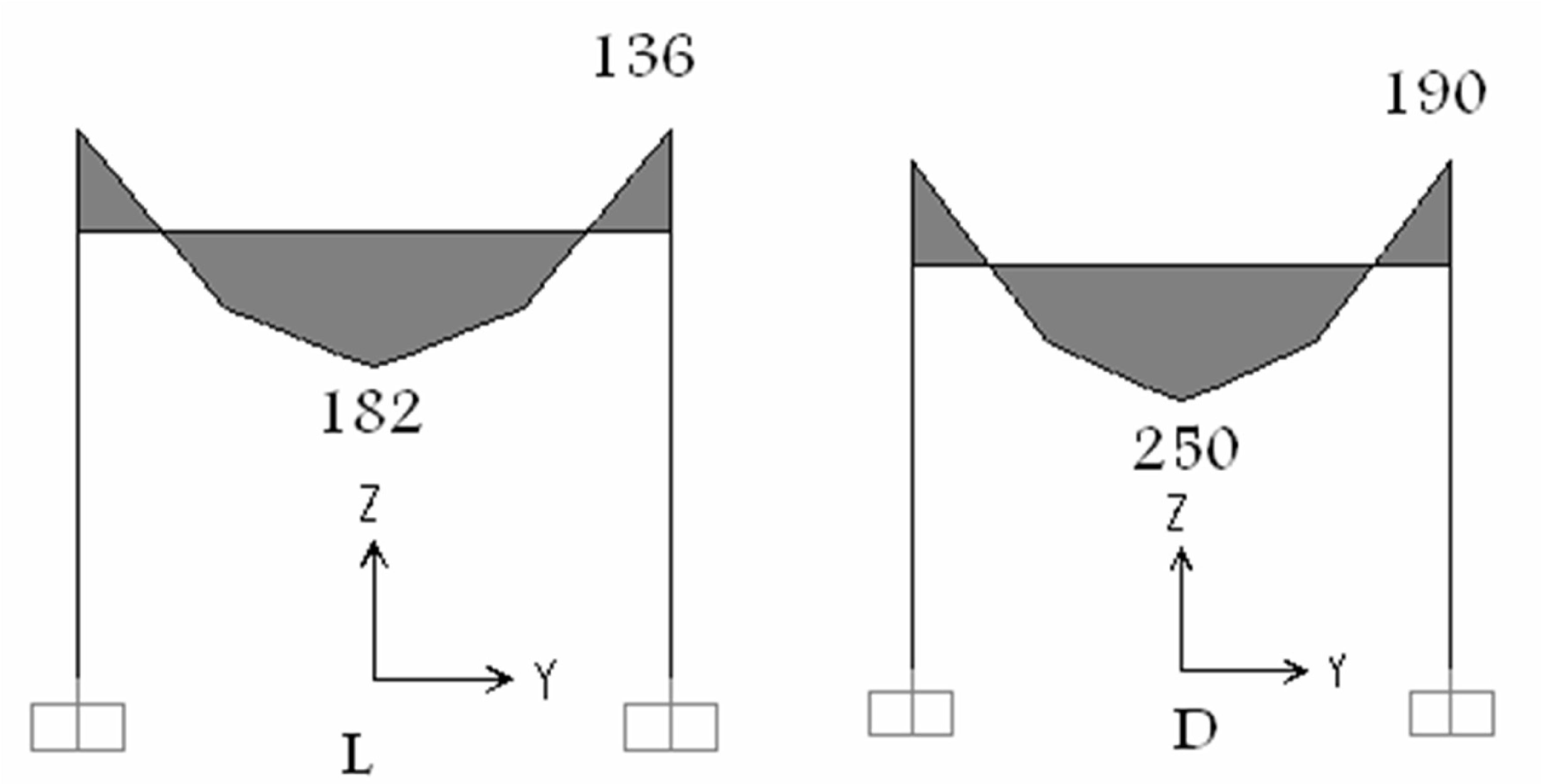
	OutputCase Text	CaseType Text	GlobalFX KN	GlobalFY KN	GlobalFZ KN	GlobalMX KN-m	GlobalMY KN-m	GlobalMZ KN-m
▶	DEAD	LinStatic	1.776E-15	0	2515	000000002615	000000004093	000000000151
	live	LinStatic	1.155E-14	-5.329E-14	1440	5.684E-14	000000008527	-5.658E-13





bending moment in slab KN.m

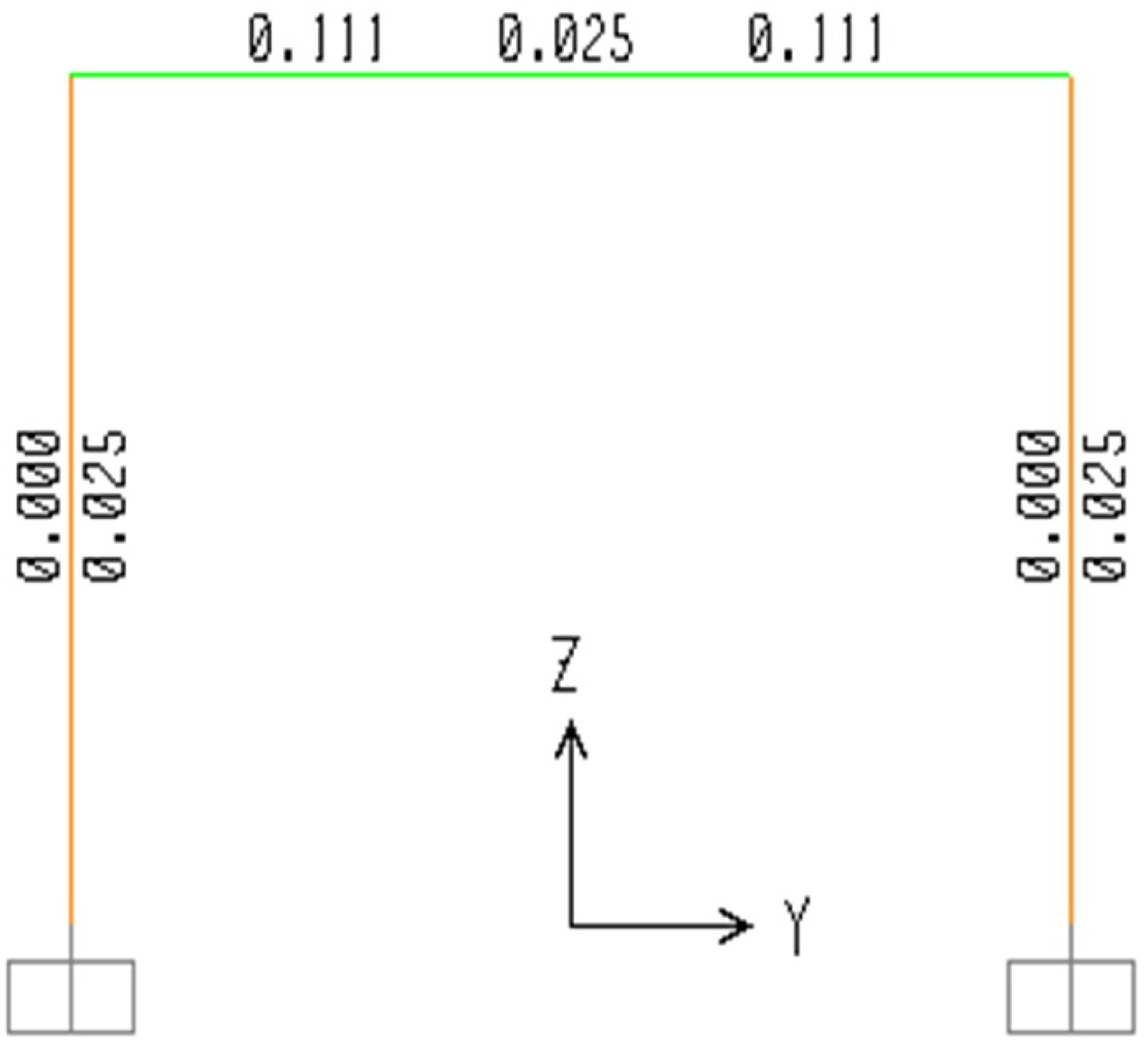
BM in beams in interior frame (KN.m)



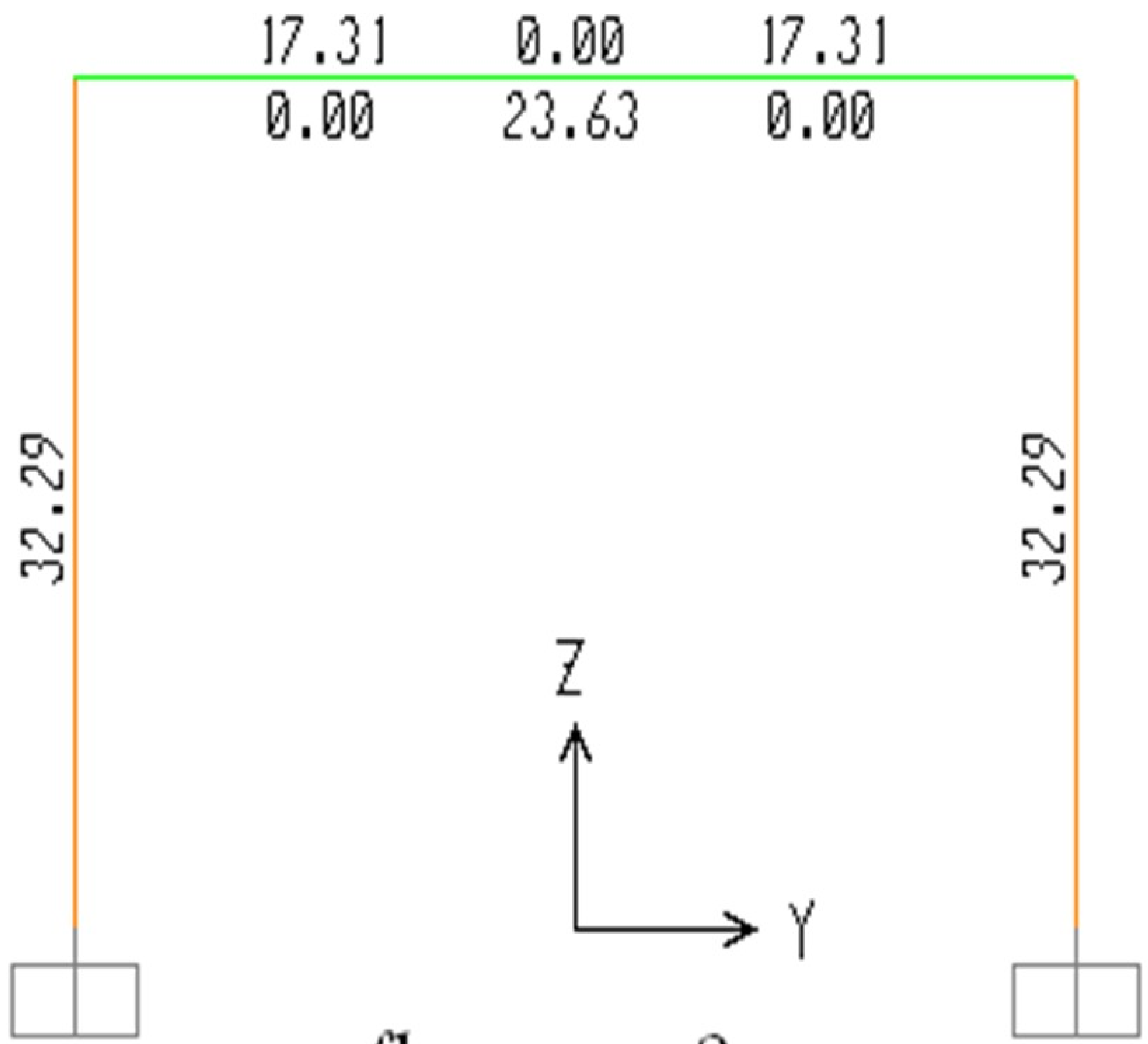
Design for D and L (1.2D+1.6L)

- Conceptual check for dead
  - W_d=(.25X24.5+5)X5=55.6KN/m
  - M_d=55.6X8^2 /8=445KN.m (compare with 250+190=440KN.m ok)
- Conceptual check for live
  - W_L=9X5=45KN/m
  - M_L=45X8^2 /8=360KN.m (compare with 182+136=318KN.m ok)
- Conceptual design for positive moment
  - M_u=1.2*250+1.6*182=591KN.m
  - A_s=3*591/74=24cm^2.

Reinforcement calculation



shear Av/s (cm)



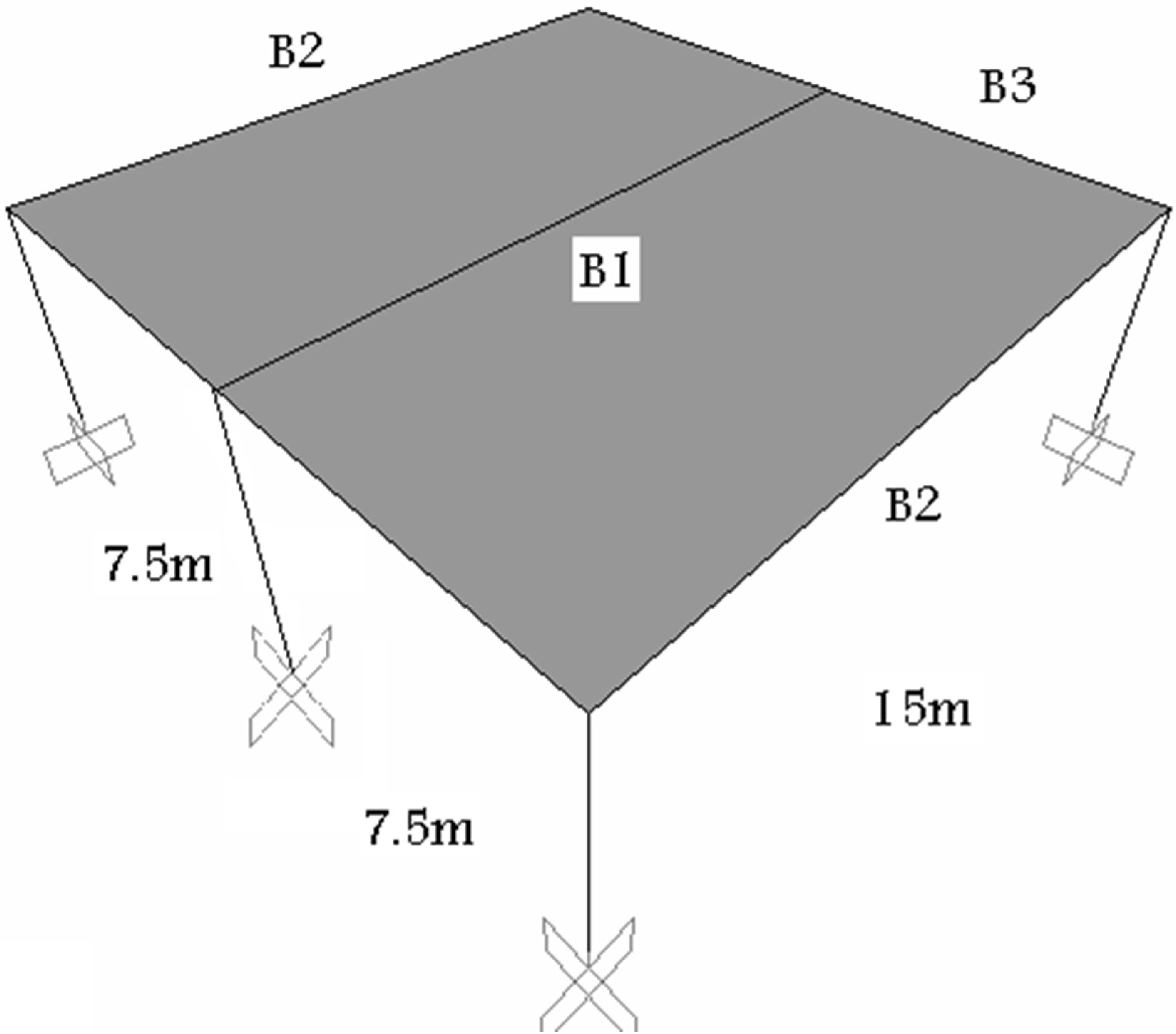
flexure cm2

Conclusion:

- If 3D analysis results are used conceptual understanding of edge beam is wrong, thus expect failure in torsion

Problem set #6

- Analyze and design a one story reinforced concrete structure (entertainment hall) made of one way solid slab sitting on drop beams supported on six square columns 50cm dimensions. The superimposed and live loads are $3KN/m^2$ and $4KN/m^2$ respectively.


B2
B3
B1
B2
7.5m
15m
7.5m

End of section 5.1

Let Learning Continue

5.2 Ribbed slab systems

View of Pan Joist Slab from Below

Pan Joist Floor Systems

- Definition: The type of slab is also called a ribbed slab. It consists of a floor slab, usually 5-10cm thick, supported by reinforced concrete ribs. The ribs are usually uniformly spaced at distances that do not exceed 75cm. The space between ribs is usually filled with permanent fillers to provide a horizontal slab soffit.

Pan Joist Floor Systems

- <u>ACI Requirements for Joist Construction</u>
  (Sec. 8.13, ACI 318-08)
  - Slabs and ribs must be cast monolithically.
  - Ribs may not be less than 10cm in width
  - Depth of ribs may not be more than 3.5 times the minimum rib width
  - Clear spacing between ribs shall not exceed 750mm

  ** Ribbed slabs not meeting these requirements are designed as slabs and beams. **

Pan Joist Floor Systems

Slab Thickness

– (ACI Sec. 8.13.6.1)

$t \geq 5cm$

$t \geq$ one twelfth the clear distance between ribs

Building codes give minimum fire resistance rating:

1-hour fire rating: 2cm cover, 7.5-9cm slab thick.

2-hour fire rating: 2.5cm cover, 12cm slab thick.

Shear strength

8.13.8 — For joist construction, V_c shall be permitted to be 10 percent more than that specified in Chapter 11.

Pan Joist Floor Systems

- Laying Out Pan Joist Floors (*cont.*)

  – Typically no stirrups are used in joists

  – Reducing Forming Costs:
    - Use constant joist depth for entire floor
    - Use same depth for joists and beams (not always possible)

Pan Joist Floor Systems

Distribution Ribs

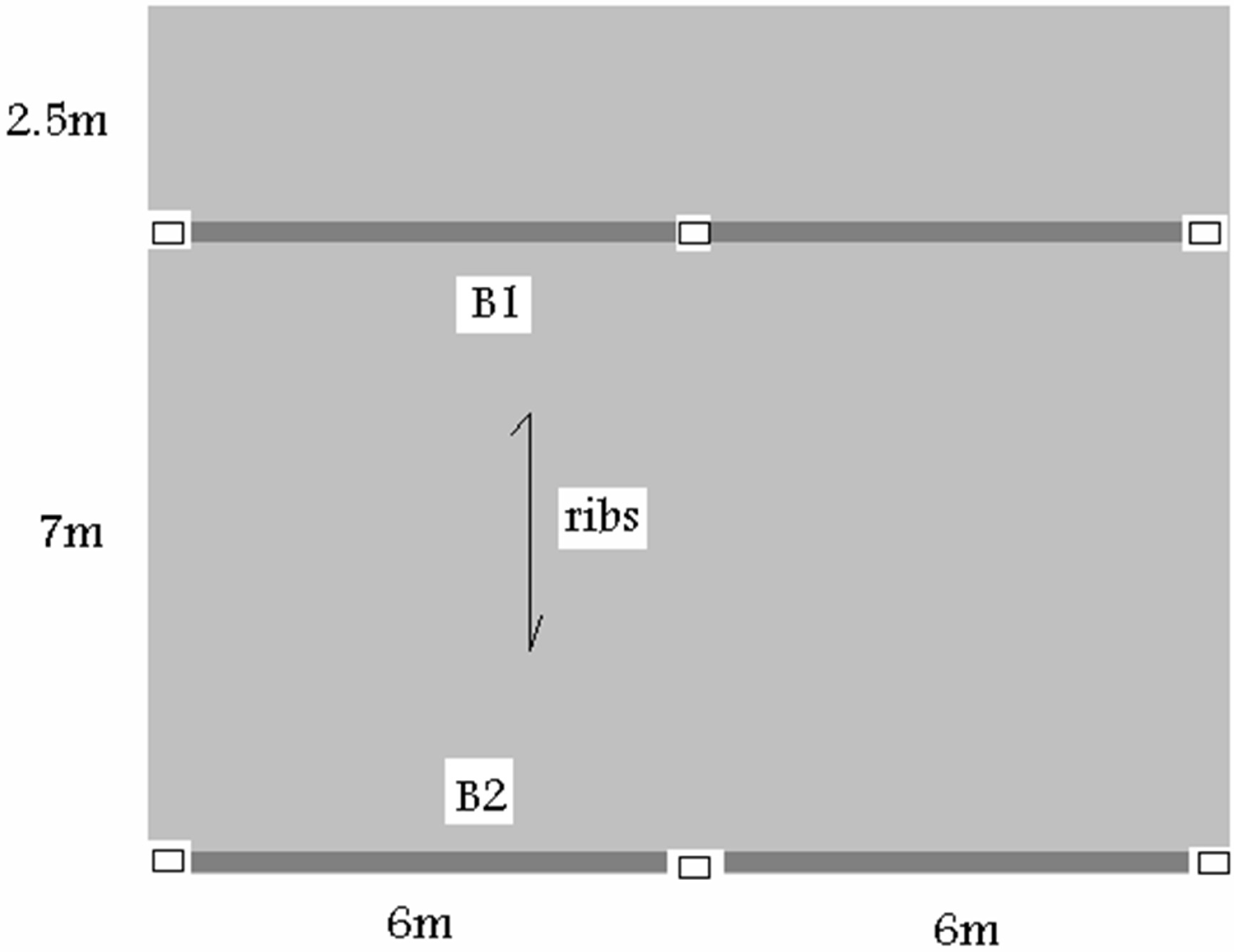
- Placed perpendicular to joists*
- Spans < 6m.: None
- Spans 6-9m: Provided at midspan
- Spans > 9m: Provided at third-points
- At least one continuous #12mm bar is provided at top and bottom of distribution rib.

*Note: not required directly by ACI Code, but typically used in construction and required indirectly in ACI 10.4.1:

10.4.1 — Spacing of lateral supports for a beam shall not exceed 50 times ***b***, the least width of compression flange or face.

Ribbed Slab example

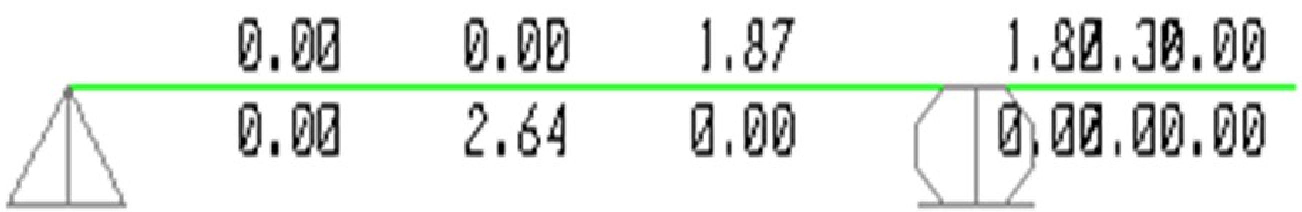
- Analyze and design (as a one-way ribbed slab in the 7m direction) the following one story structure (3m height) using 3D model (figure next slide):
  - A. Specifications: B250, fy=4200 kg/cm^2, superimposed= 70 kg/m^2 , live loads= 200 kg/m^2, ribs 34cm height/ 15cm width, blocks 40X25X24cm height (density=1t/m^3), beam 25cm width by 50cm depth, column dimensions 25cmX25cm,


2.5m
B1
7m
ribs
B2
6m
6m

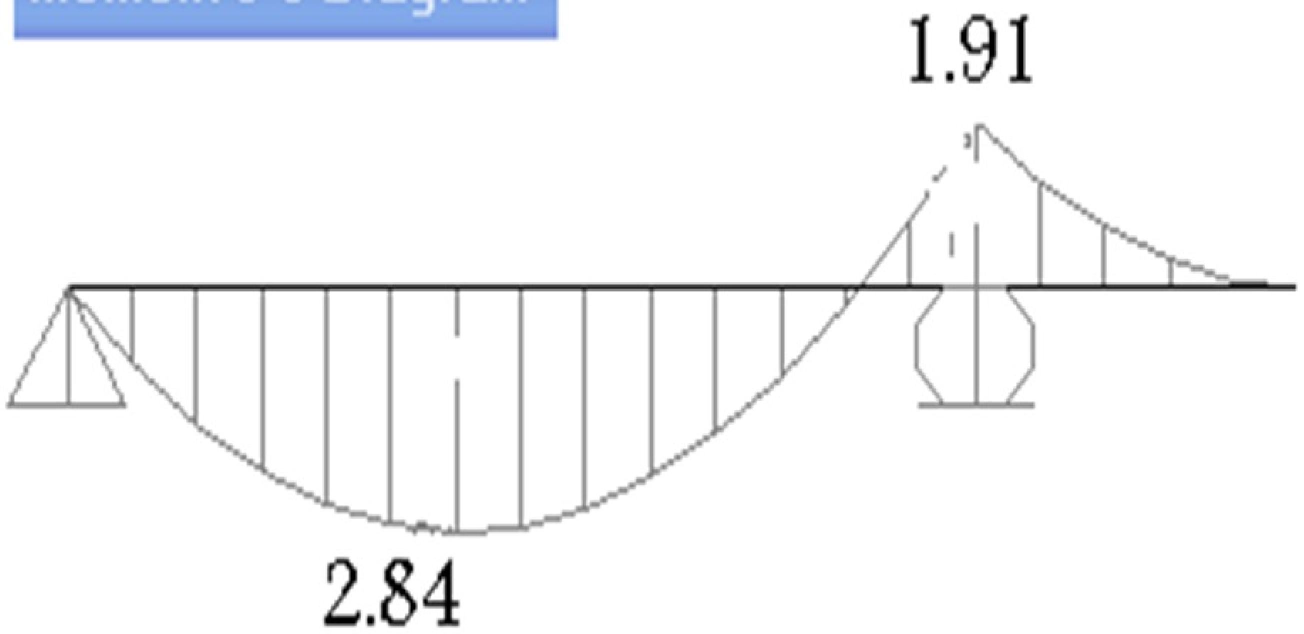
Local practice: slab-beam-column construction

- Slab: assume c=5cm
  - w_d=[(0.15*.24+0.55*0.1)*2.5+0.4*0.24*1]/0.55+0.07=0.658t/m^2
  - w_u =[1.2*0.658+1.6*0.2]*0.55=0.61t/m/rib
  - M_u^- =0.61(2.5)^2 /2=1.91t.m., As=1.87cm^2.
  - M_u^+ =2.84t.m., As=2.64cm^2
  - verify that change of shape (rectangular) or fc (take 300) has minor effect on change of As

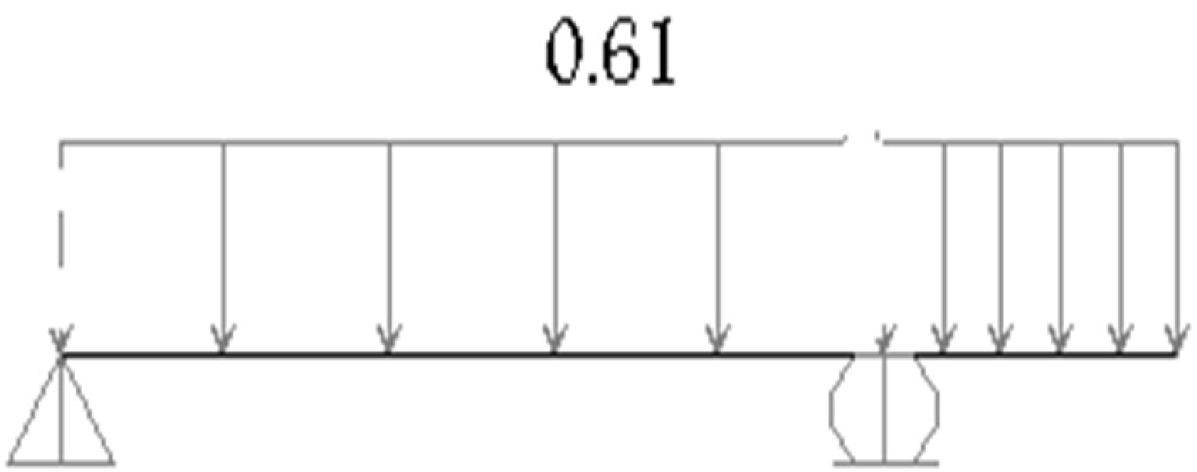
Area



Moment 3-3 Diagram



Span Loads

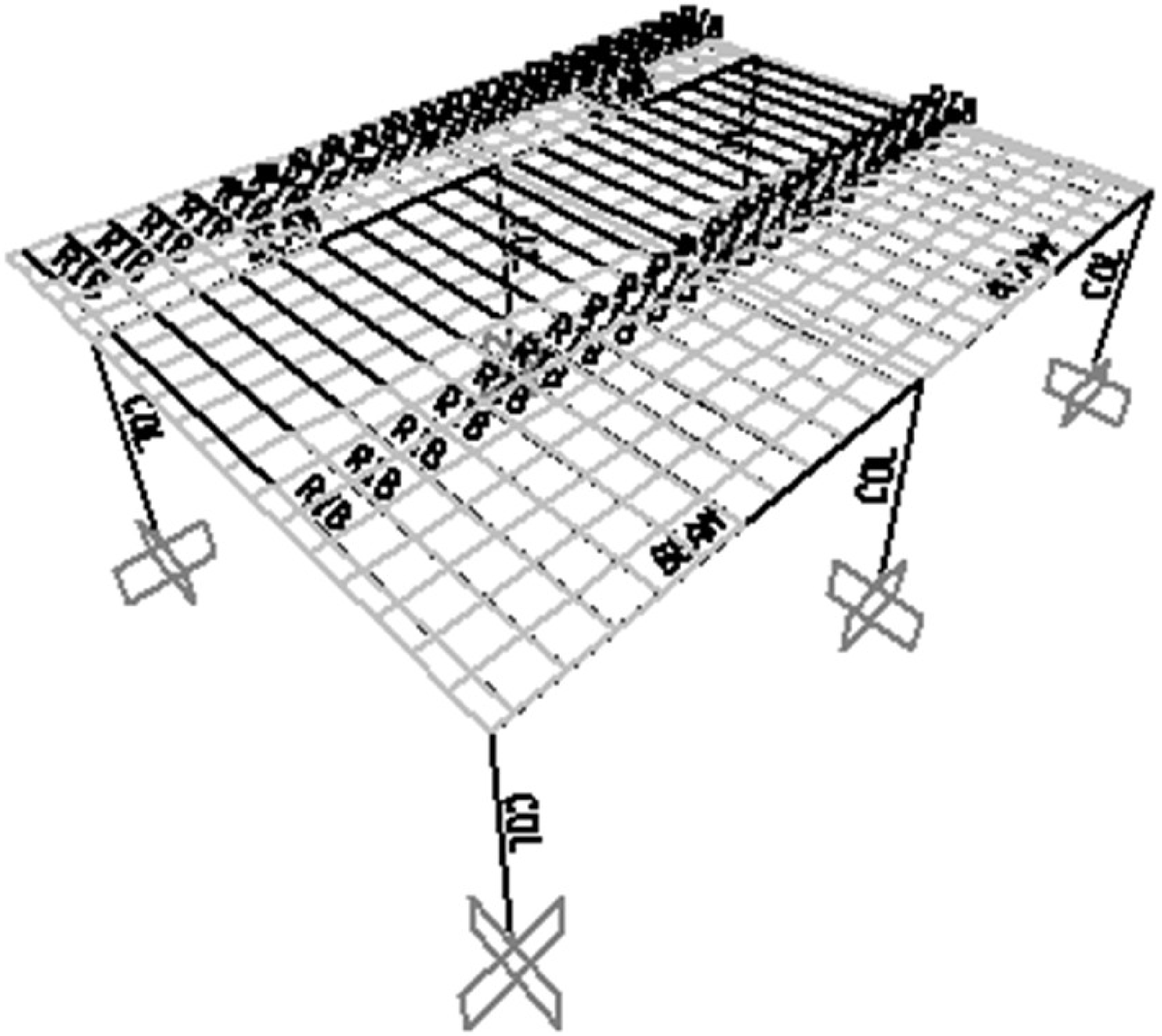


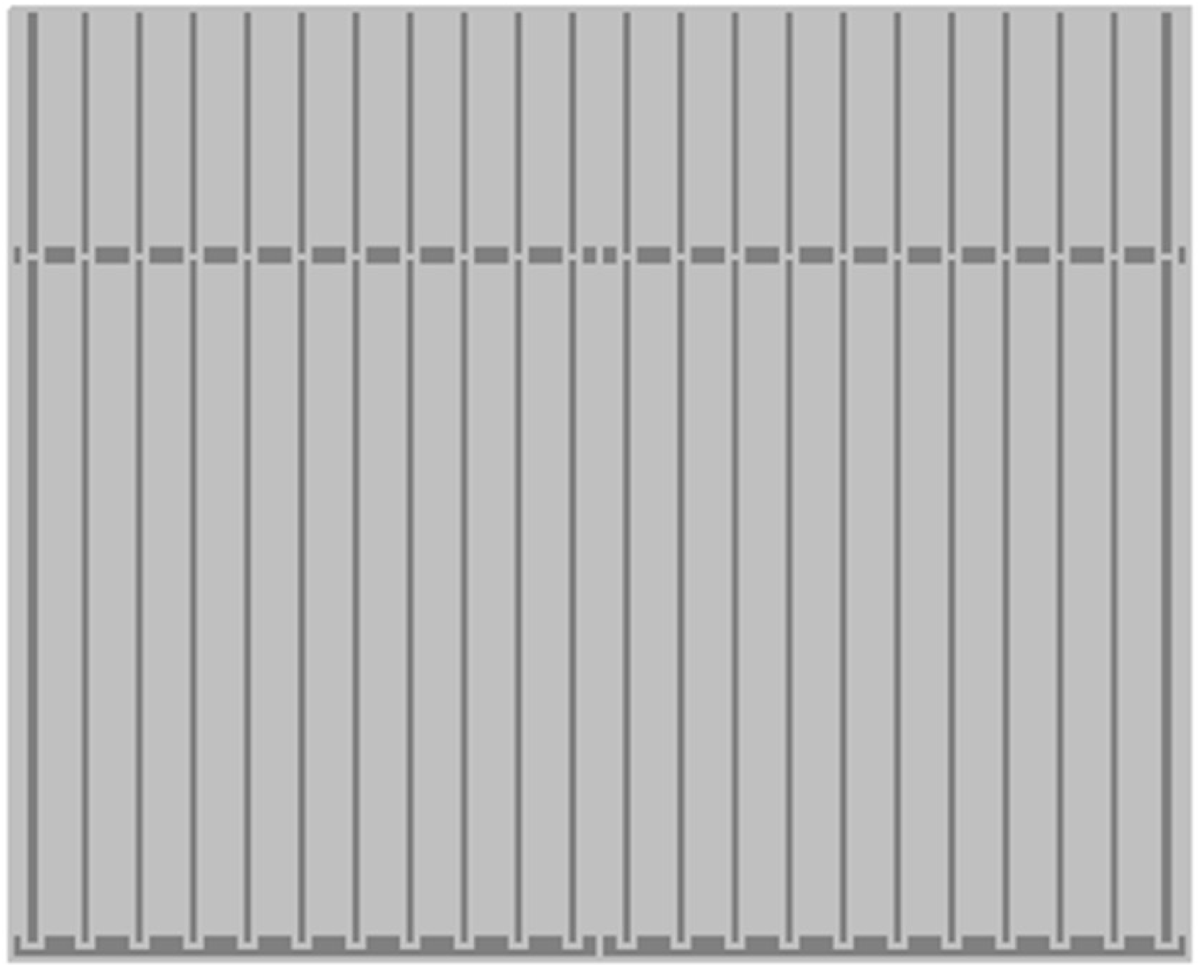
Joint Reactions

Beam analysis and design

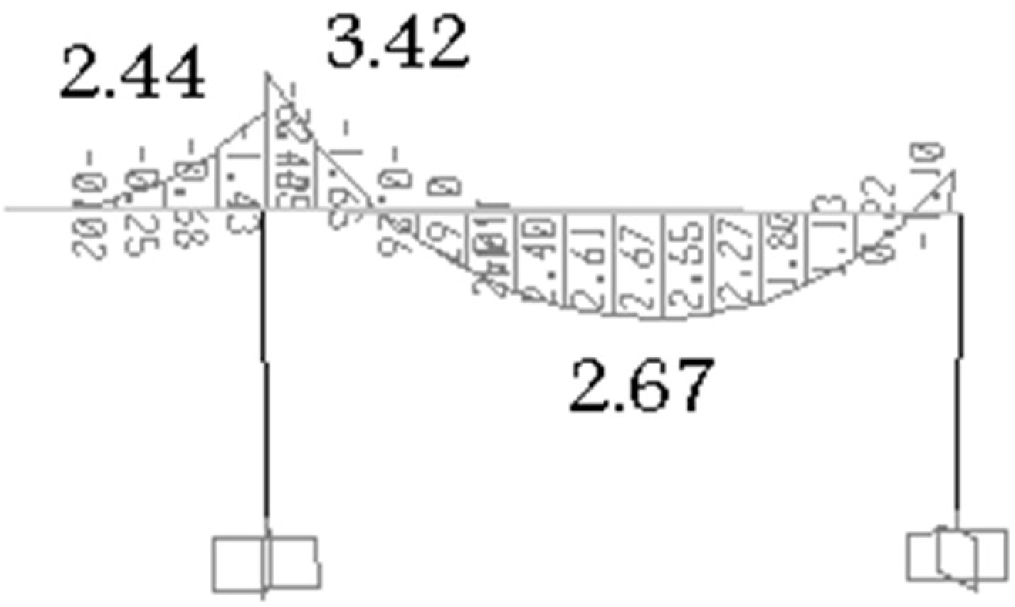
- Beam B1 (interior frame)
  - w_u =(3.93/0.55)+0.25*0.5*2.5*1.2 =7.52 t/m
  - M_u^- =7.52(6)^2 /8=33.8t.m., As=33.8X30/45=22.6cm^2
  - M_u^+ =7.52(6)^2 /14.2=19.1t.m., As=19.1X30/45=12.7cm^2
- Beam B2: (exterior frame)
  - w_u =(1.86/0.55)+0.25*0.5*2.5*1.2 =3.76 t/m
  - M_u^- =3.76(6)^2 /8=16.9t.m., As=16.9X30/45=11.3cm^2
  - M_u^+ =3.76(6)^2 /14.2=9.53t.m., As=9.53X30/45=6.4cm^2

3D Model

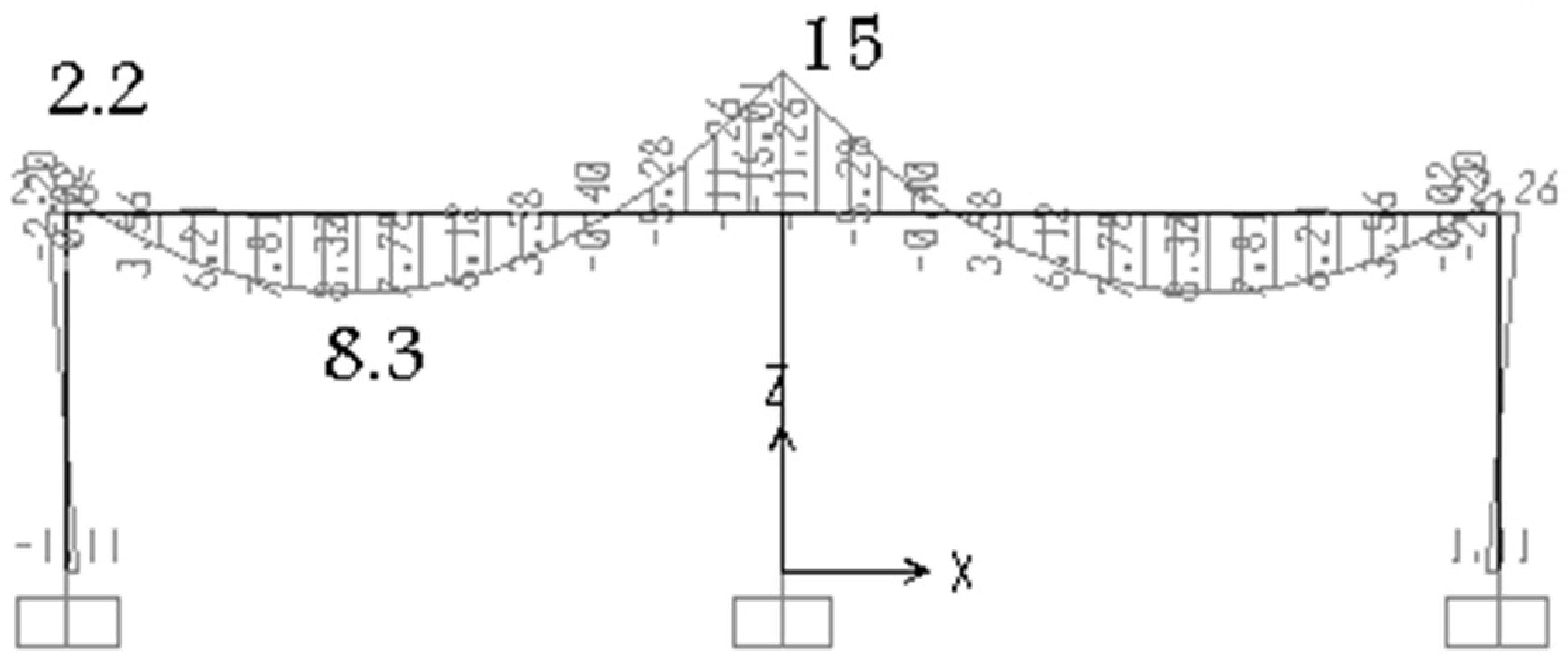




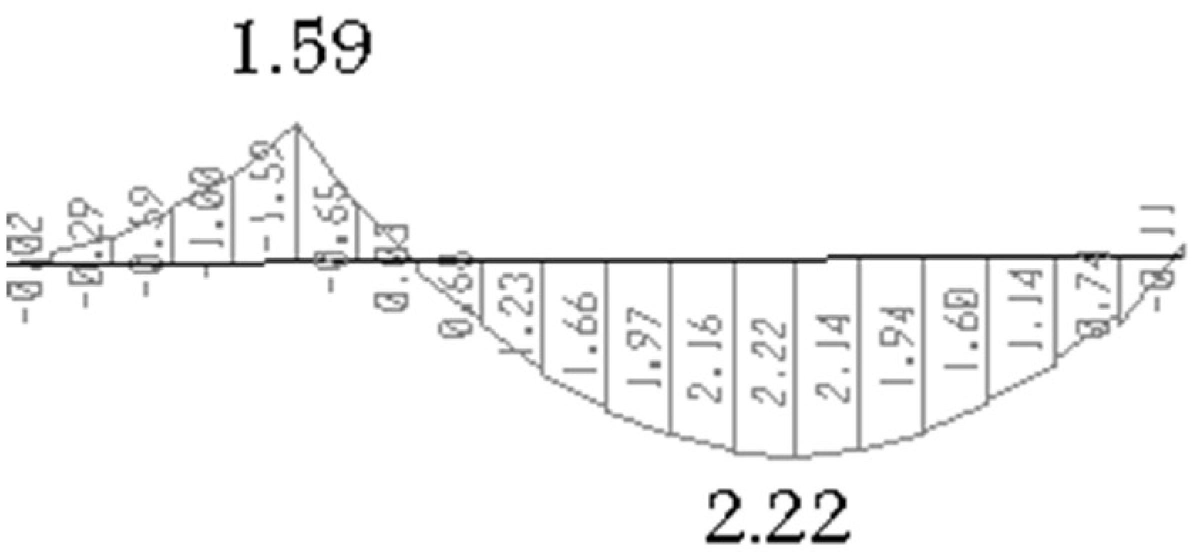
3D



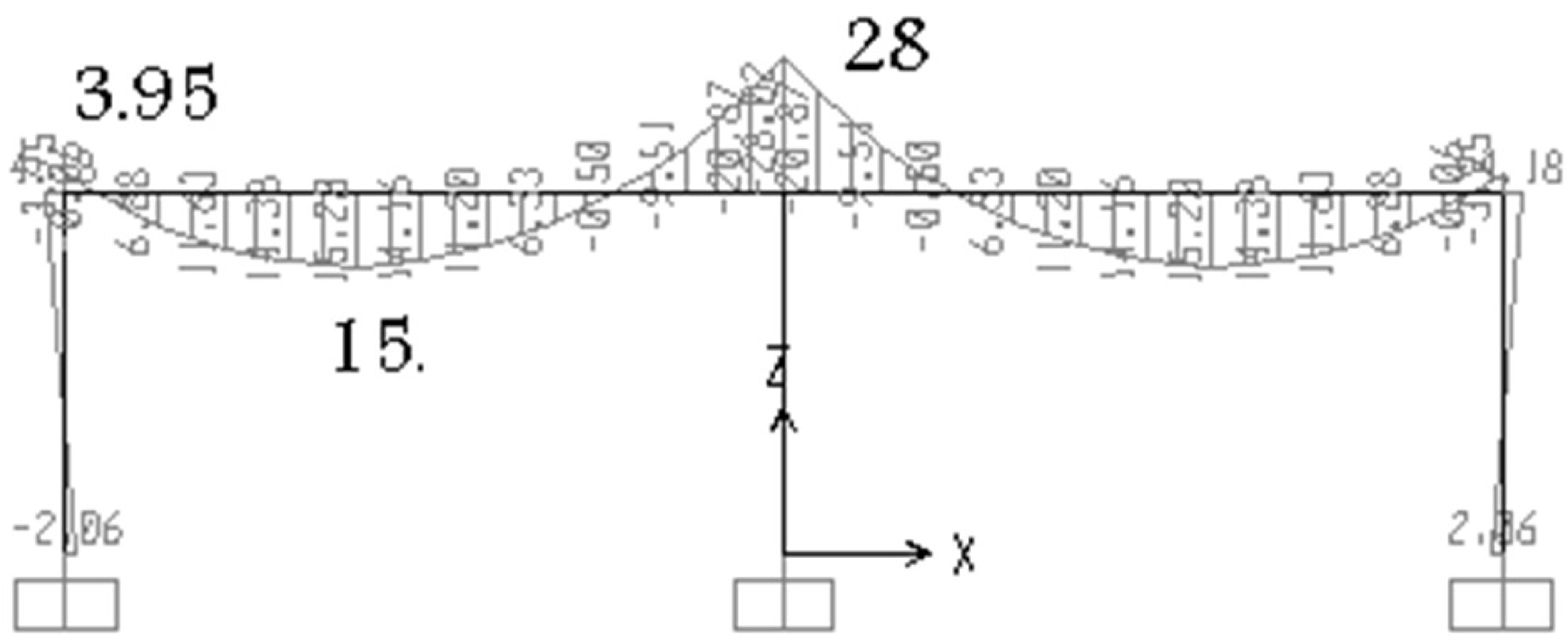
interior rib/ col



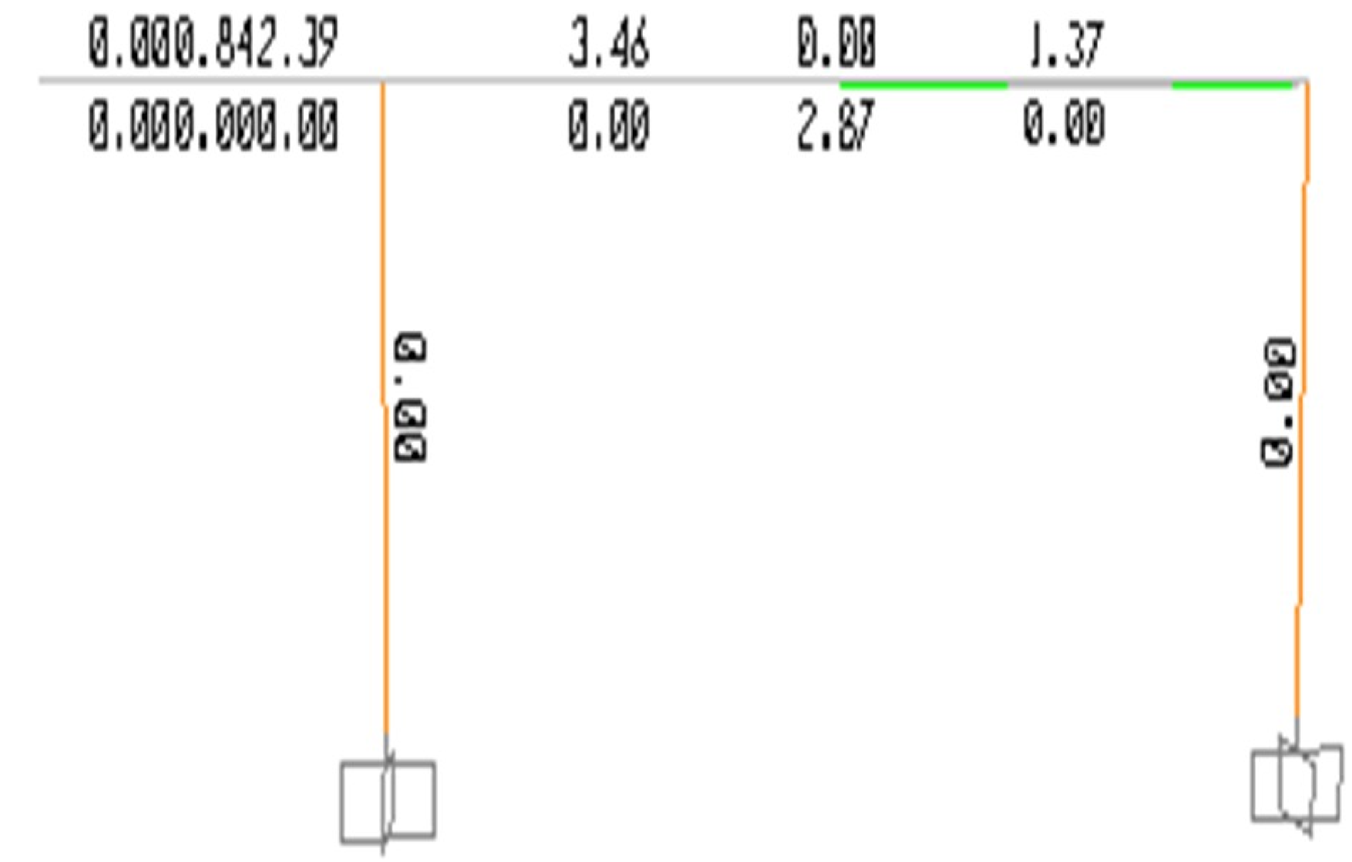
exterior frame

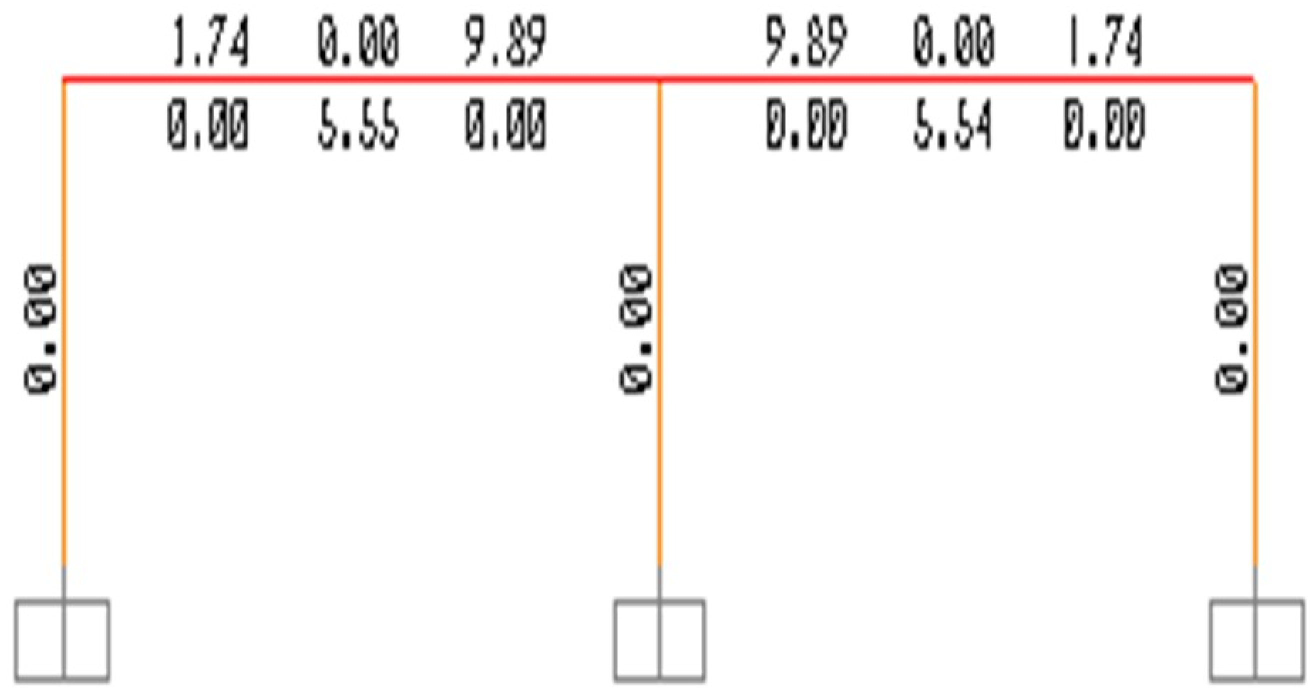


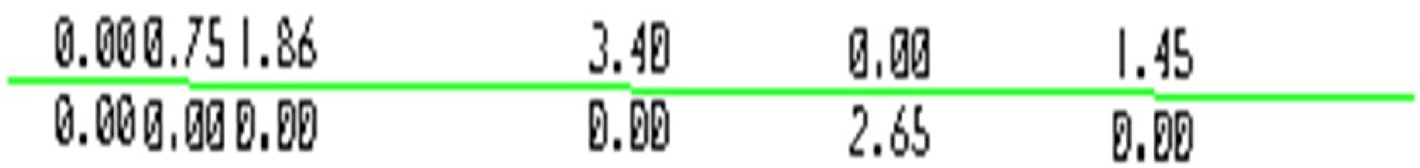
interior rib/midspan

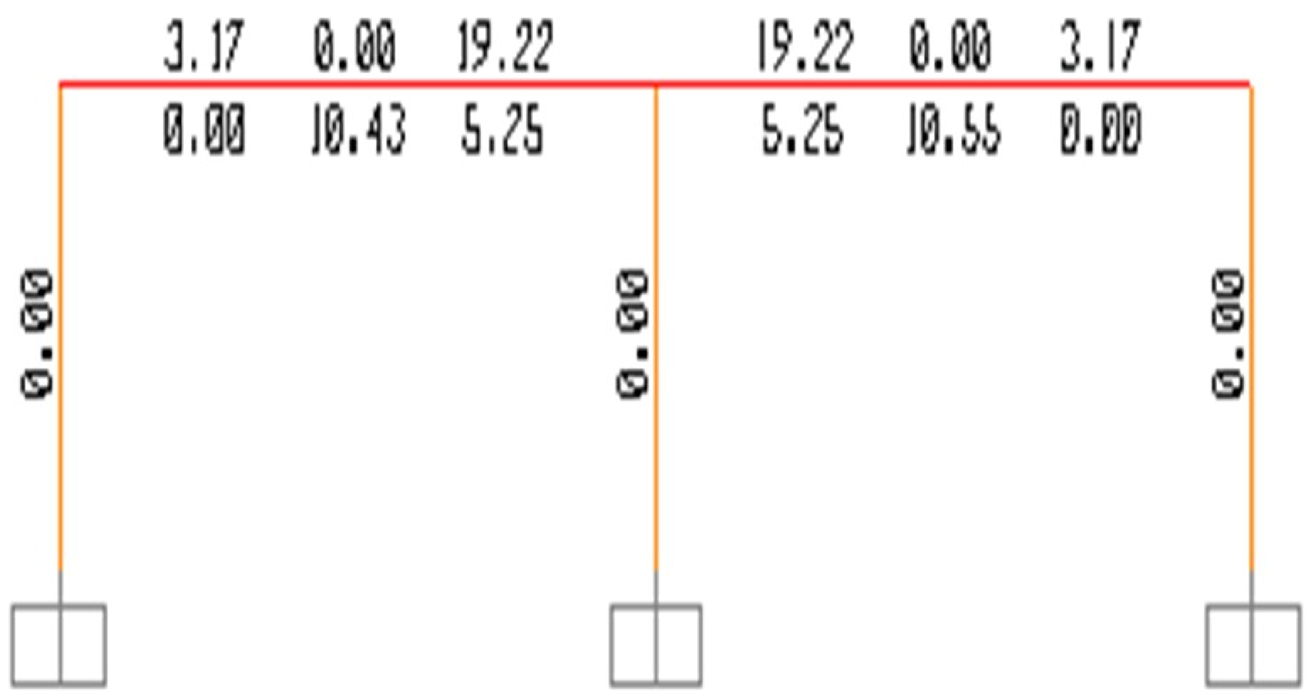


interior frame


0.000.842.39
3.46
0.00
1.37
0.000.000.00
0.00
2.87
0.00
0.00
0.00


1.74
0.00
9.89
9.89
0.00
1.74
0.00
5.55
0.00
0.00
5.54
0.00
0.00
0.00
0.00

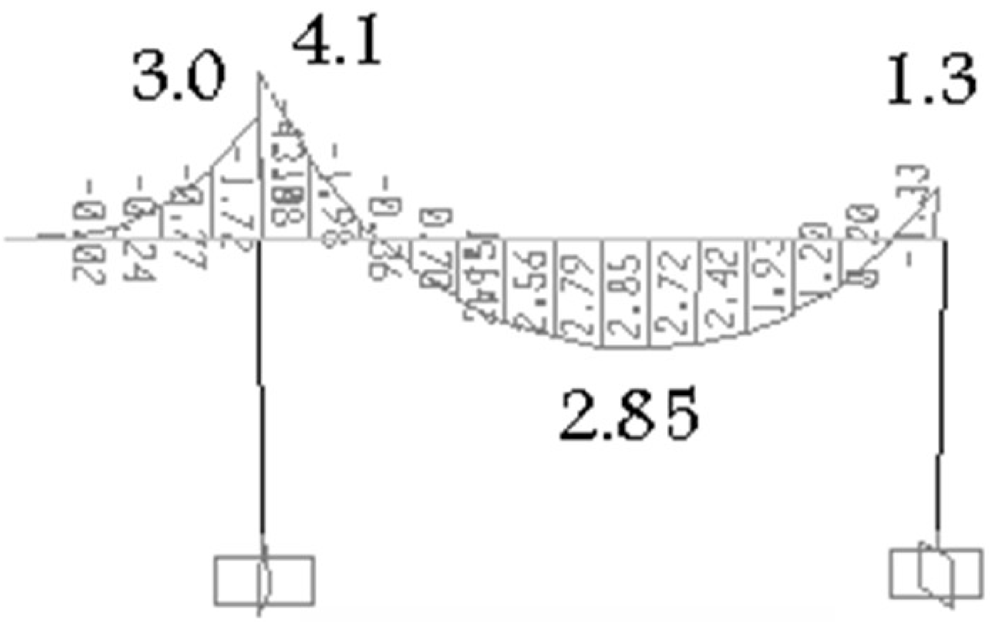

0.000.75 1.86
3.40
0.00
1.45
0.000.00 0.00
0.00
2.65
0.00


3.17
0.00
19.22
19.22
0.00
3.17
0.00
10.43
5.25
5.25
10.55
0.00
0.00
0.00
0.00

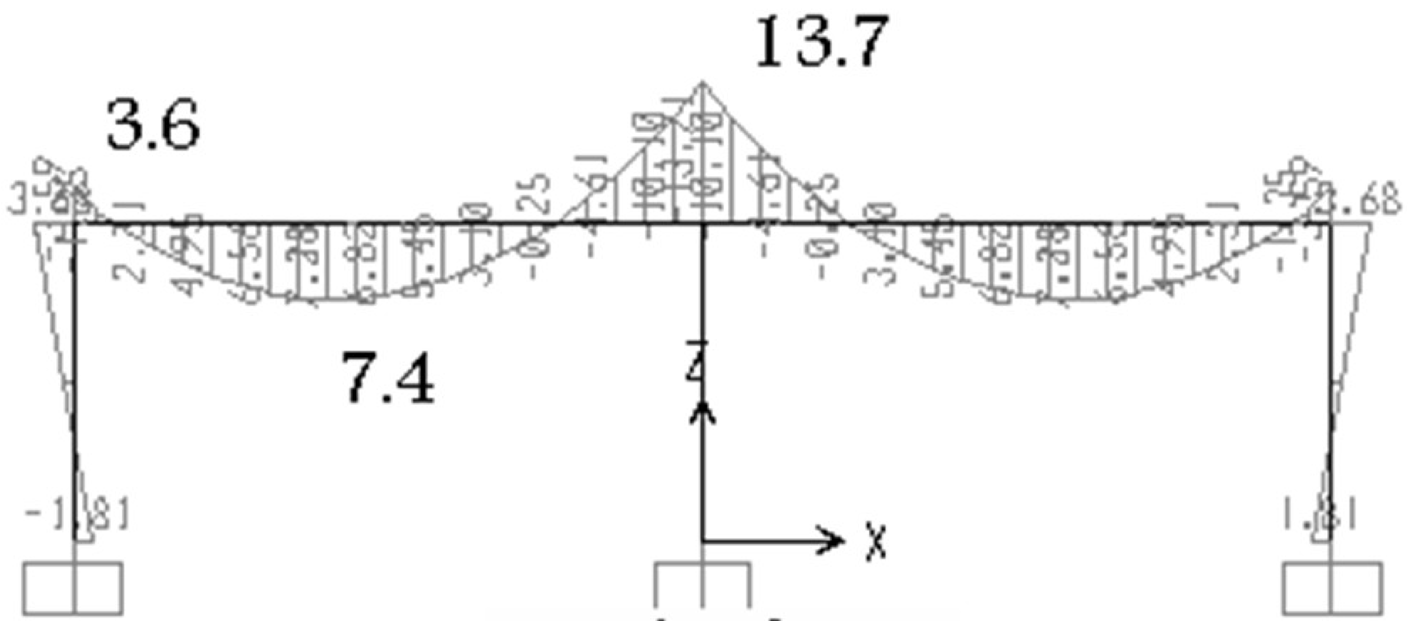
Problem set #7

- Repeat previous example but if the beams are 34cm depth by 37cm width .(to preserve beam weight)
- Draw conclusions

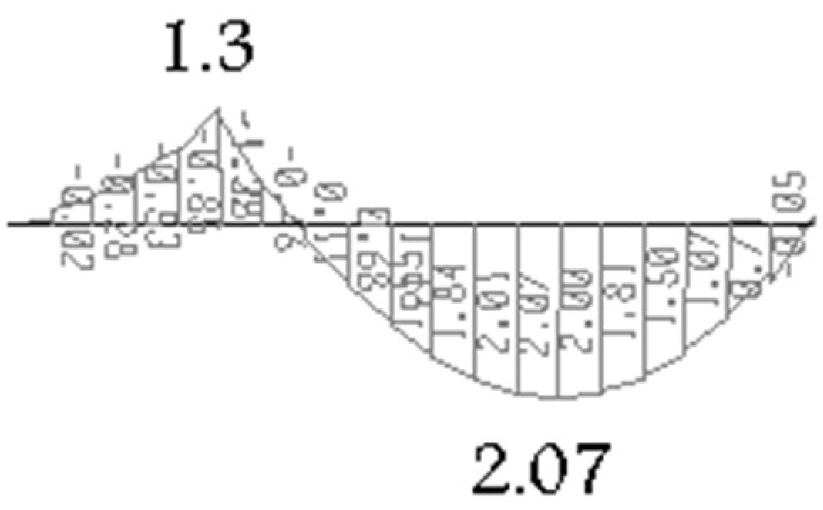
Problem set #7 (solution)



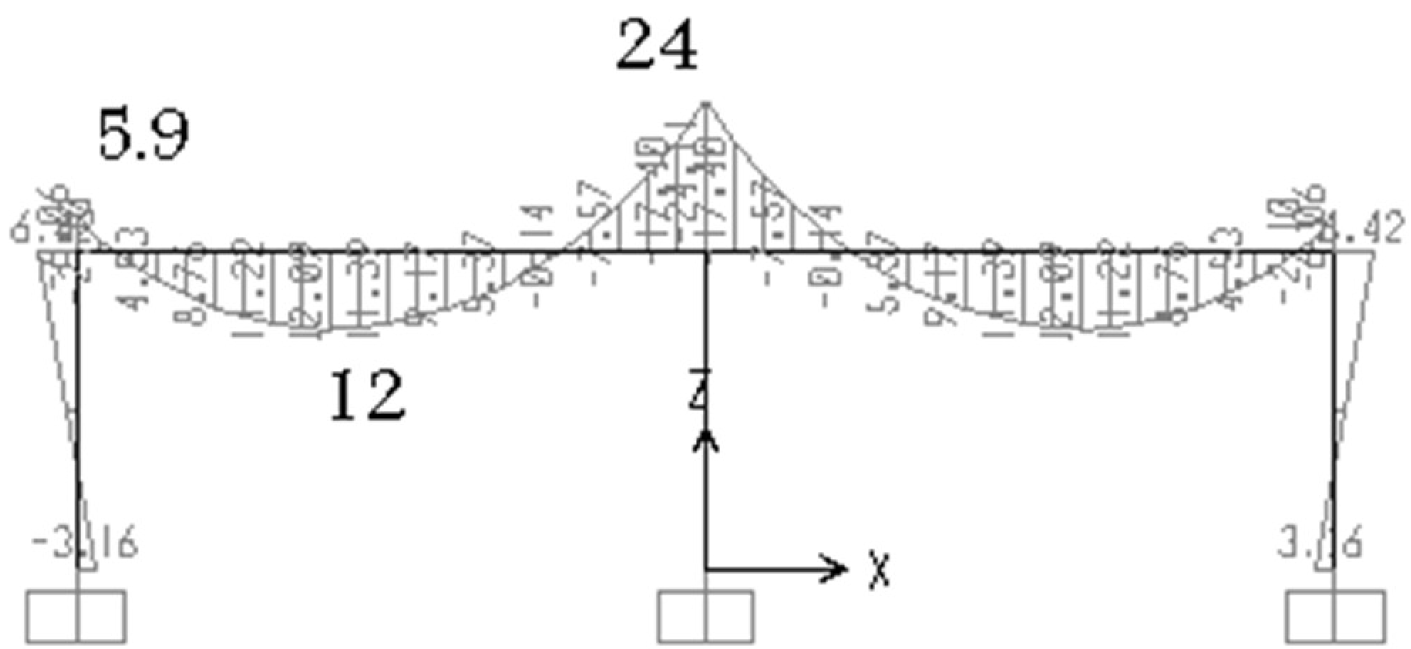
interior rib/ col



exterior frame



interior rib/midspan



interior frame

Problem set #7 (solution)

Conclusions: Ribs

Moments increased on interior column strip and reduced on interior middle strip, which increases the difference existed previously. Why?

Do you expect problems in local practice, why? Yes, at cantilevers due to large increase

Problem set #7 (solution)

Conclusions: beams

All moments are reduced (except at exterior, almost the same), why? Smaller load is transferred to column directly

Exterior moment increases for hidden, why? Exterior end is more restrained by column for hidden, thus more fixity and more moment.

Do you expect problems in local practice? No, usually steel is provided at –ve moment in detailing practice at the support + beams are most of the time placed over masonry walls, so no stresses exist in them.

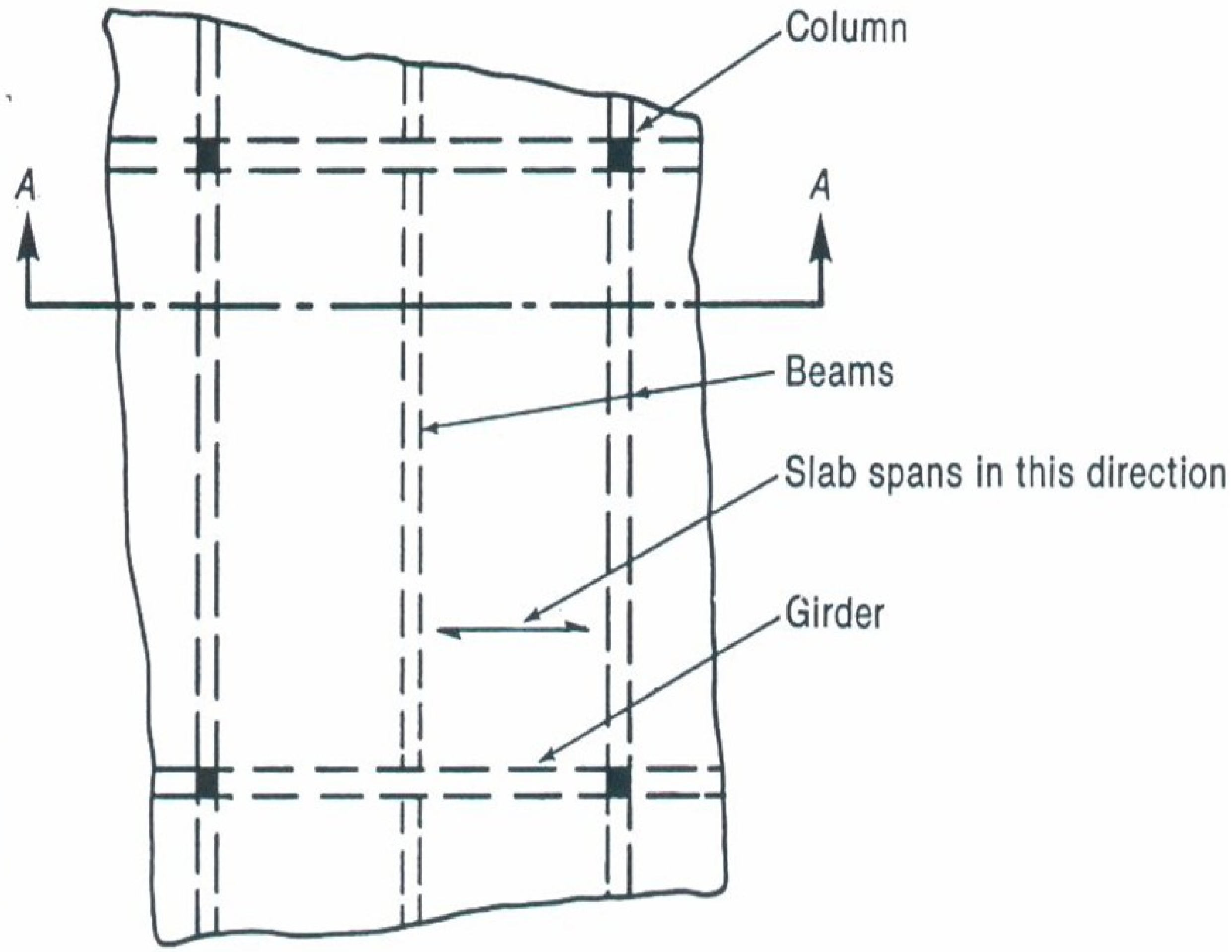
Is it now necessary to change local practice? Yes, steel savings

End of section 5.2

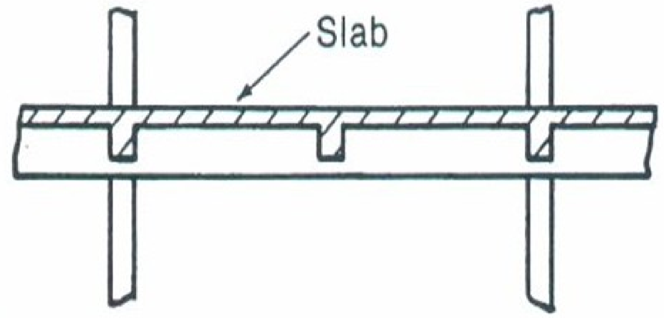
Let Learning Continue

5.3 Two way slab systems review

- One-way Slab on beams suitable span 3 to 6m with LL= 3-5kN/m^2.
  - Can be used for larger spans with relatively higher cost and higher deflections
  - One-way joist system suitable span 6 to 9m with LL= 4-6kN/m^2.
  - Deep ribs, the concrete and steel quantities are relatively low Expensive formwork expected.



(a) Plan-beams at middle of panel.



(b) Section A-A.

Flat Plate

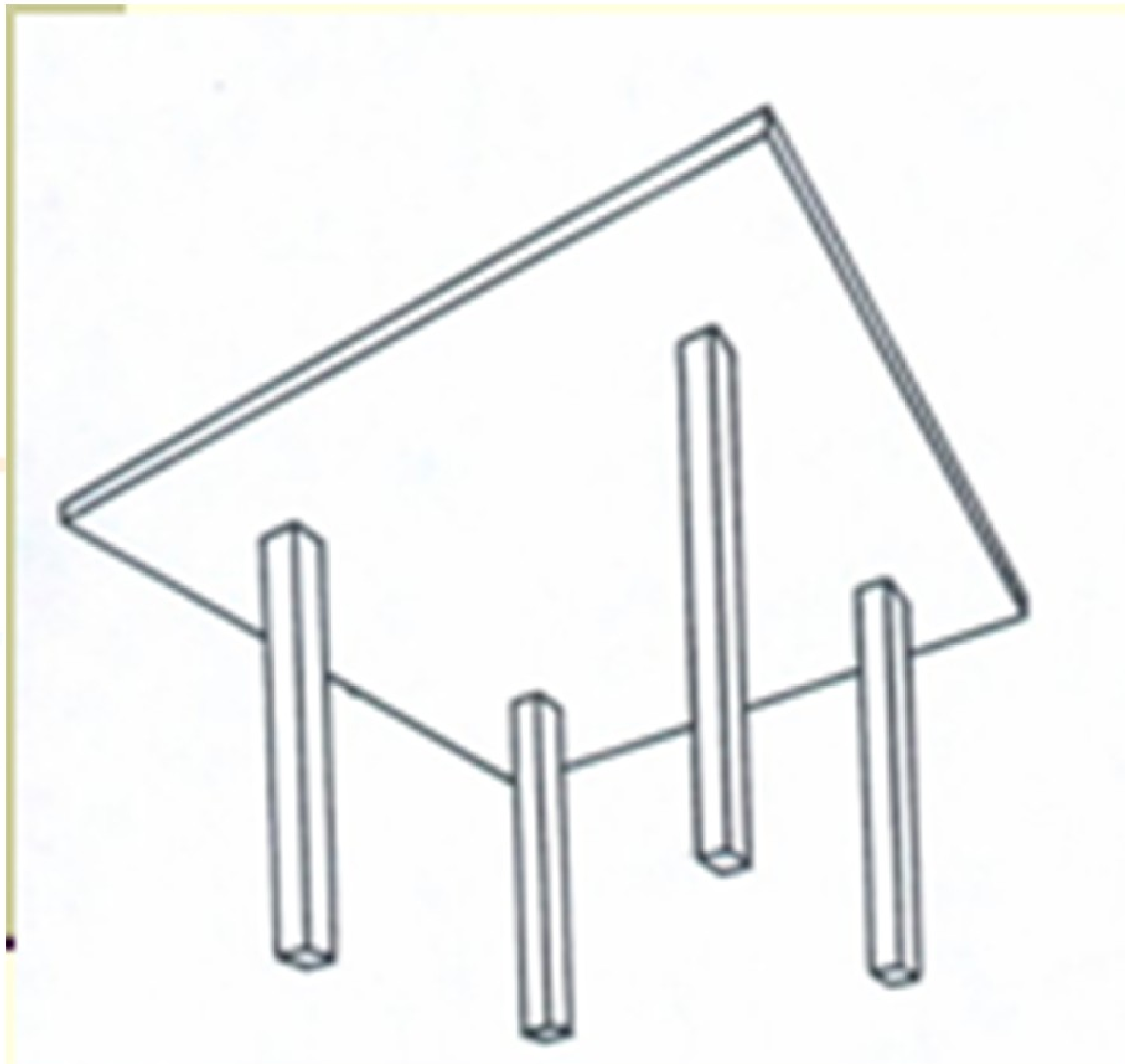
Flat Plate suitable span 6 to 7.5m with LL= 3-5kN/m^2.

Advantages

- Low cost formwork
- Exposed flat ceilings
- Fast

Disadvantages

- Low shear capacity
- Low Stiffness (notable deflection)



Flat Plate

5.5. Review: Two way slab systems
Flat slab

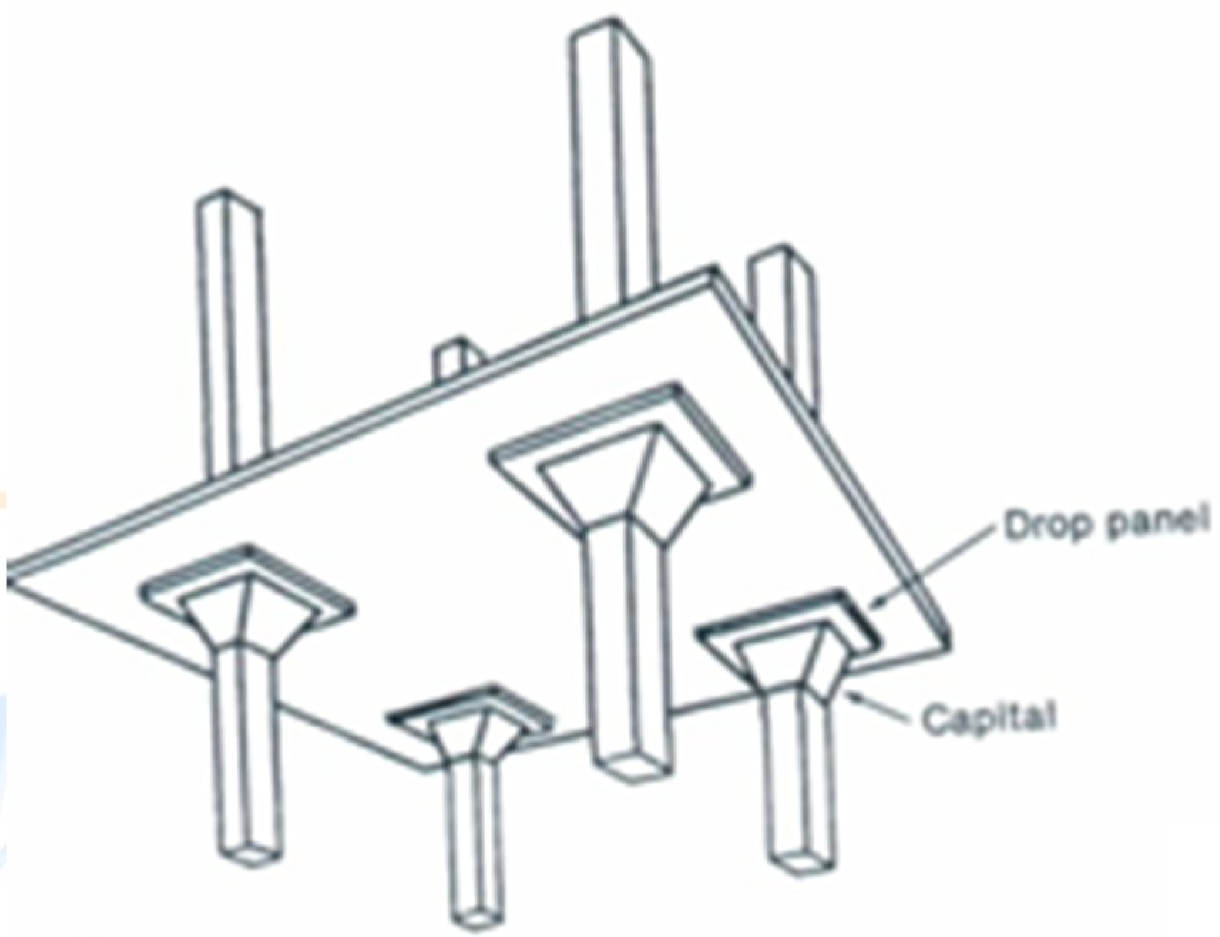
Flat Slab suitable span 6 to 9m with LL= 4-7.5kN/m^2.

Advantages

- Low cost formwork
- Exposed flat ceilings
- Fast

Disadvantages

- Need more formwork for capital and panels



Flat slab

Waffle Slab

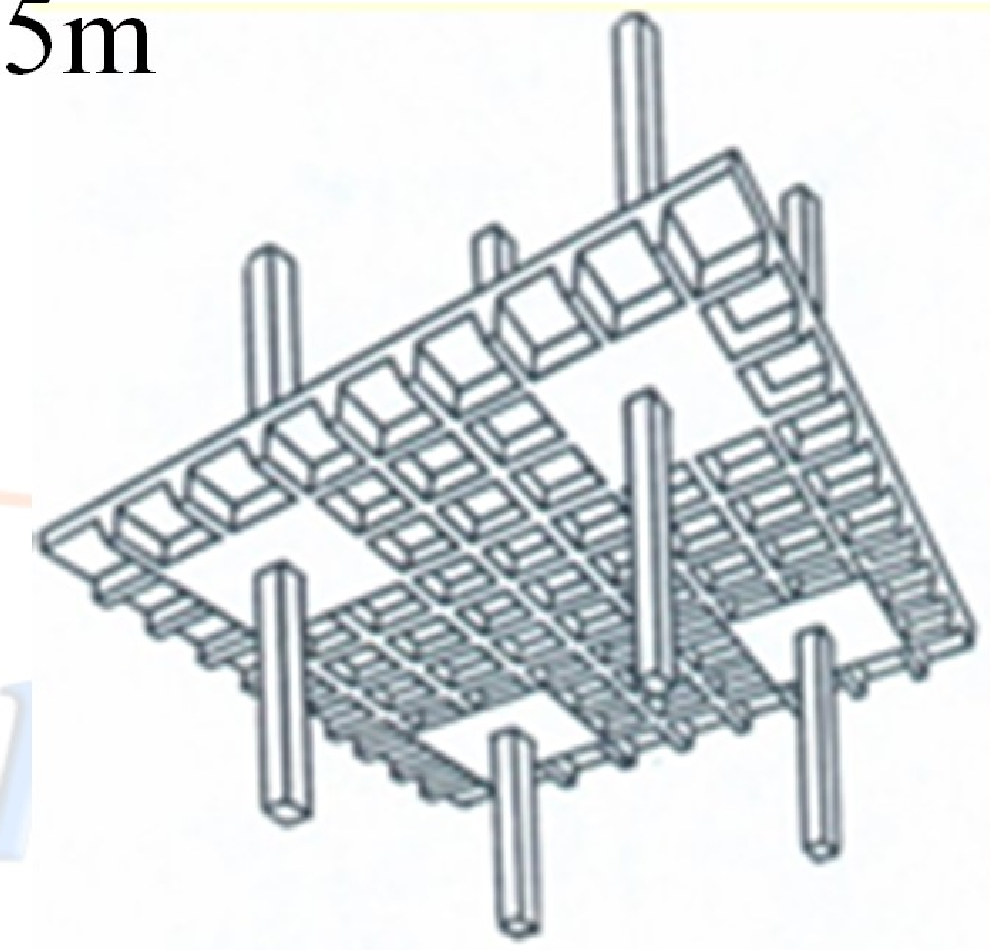
- Waffle Slab suitable span 9 to 14.5m with LL= 4-7.5kN/m^2.

Advantages

– Carries heavy loads
– Attractive exposed ceilings
– Fast

Disadvantages

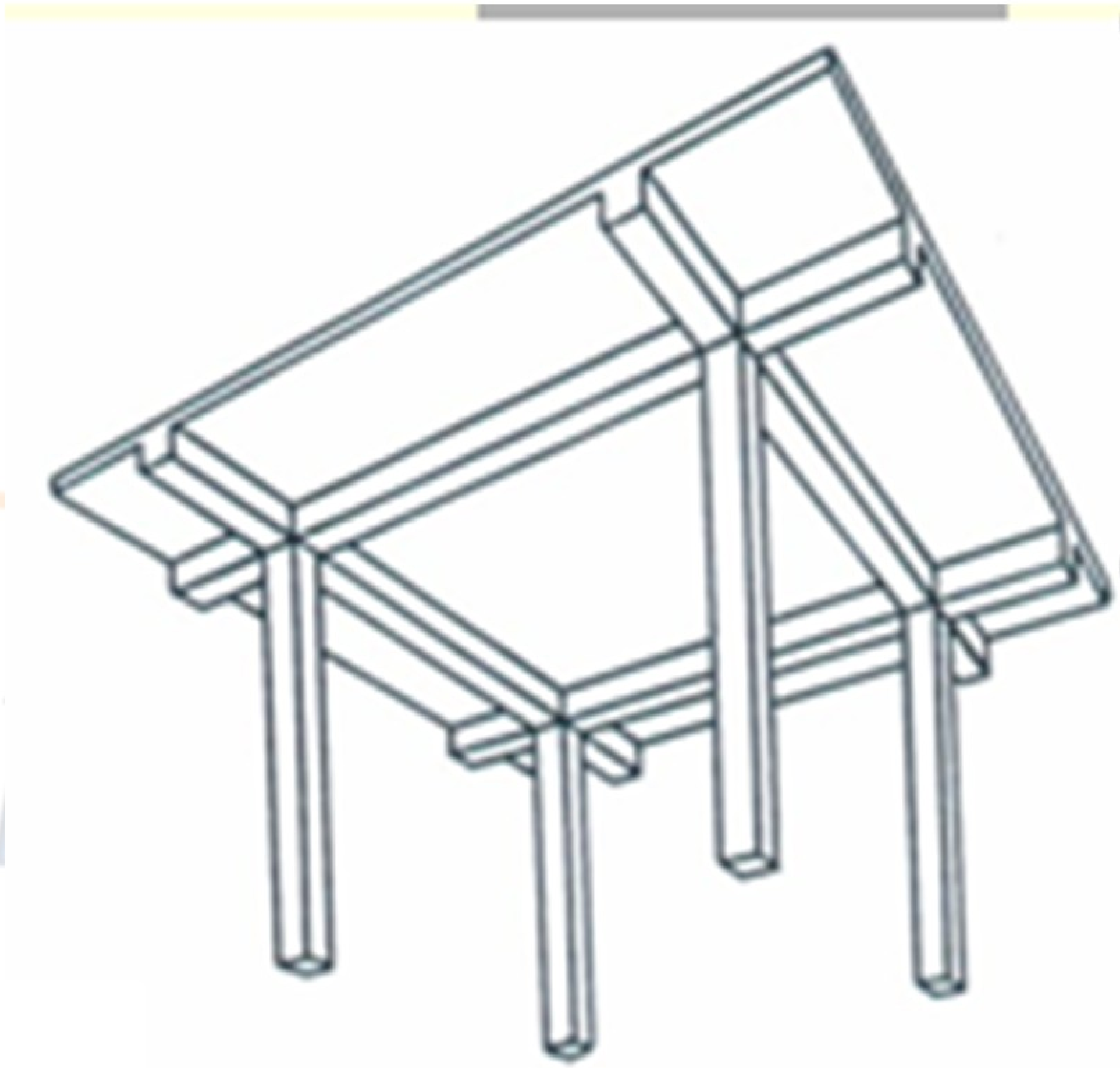
– Formwork with panels is expensive



Waffle slab

The two-way ribbed slab and waffled slab system: General thickness of the slab is 5 to 10cm.

Two-way slab with beams



Two-way slab with beams

Two-way slab behavior

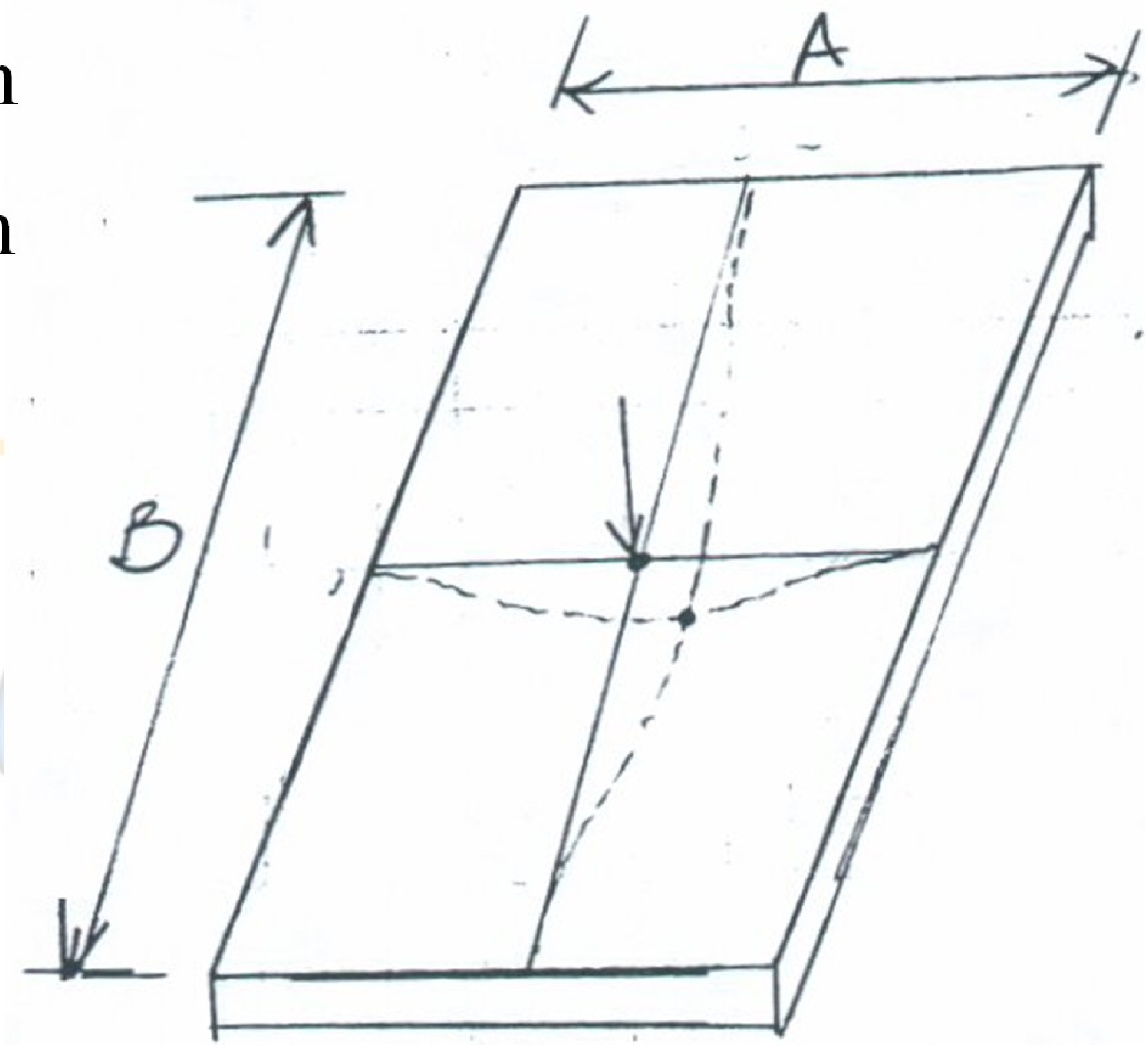
w_s =load taken by short direction

w_l = load taken by long direction

$$\delta_A = \delta_B$$

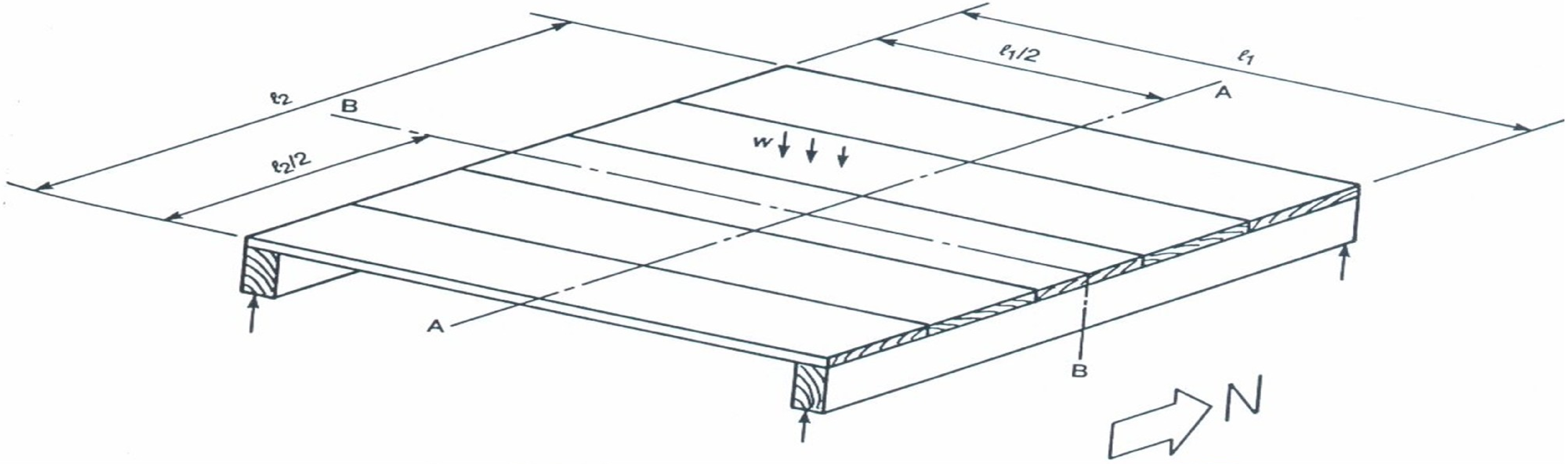
$$\frac{5w_s A^4}{384EI} = \frac{5w_l B^4}{384EI}$$

$$\frac{w_s}{w_l} = \frac{B^4}{A^4} \quad \text{For } B = 2A \Rightarrow w_s = 16w_l$$



Rule of Thumb: For B/A > 2, design as one-way slab

Analogy of 2-way slab to plank- beam floor

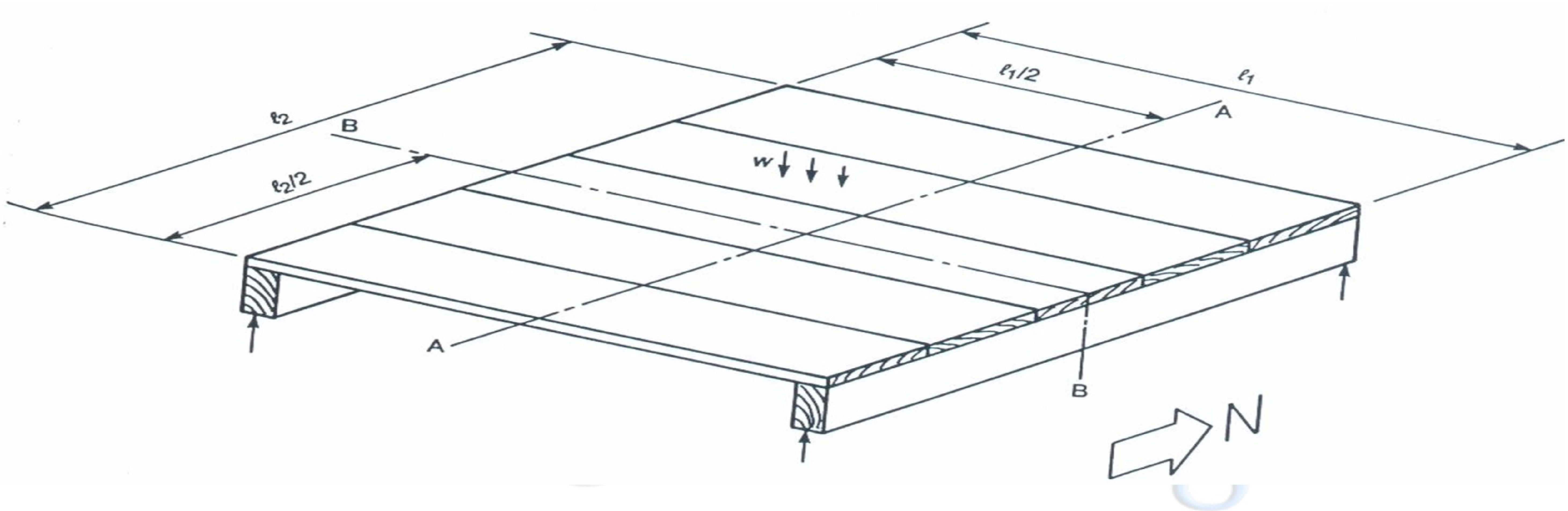


Section A-A: $\Rightarrow M = \frac{wl_1^2}{8}$ KN-m/m

Moment per m width in planks

Total Moment $\Rightarrow M_f = (wl_2)\frac{l_1^2}{8}$ KN-m

Analogy of 2-way slab to plank- beam floor

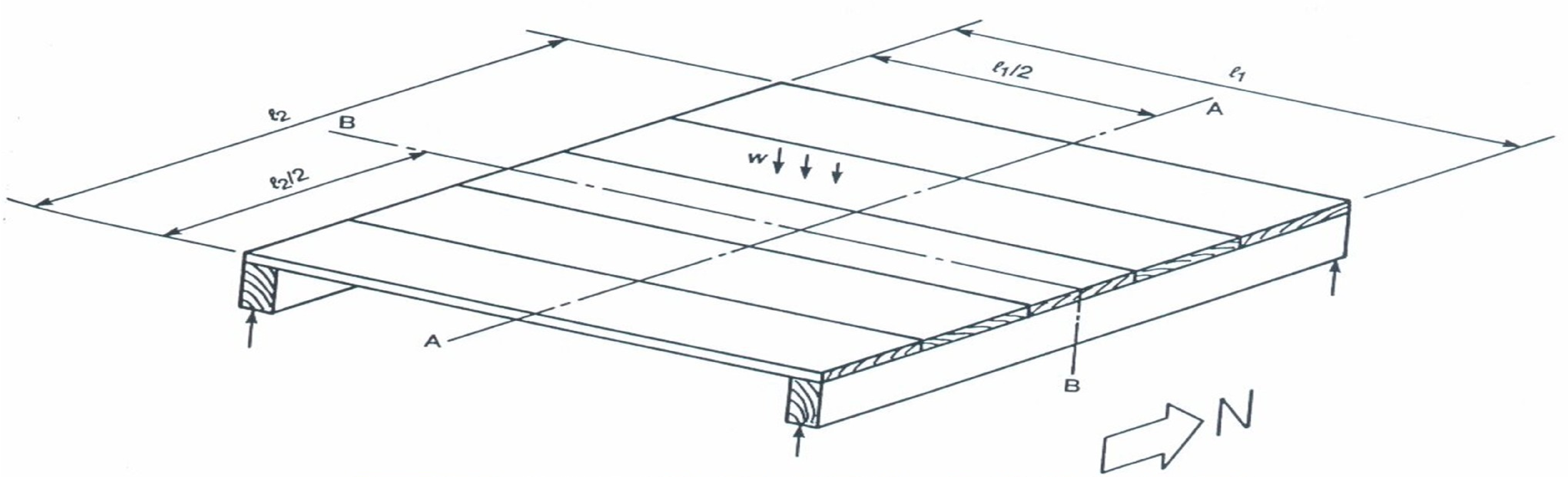


Uniform load on each beam $\Rightarrow \dfrac{wl_1}{2}$ KN/m

Moment in one beam (Sec: B-B)

$$\Rightarrow M_{lb} = \left(\frac{wl_1}{2}\right)\frac{l_2^2}{8} \text{ KN.m}$$

Two-Way Slab Design

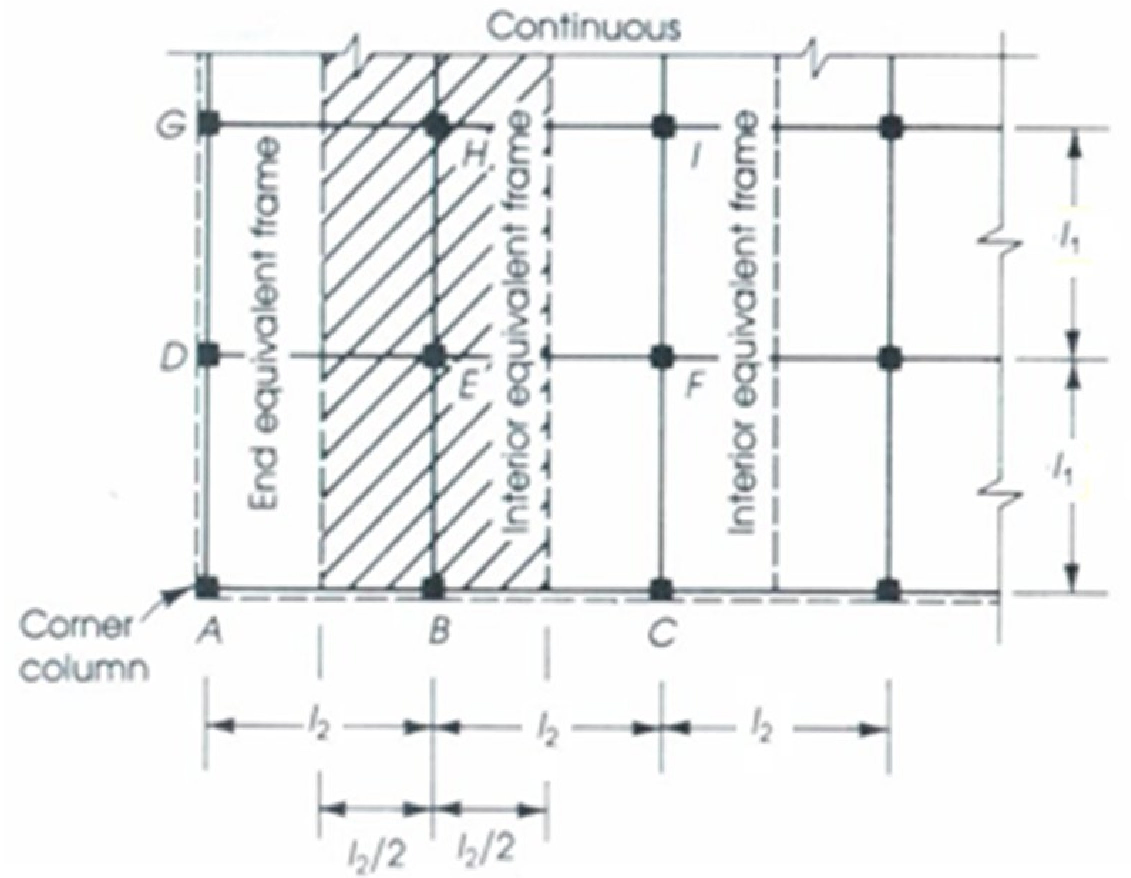


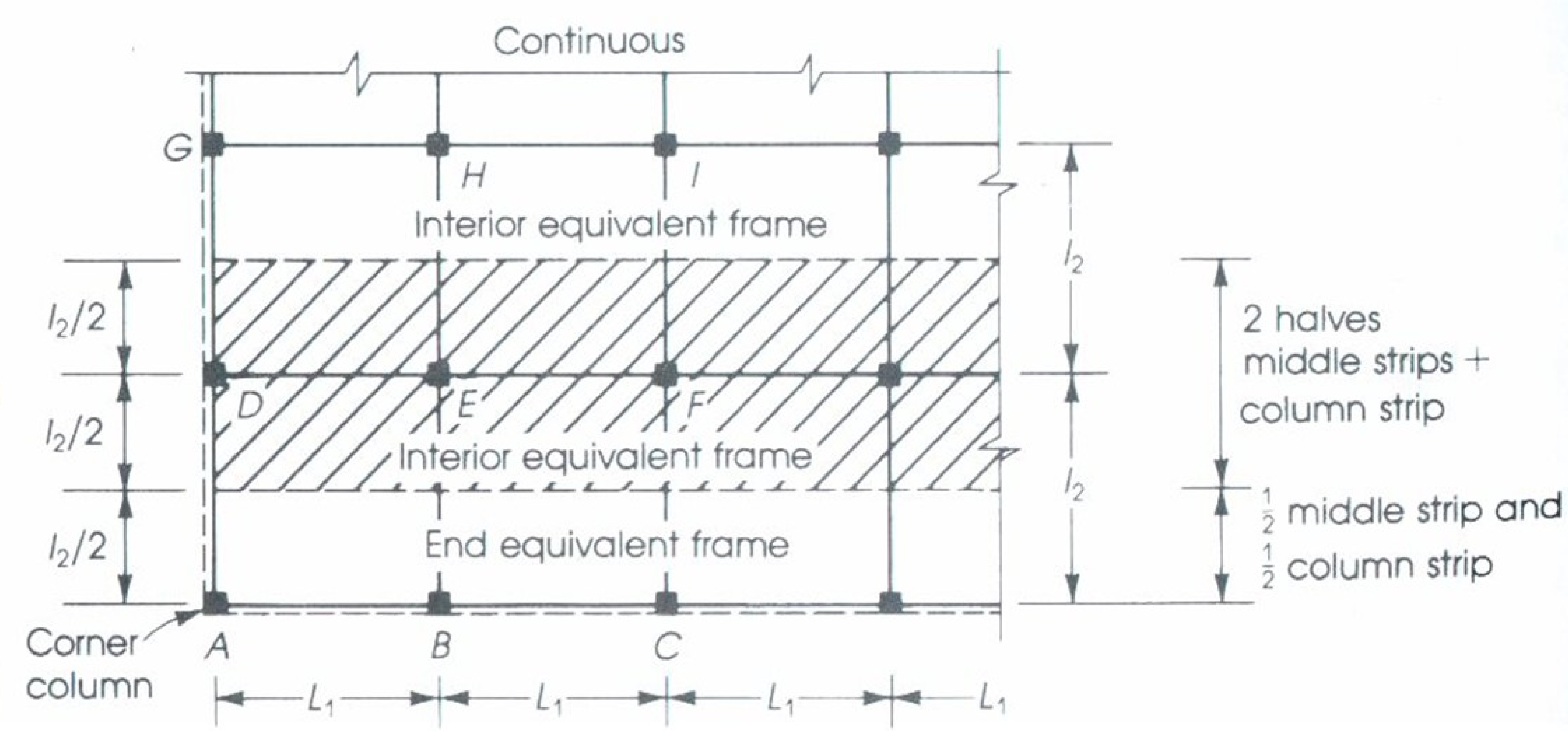
Total Moment in both beams $\Rightarrow M = (wl_1)\dfrac{l_2^2}{8}$ KN.m

Full load was transferred east-west by the planks and then was transferred north-south by the beams;

The same is true for a two-way slab or any other floor system.

Equivalent Frames





Longitudinal equivalent frame

Transverse equivalent frame

General Design Concepts

(1) Direct Design Method (DDM)

Limited to slab systems to uniformly distributed loads and supported on equally spaced columns. Method uses a set of coefficients to determine the design moment at critical sections as long as two-way slab system meet the limitations of the ACI Code 13.6.1.

Minimum Slab Thickness for Two-way Construction

ACI Code 9.5.3 specifies min. thickness to control deflection. Three empirical limitations based on experimental research are necessary to be met:

(a) For $0.2 \le \alpha_{fm} \le 2$

$$h = \frac{l_n\left(0.8 + \frac{f_y}{1400}\right)}{36 + 5\beta\left(\alpha_{fm} - 0.2\right)}$$

f_y in MPa. But h not less than 12.5cm

Minimum Slab Thickness for Two-way

(b) For $2 < \alpha_{fm}$

$$h = \frac{l_n\left(0.8 + \frac{f_y}{1400}\right)}{36 + 9\beta}$$

f_y in MPa. But h not less than 9cm.

(c) For $\alpha_{fm} < 0.2$

Use table 9.5(c) in ACI code:

Minimum Slab Thickness for two-way construction

The definitions of the terms are:

h = Minimum slab thickness without interior beams

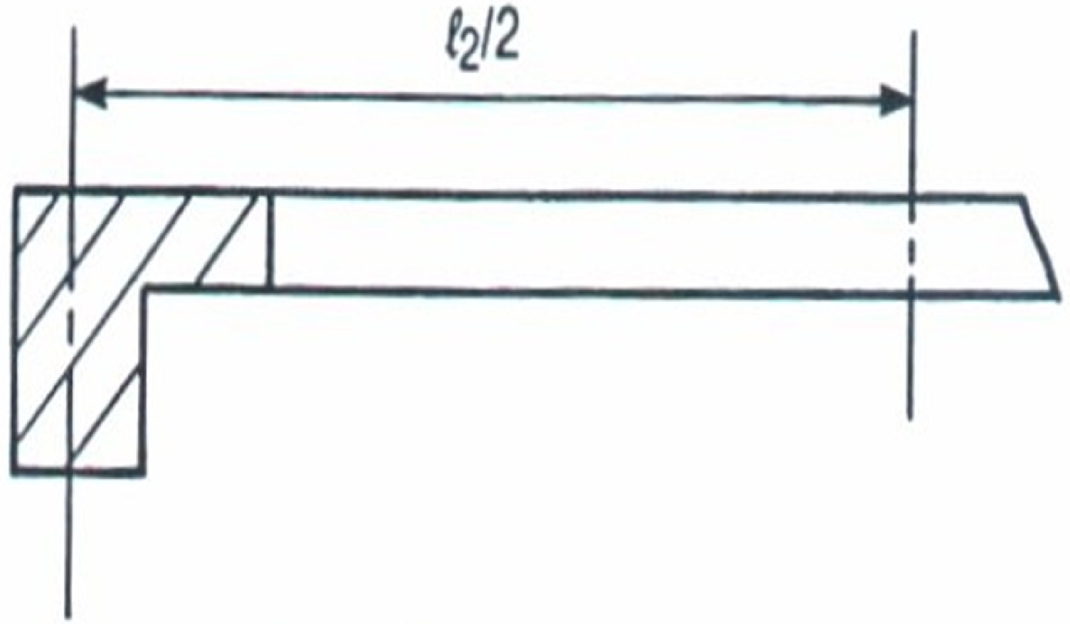
l_n = Clear span in long direction measured face to face of beam or column

β = ratio of the long to short clear span

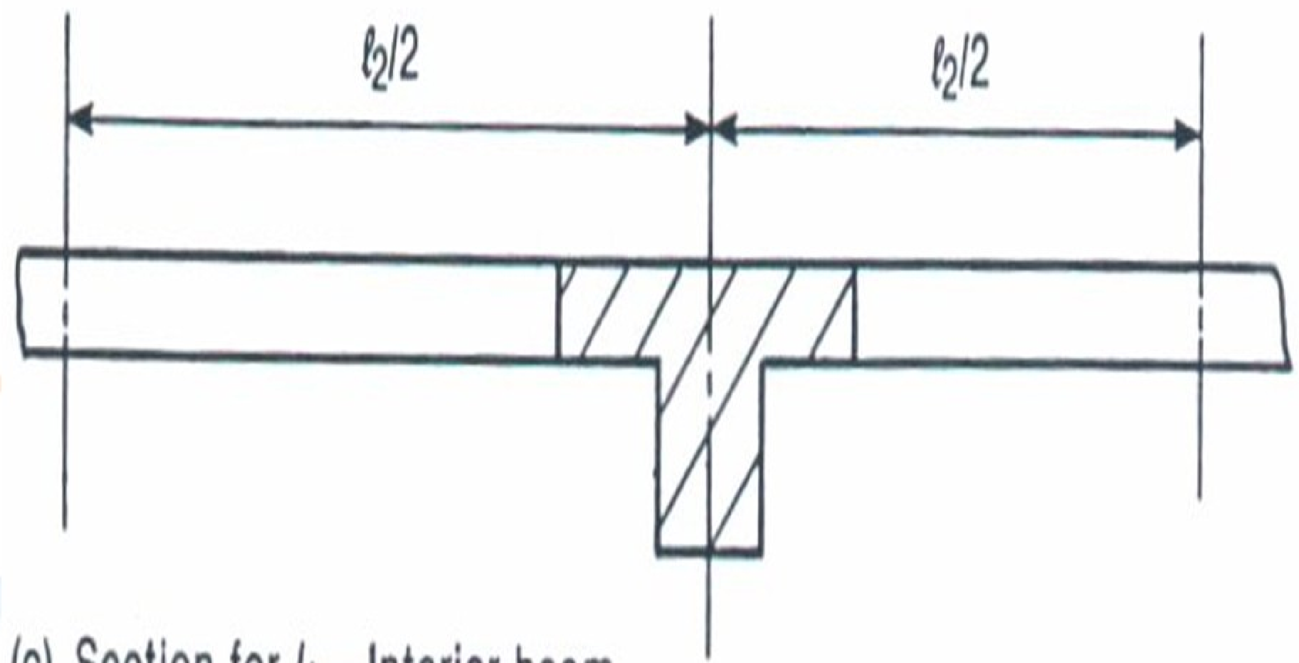
α_{fm} = average value of α_f for all beams on sides of panel.

$$\alpha_f = \frac{\text{beam flex stiffn}}{\text{slab flex stiffn}} = \frac{4E_{cb}I_b / l}{4E_{cs}I_s / l} = \frac{E_{cb}I_b}{E_{cs}I_s}$$

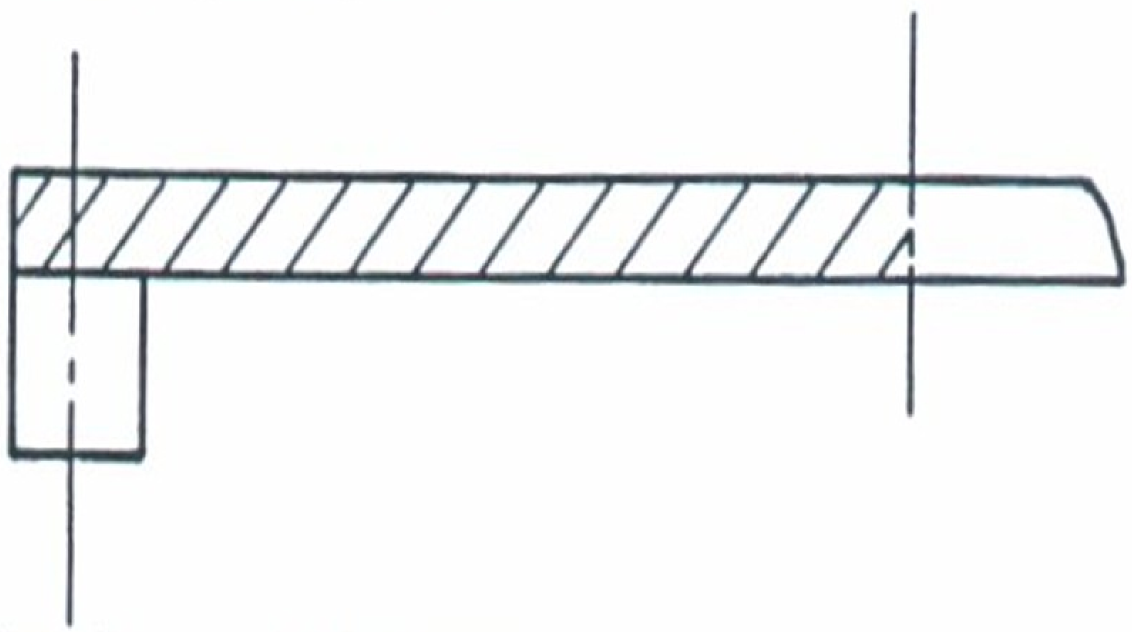
Beam and Slab Sections for calculation of α



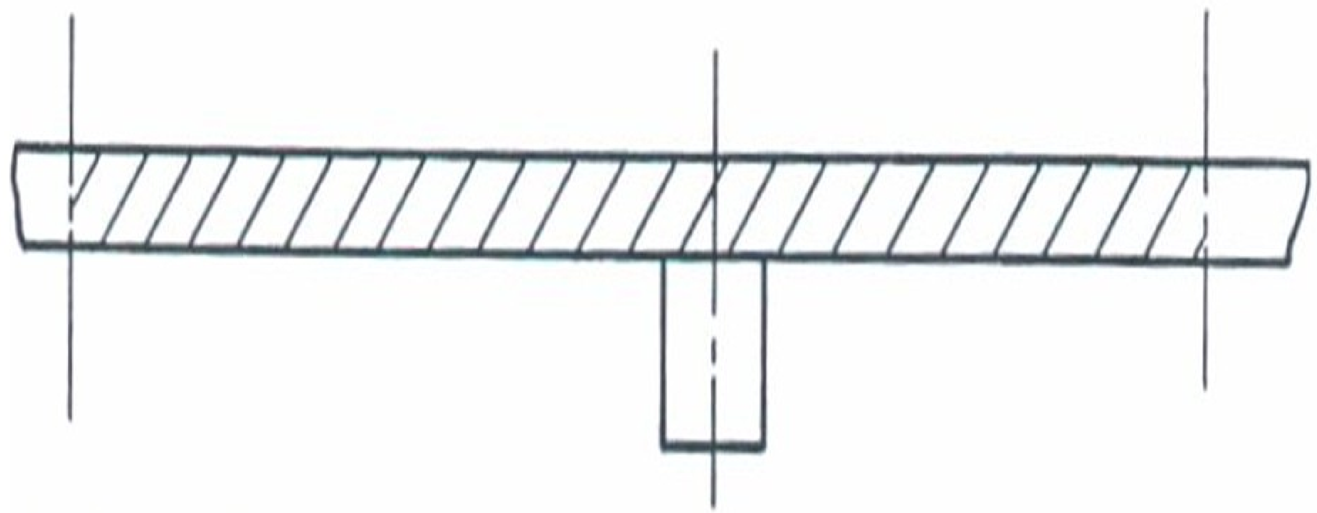
(a) Section for I_b—Edge beam.



(c) Section for I_b—Interior beam.

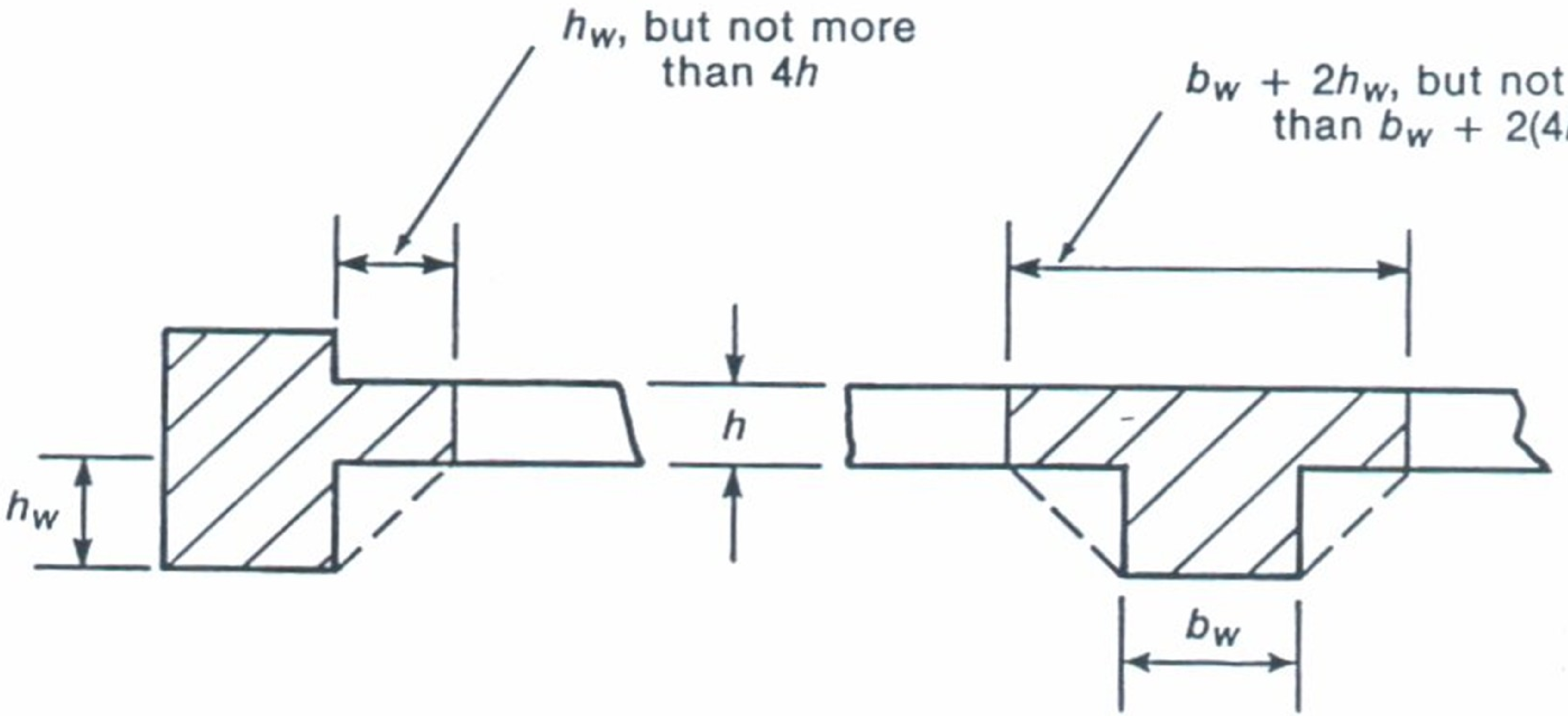


(b) Section for I_s—Edge beam.



(d) Section for I_s—Interior beam.

Beam and Slab Sections for calculation of α



Definition of beam cross-section, Charts used to calculate α

Slabs without drop panels meeting 13.3.7.1 and 13.3.7.2,

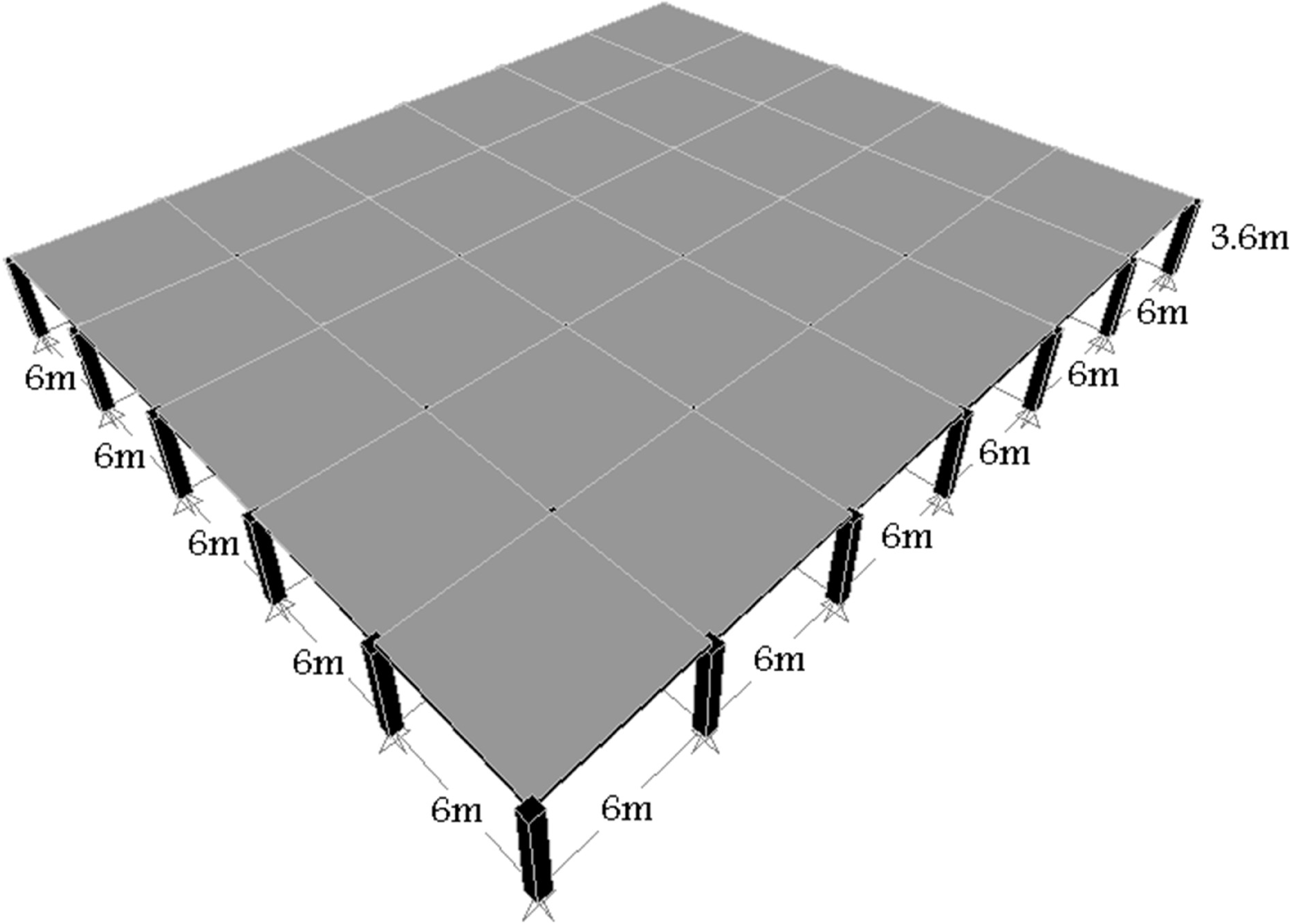
h_{min} = 12.5cm

Slabs with drop panels meeting 13.3.7.1 and 13.3.7.2,

h_{min} = 10cm

Two way slab: Example 1

- Analyze and design (as a two way slab without beams) the following one story structure (3.6m height) using 3D model (figure next page):
  - Specifications: B350, f_y=4200 kg/cm^2, superimposed= 50 kg/m^2 , live loads= 350 kg/m^2, column dimensions 50cmX50cm


3.6m
6m
6m
6m
6m
6m
6m
6m
6m
6m
6m
6m
6m

solution

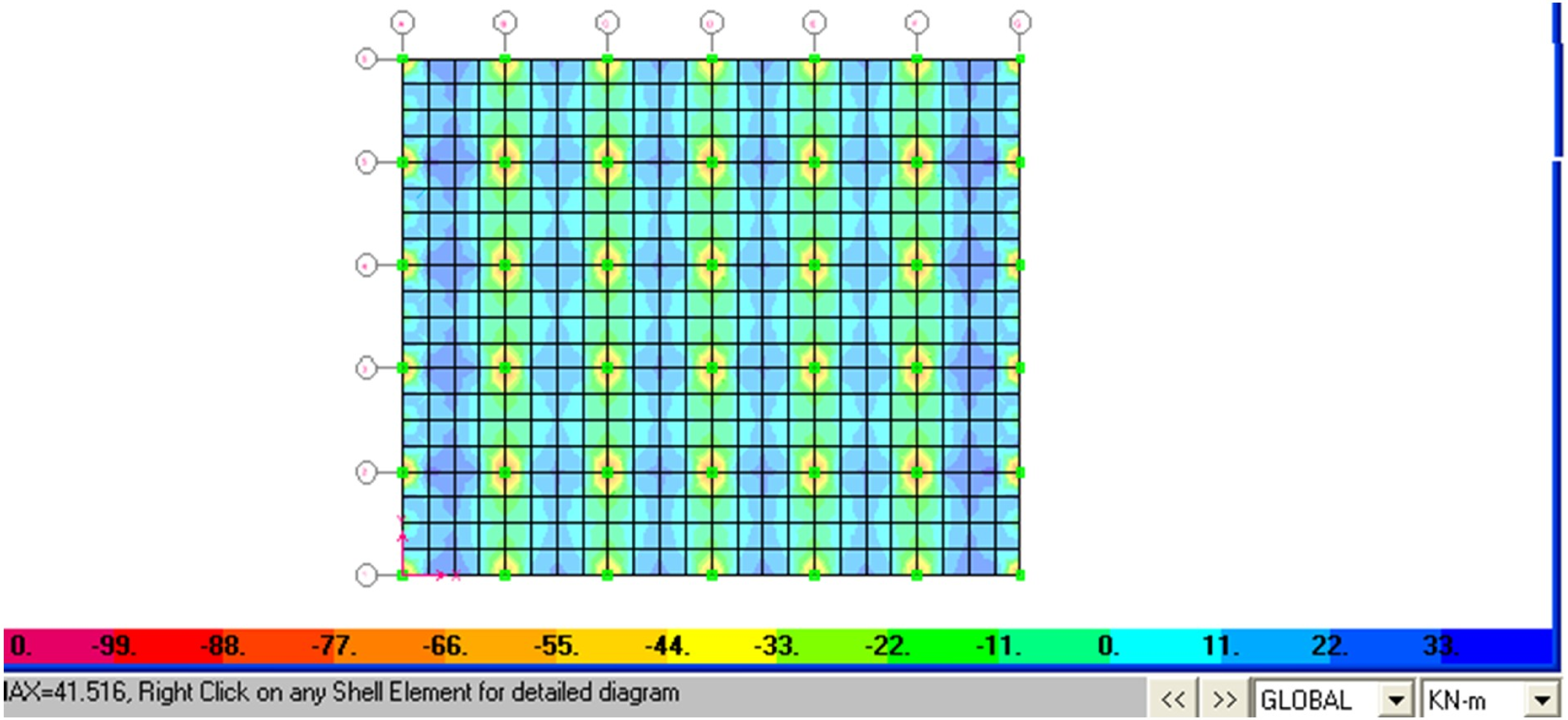
- Slab:
  - $h=550/30=18.33cm$, use 20cm
  - $w_d = (0.2*2.5+0.05)=.55t/m^2$, $w_l =0.35t/m^2$
  - $w_u=1.2*.55+1.6*0.35=1.22t/m^2$
  - $M_o =1.22*6*(5.5)^2 /8=27.7t.m$
  - $M_o^- =0.65*27.7=18t.m.$, $M_o^+ = 9.7t.m.$,
  - $(M_o^-)c.s.=0.75*18=13.5t.m.$ $(13.5/3=4.5t.m/m)$,
  - $(M_o^-)m.s.=0.25*18=4.5t.m.$ $(4.5/3=1.5t.m/m)$,
  - $(M_o^+)c.s= 0.6*9.7=5.8t.m.$ $(5.8/3=1.9t.m/m)$,
  - $(M_o^+)m.s= 0.4*9.7=3.9t.m.$ $(3.9/3=1.3t.m/m)$,

Verify equilibrium: Etabs output

Support Reactions

Story	Point	Load	FX	FY	FZ	MX	MY	MZ
BASE	34	LIVE	1.79	-0.25	130.35	0.270	2.147	0.000
BASE	42	LIVE	-4.88	-4.89	25.34	5.604	-5.581	0.000
Summation	0, 0, Base	DEAD	0.00	0.00	6747.84	101217.600	-121461.120	0.000
Summation	0, 0, Base	LIVE	0.00	0.00	3708.18	55622.700	-66747.240	0.000

Verify stress-strain relationships mesh each 1m



Column strip -ve: kN.m

Section Cutting Line

	X	Y	Z
Start Point	18	19.5	3.6
End Point	18	16.5	3.6

Resultant Force Location and Angle

X	Y	Z	Angle
18	18	3.6	-90.

Include: ☑ Floors ☑ Beams ☐ Braces ☐ Columns ☐ Walls ☐ Ramps

Integrated Forces

	Right Side 1	Right Side 2	Right Side Z	Left Side 1	Left Side 2	Left Side Z
Force	-0.3814	20.0929	-142.708	-0.3814	-20.0929	-142.708
Moment	166.1153	0.8749	-0.2674	-166.1153	0.8749	0.2674

Middle strip -ve: kN.m

Section Cutting Line

	X	Y	Z
Start Point	18	16.5	3.6
End Point	18	13.5	3.6

Resultant Force Location and Angle

X	Y	Z	Angle
18	15	3.6	-90.

Include: ☑ Floors ☑ Beams ☐ Braces ☐ Columns ☐ Walls ☐ Ramps

Integrated Forces

	Right Side 1	Right Side 2	Right Side Z	Left Side 1	Left Side 2	Left Side Z
Force	-8.926E-14	20.0192	-19.3793	5.960E-14	-20.0192	-19.3793
Moment	42.5449	-1.798E-13	-4.965E-14	-42.5449	-7.411E-13	-3.268E-14

Two way slabs: Example 2

- Analyze and design (as a two way slab with beams) the previous one story structure Specifications: B350, f_y=4200 kg/cm^2, superimposed= 50 kg/m^2, live loads= 350 kg/m^2, beam 30cm width by 50cm depth, column dimensions 50cmX50cm,

Solution:

- h=550/36=15.3cm , use 20cm. Beam use 30cm*50cm depth (ignore additional weight of beam)
  - w_d = (0.2*2.5+0.05)=.55t/m^2, w_l=0.35t/m^2
  - w_u=1.2*.55+1.6*0.35=1.22t/m^2
  - M_o =1.22*6*$(5.5)^2$ /8=27.7t.m
  - M_o^- =0.65*27.7=18t.m., M_o^+ = 9.7t.m.,
  - I_b =5*10^{-3} m^4, I_s =4*10^{-3} m^4, α=1.25, αl_2 /l_1 =1.25
  - (M_o^-)cs=0.75*18=13.5t.m. (2/2.1=0.95t.m/m, B=11.5t.m)
  - (M_o^-)ms=0.25*18=4.5t.m. (4.5/3=1.5t.m/m),
  - (M_o^+)cs= 0.75*9.7=7.3t.m(1.1/2.1=0.52t.m/m, B=6.2t.m)
  - (M_o^+)ms= 0.25*9.7=2.4t.m. (2.4/3=0.8t.m/m),

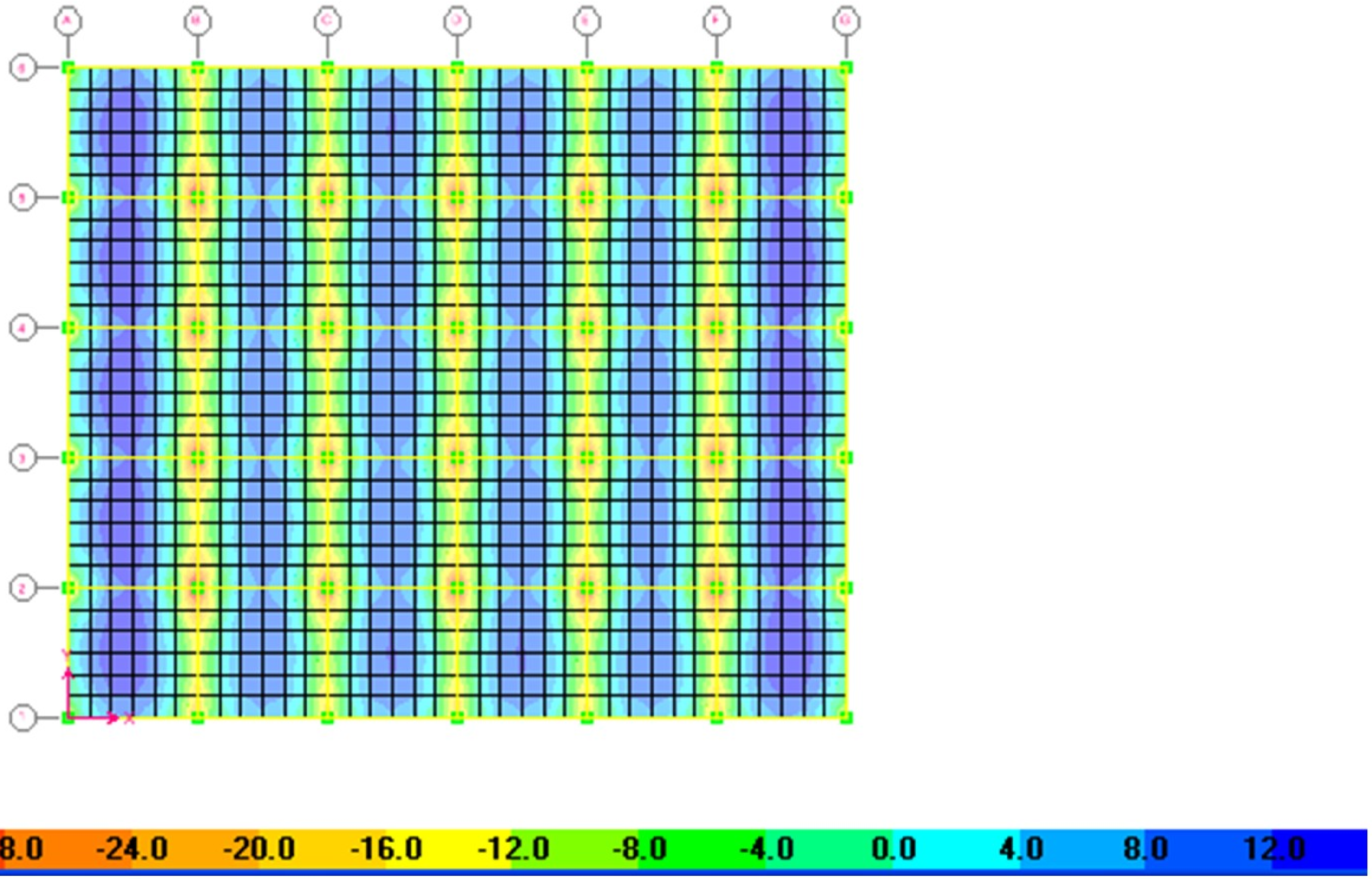
Verify equilibrium: Etabs output

View

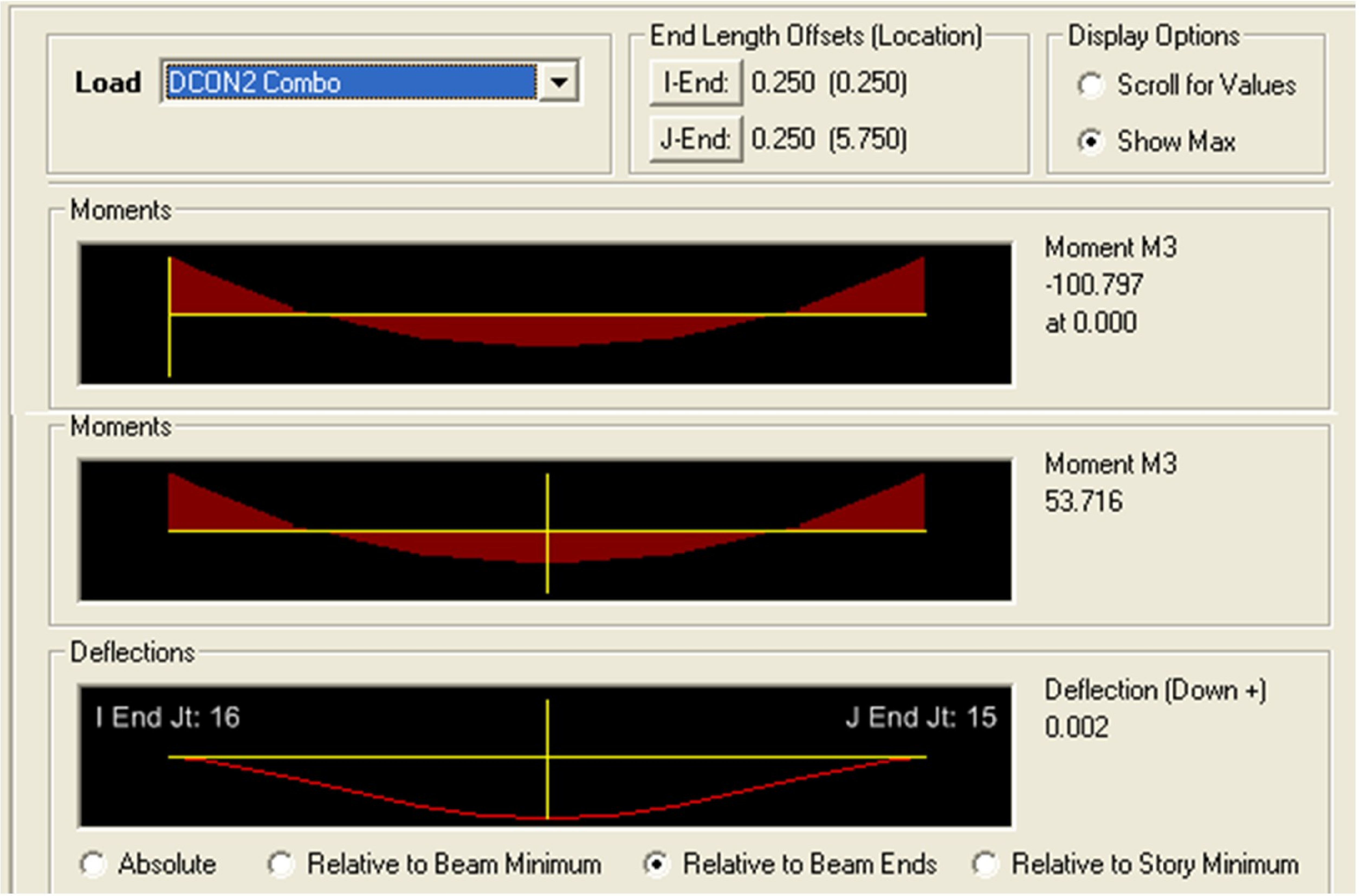
Support Reactions

Story	Point	Load	FX	FY	FZ	MX	MY	MZ
BASE	38	DCON2	-47.81	-4.34	269.57	5.235	-55.265	0.010
Summation	0, 0, Base	DEAD	0.00	0.00	8313.39	124700.850	-149641.020	0.000
Summation	0, 0, Base	LIVE	0.00	0.00	3708.18	55622.700	-66747.240	0.000

Verify stress-strain relationships mesh each 1m

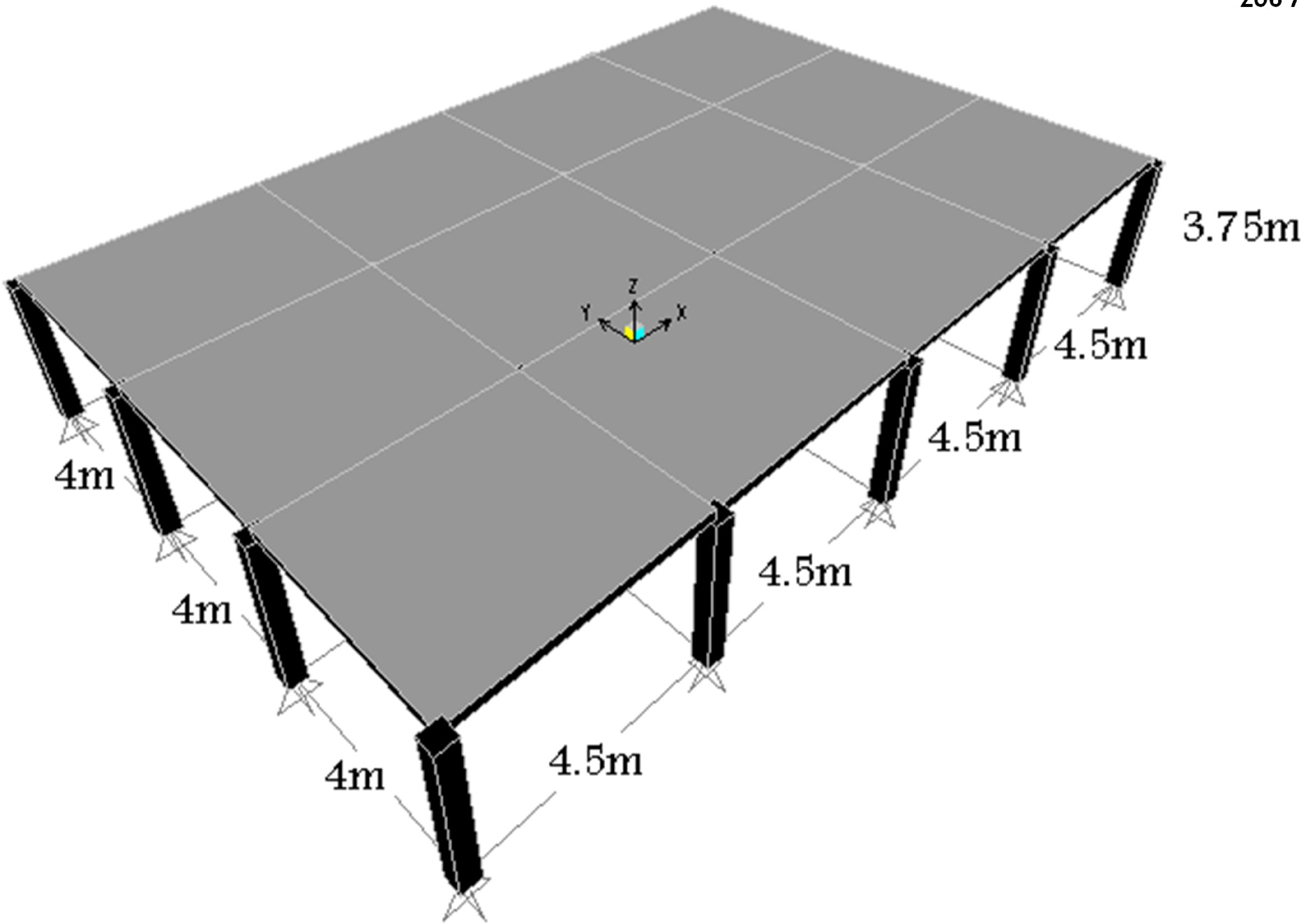


Bending moment in interior beam: kN.m



Problem set # 8

- Analyze and design (as a two way slab) the following one story structure (3.75m height) using 3D model (figure next slide):
  - Specifications: B350, fy=4200 kg/cm^2, superimposed= 100 kg/m^2 , live loads= 200 kg/m^2, column dimensions 35cmX35cm
- Slab without beams 14cm thickness
- Slab 14cm thickness, beams 35cm width by 55cm depth
- Slab 14cm thickness, beams 35cm width by 25cm depth



3.75m
4.5m
4.5m
4.5m
4.5m
4m
4m
4m
Z
Y
X

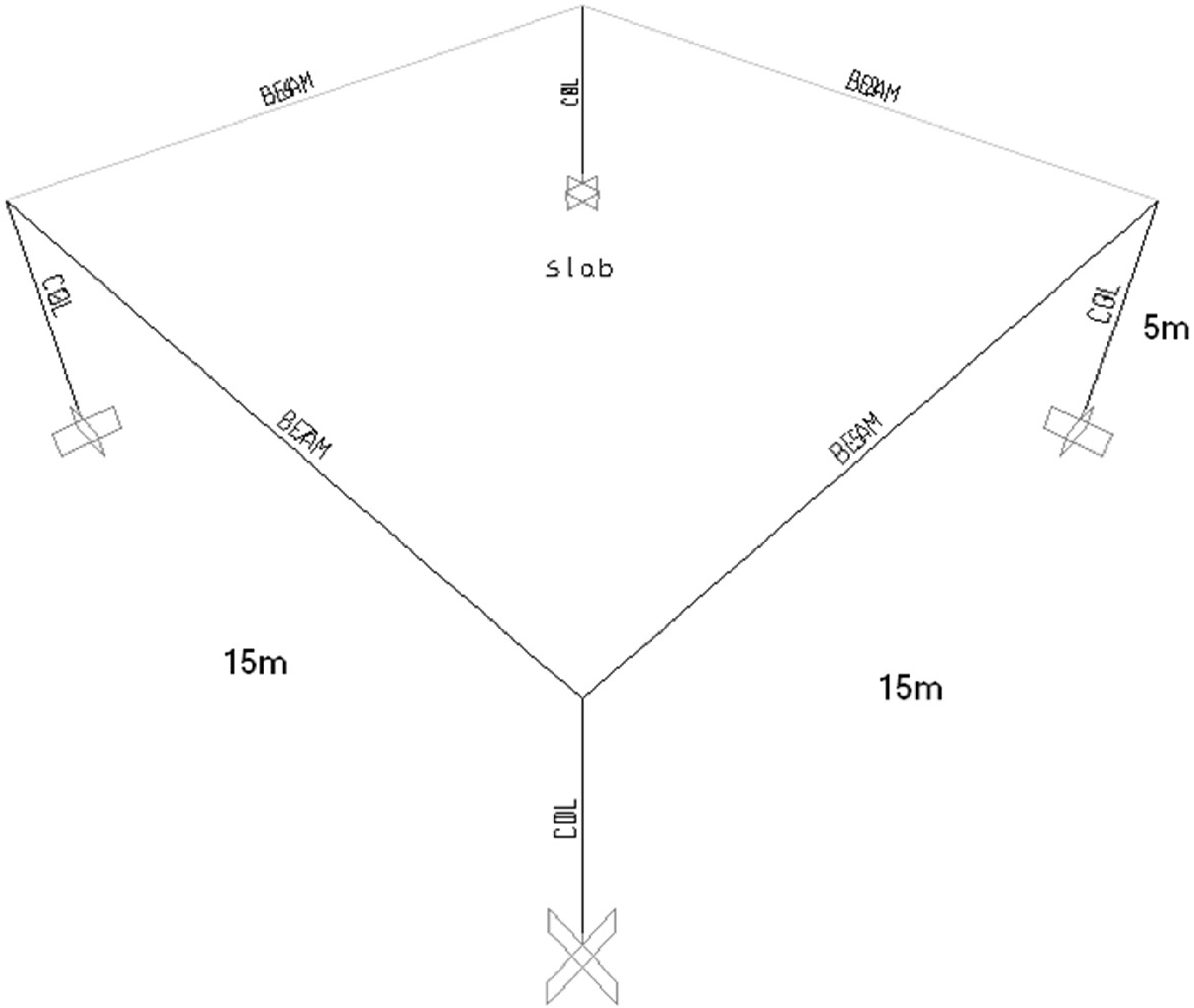
End of section 5.3

Let Learning Continue

5.4 Systems without vertical continuity

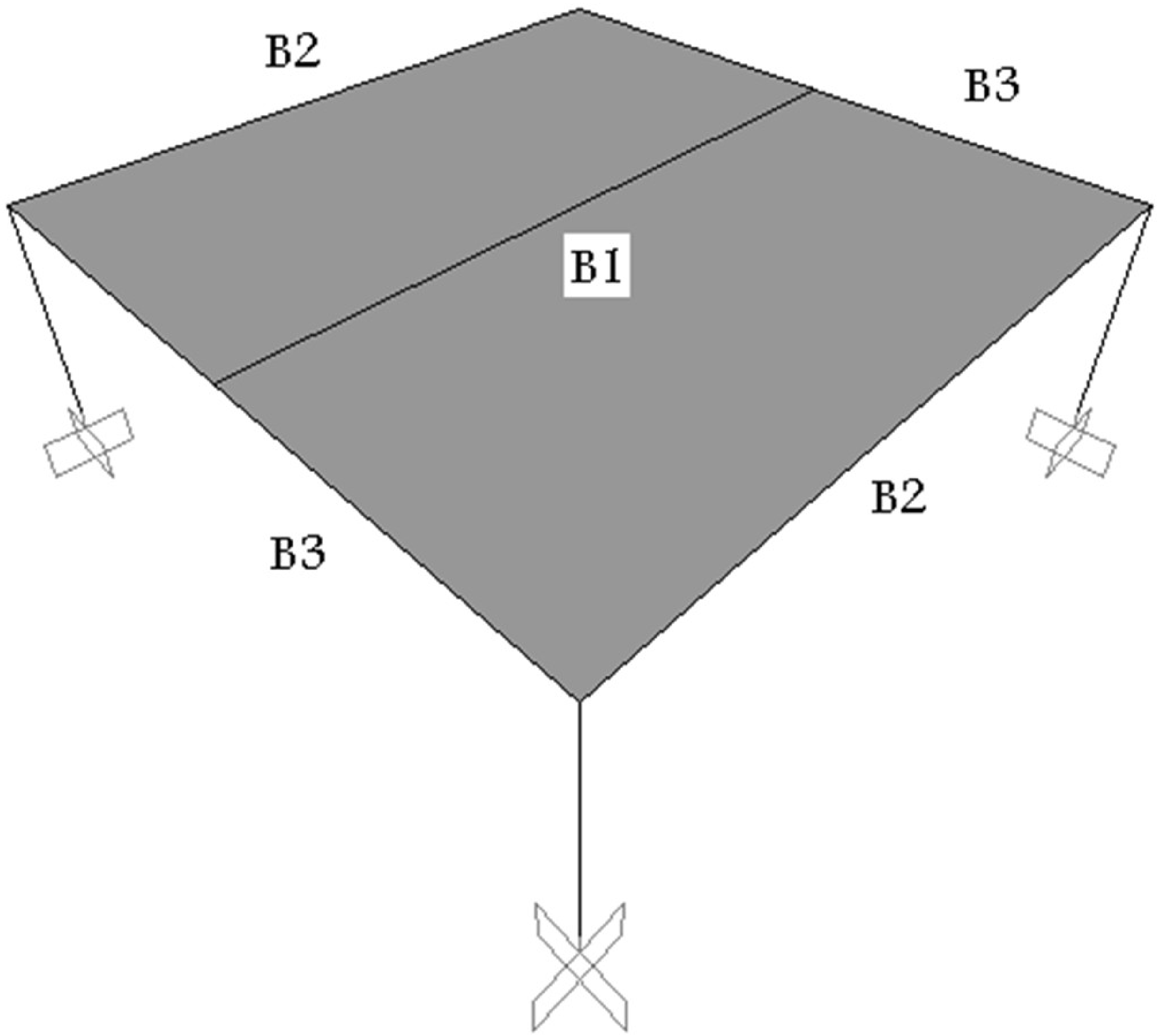
- Analyze a one story reinforced concrete structure (entertainment hall) made of one panel 50cm solid slab sitting on drop beams of 0.5m width and 1m depth supported on four square columns 50cm dimensions, 5m height and 15m span. The superimposed and live loads are 300kg/m^2 and 400kg/m^2 respectively.

Example Model



Consider Design Alternatives

- The structural engineer is required to consider the following design alternative for the entertainment hall



Problem set #9

- Analyze the design alternative using local practice (slab-beam-column load path)
- Analyze the design alternative using 3D model:
- C. Compare A and B
- D. Write a report to the client persuading him the validity of your findings

End of section 5.4

Let Learning Continue

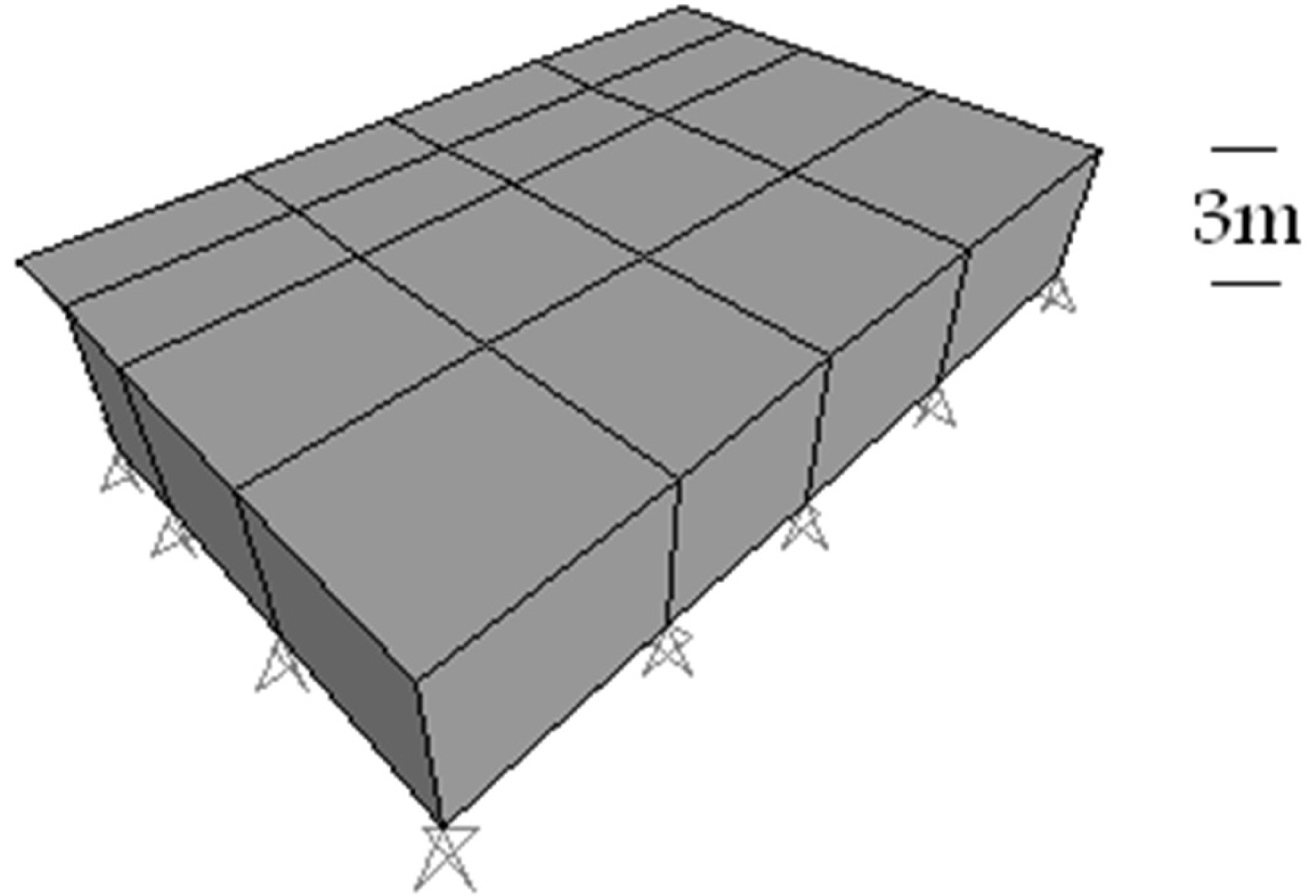
5.5 General shape building systems

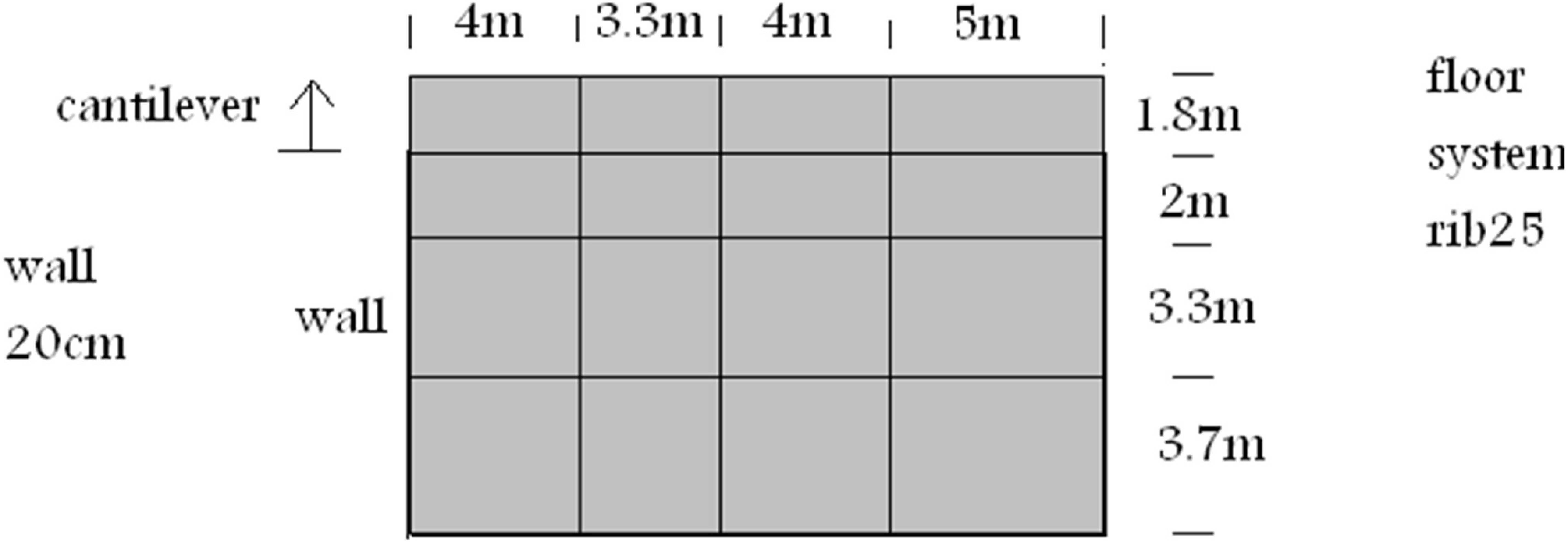
Representation of ribs over slabs is usually inefficient modeling in general shape buildings. Another procedure is to use an equivalent solid slab of uniform thickness but preserving:

- ☐ Stiffness ratios in both directions.
- ☐ Dead weight of slab.

General Shape building
Problem set # 10

- **Floor system ribs 25cm**
- **Wall 20cm**
- **Superimposed 300kg/m^2**
- **Live load 300kg/m^2**
- **E_{con}=2.20Mt/m^2, density=2.5t/m^3**
- **Columns are rectangular 20cmX30cm**


3m


4m
3.3m
4m
5m
cantilever
1.8m
2m
3.3m
3.7m
wall
20cm
wall
floor
system
rib25

End of section 5.5

Let Learning Continue

Appendices

- Table 1604.5 IBC2009\ Occupancy category
- Table 1607.1 IBC2009\ Live load
- Table 9.5a ACI code
- Table 9.5c
- Table 12.15.2
- ACI 13.6.1 DDM limitations
- Fig. 13.3.8

TABLE 1604.5
OCCUPANCY CATEGORY OF BUILDINGS AND OTHER STRUCTURES

OCCUPANCY CATEGORY	NATURE OF OCCUPANCY
I	Buildings and other structures that represent a low hazard to human life in the event of failure, including but not limited to: • Agricultural facilities. • Certain temporary facilities. • Minor storage facilities.
II	Buildings and other structures except those listed in Occupancy Categories I, III and IV
III	Buildings and other structures that represent a substantial hazard to human life in the event of failure, including but not limited to: • Buildings and other structures whose primary occupancy is public assembly with an occupant load greater than 300. • Buildings and other structures containing elementary school, secondary school or day care facilities with an occupant load greater than 250. • Buildings and other structures containing adult education facilities, such as colleges and universities with an occupant load greater than 500. • Group I-2 occupancies with an occupant load of 50 or more resident patients but not having surgery or emergency treatment facilities. • Group I-3 occupancies. • Any other occupancy with an occupant load greater than 5,000[a]. • Power-generating stations, water treatment facilities for potable water, waste water treatment facilities and other public utility facilities not included in Occupancy Category IV. • Buildings and other structures not included in Occupancy Category IV containing sufficient quantities of toxic or explosive substances to be dangerous to the public if released.
IV	Buildings and other structures designated as essential facilities, including but not limited to: • Group I-2 occupancies having surgery or emergency treatment facilities. • Fire, rescue, ambulance and police stations and emergency vehicle garages. • Designated earthquake, hurricane or other emergency shelters. • Designated emergency preparedness, communications and operations centers and other facilities required for emergency response. • Power-generating stations and other public utility facilities required as emergency backup facilities for Occupancy

TABLE 1607.1
MINIMUM UNIFORMLY DISTRIBUTED LIVE LOADS, L_o, AND MINIMUM CONCENTRATED LIVE LOADS[g]

OCCUPANCY OR USE	UNIFORM (psf)	CONCENTRATED (lbs.)
1. Apartments (see residential)	—	—
2. Access floor systems		
Office use	50	2,000
Computer use	100	2,000
3. Armories and drill rooms	150	—
4. Assembly areas and theaters		—
Fixed seats (fastened to floor)	60	
Follow spot, projections and control rooms	50	
Lobbies	100	
Movable seats	100	
Stages and platforms	125	
Other assembly areas	100	
5. Balconies (exterior) and decks[h]	Same as occupancy served	—
6. Bowling alleys	75	—
7. Catwalks	40	300
8. Cornices	60	—
9. Corridors, except as otherwise indicated	100	—

TABLE 1607.1—continued
MINIMUM UNIFORMLY DISTRIBUTED LIVE LOADS, L_o, AND MINIMUM CONCENTRATED LIVE LOADS[g]

OCCUPANCY OR USE	UNIFORM (psf)	CONCENTRATED (lbs.)
23. Manufacturing		
Heavy	250	3,000
Light	125	2,000
24. Marquees	75	—
25. Office buildings		
Corridors above first floor	80	2,000
File and computer rooms shall be designed for heavier loads based on anticipated occupancy	—	—
Lobbies and first-floor corridors	100	2,000
Offices	50	2,000
26. Penal institutions		—
Cell blocks	40	
Corridors	100	
27. Residential		—
One- and two-family dwellings		
Uninhabitable attics without storage[i]	10	
Uninhabitable attics with limited storage[i, j, k]	20	
Habitable attics and sleeping areas	30	
All other areas	40	
Hotels and multifamily dwellings		
Private rooms and corridors serving them	40	
Public rooms and corridors serving them	100	

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10. Dance halls and ballrooms	100	—
11. Dining rooms and restaurants	100	—
12. Dwellings (see residential)	—	—
13. Elevator machine room grating (on area of 4 in^2)	—	300
14. Finish light floor plate construction (on area of 1 in^2)	—	200
15. Fire escapes On single-family dwellings only	100 40	—
16. Garages (passenger vehicles only) Trucks and buses	40 See Section 1607.6	Note a
17. Grandstands (see stadium and arena bleachers)	—	—
18. Gymnasiums, main floors and balconies	100	—
19. Handrails, guards and grab bars	See Section 1607.7	
20. Hospitals Corridors above first floor Operating rooms, laboratories Patient rooms	 80 60 40	 1,000 1,000 1,000
21. Hotels (see residential)	—	—
22. Libraries Corridors above first floor Reading rooms Stack rooms	 80 60 150[b]	 1,000 1,000 1,000

continued

28. Reviewing stands, grandstands and bleachers	Note c	
29. Roofs All roof surfaces subject to maintenance workers Awnings and canopies Fabric construction supported by a lightweight rigid skeleton structure All other construction Ordinary flat, pitched, and curved roofs Primary roof members, exposed to a work floor Single panel point of lower chord of roof trusses or any point along primary structural members supporting roofs: Over manufacturing, storage warehouses, and repair garages All other occupancies Roofs used for other special purposes Roofs used for promenade purposes Roofs used for roof gardens or assembly purposes	 5 nonreducible 20 20 Note 1 60 100	 300 2,000 300 Note 1
30. Schools Classrooms Corridors above first floor First-floor corridors	 40 80 100	 1,000 1,000 1,000
31. Scuttles, skylight ribs and accessible ceilings	—	200
32. Sidewalks, vehicular driveways and yards, subject to trucking	250[d]	8,000[e]
33. Skating rinks	100	—

continued

TABLE 1607.1—continued
MINIMUM UNIFORMLY DISTRIBUTED LIVE LOADS, L_o, AND MINIMUM CONCENTRATED LIVE LOADS[g]

OCCUPANCY OR USE	UNIFORM (psf)	CONCENTRATED (lbs.)
34. Stadiums and arenas		
Bleachers	100[c]	—
Fixed seats (fastened to floor)	60[c]	
35. Stairs and exits		Note f
One- and two-family dwellings	40	
All other	100	
36. Storage warehouses (shall be designed for heavier loads if required for anticipated storage)		
Heavy	250	
Light	125	
37. Stores		
Retail		
First floor	100	1,000
Upper floors	75	1,000
Wholesale, all floors	125	1,000
38. Vehicle barrier systems	See Section 1607.7.3	
39. Walkways and elevated platforms (other than exitways)	60	—
40. Yards and terraces, pedestrians	100	—

For SI: 1 inch = 25.4 mm, 1 square inch = 645.16 mm^2,
1 square foot = 0.0929 m^2,
1 pound per square foot = 0.0479 kN/m^2, 1 pound = 0.004448 kN,
1 pound per cubic foot = 16 kg/m^3

TABLE 9.5(a) — MINIMUM THICKNESS OF NONPRESTRESSED BEAMS OR ONE-WAY SLABS UNLESS DEFLECTIONS ARE CALCULATED

	Minimum thickness, *h*			
	Simply supported	One end continuous	Both ends continuous	Cantilever
Member	Members not supporting or attached to partitions or other construction likely to be damaged by large deflections			
Solid one-way slabs	$\ell/20$	$\ell/24$	$\ell/28$	$\ell/10$
Beams or ribbed one-way slabs	$\ell/16$	$\ell/18.5$	$\ell/21$	$\ell/8$

Notes:
Values given shall be used directly for members with normalweight concrete and Grade 420 reinforcement. For other conditions, the values shall be modified as follows:
a) For lightweight concrete having equilibrium density, w_c, in the range of 1440 to 1840 kg/m^3, the values shall be multiplied by $(1.65 - 0.0003w_c)$ but not less than 1.09.
b) For f_y other than 420 MPa, the values shall be multiplied by $(0.4 + f_y/700)$.

TABLE 9.5(c)—MINIMUM THICKNESS OF SLABS WITHOUT INTERIOR BEAMS*

f_y, MPa†	Without drop panels‡			With drop panels‡		
	Exterior panels		Interior panels	Exterior panels		Interior panels
	Without edge beams	With edge beams§		Without edge beams	With edge beams§	
280	$\ell_n/33$	$\ell_n/36$	$\ell_n/36$	$\ell_n/36$	$\ell_n/40$	$\ell_n/40$
420	$\ell_n/30$	$\ell_n/33$	$\ell_n/33$	$\ell_n/33$	$\ell_n/36$	$\ell_n/36$
520	$\ell_n/28$	$\ell_n/31$	$\ell_n/31$	$\ell_n/31$	$\ell_n/34$	$\ell_n/34$

*For two-way construction, ℓ_n is the length of clear span in the long direction, measured face-to-face of supports in slabs without beams and face-to-face of beams or other supports in other cases.

†For f_y between the values given in the table, minimum thickness shall be determined by linear interpolation.

‡Drop panels as defined in 13.2.5.

§Slabs with beams between columns along exterior edges. The value of α_f for the edge beam shall not be less than 0.8.

TABLE R12.15.2 — TENSION LAP SPLICES

$\frac{A_s \text{ provided*}}{A_s \text{ required}}$	Maximum percent of A_s spliced within required lap length	
	50	100
Equal to or greater than 2	Class A	Class B
Less than 2	Class B	Class B

*Ratio of area of reinforcement provided to area of reinforcement required by analysis at splice locations.

13.6.1 — Limitations

Design of slab systems within the limitations of 13.6.1.1 through 13.6.1.8 by the direct design method shall be permitted.

13.6.1.1 — There shall be a minimum of three continuous spans in each direction.

13.6.1.2 — Panels shall be rectangular, with a ratio of longer to shorter span center-to-center of supports within a panel not greater than 2.

13.6.1.3 — Successive span lengths center-to-center of supports in each direction shall not differ by more than one-third the longer span.

13.6.1.4 — Offset of columns by a maximum of 10 percent of the span (in direction of offset) from either axis between centerlines of successive columns shall be permitted.

13.6.1.5 — All loads shall be due to gravity only and uniformly distributed over an entire panel. The unfactored live load shall not exceed two times the unfactored dead load.

13.6.1.6 — For a panel with beams between supports on all sides, Eq. (13-2) shall be satisfied for beams in the two perpendicular directions

$$0.2 \le \frac{\alpha_{f1} \ell_2^2}{\alpha_{f2} \ell_1^2} \le 5.0 \qquad (13\text{-}2)$$

where α_{f1} and α_{f2} are calculated in accordance with Eq. (13-3).

$$\alpha_f = \frac{E_{cb} I_b}{E_{cs} I_s} \qquad (13\text{-}3)$$

CODE

COMMENTARY

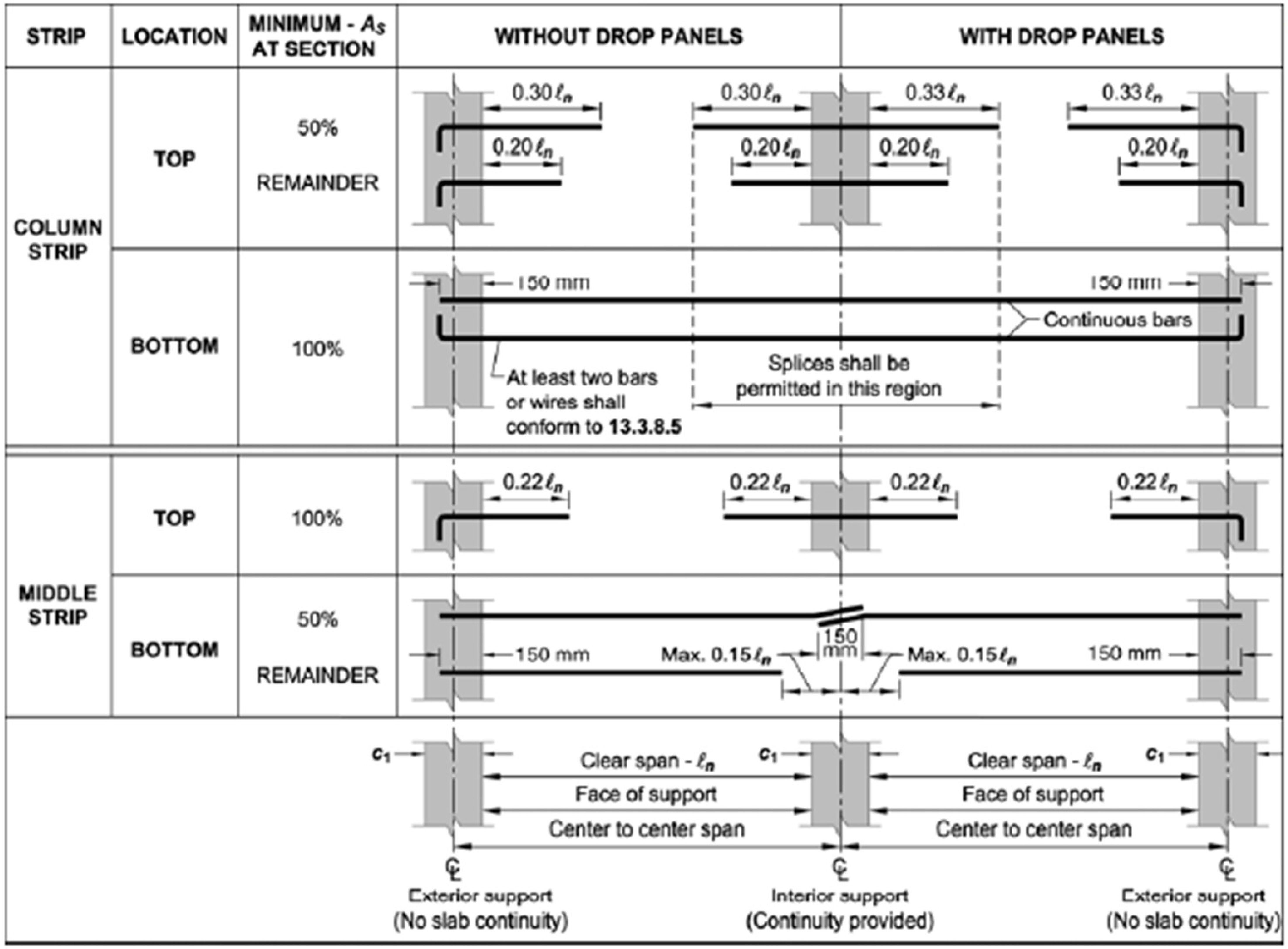

Fig. 13.3.8—Minimum extensions for reinforcement in slabs without beams. (See 12.11.1 for reinforcement extension into supports).

13.6.4.1 — Column strips shall be proportioned to resist the following portions in percent of interior negative factored moments:

ℓ_2/ℓ_1	0.5	1.0	2.0
$(\alpha_{f1}\ell_2/\ell_1) = 0$	75	75	75
$(\alpha_{f1}\ell_2/\ell_1) \geq 1.0$	90	75	45

13.6.4.4 — Column strips shall be proportioned to resist the following portions in percent of positive factored moments:

ℓ_2/ℓ_1	0.5	1.0	2.0
$(\alpha_{f1}\ell_2/\ell_1) = 0$	60	60	60
$(\alpha_{f1}\ell_2/\ell_1) \geq 1.0$	90	75	45

13.6.5.1 — Beams between supports shall be proportioned to resist 85 percent of column strip moments if $\alpha_{f1}\ell_2/\ell_1$ is equal to or greater than 1.0.

Linear interpolations shall be made between values shown.

End of Appendices

Let Long life learning Continue