Steel Structures

SE-505

Lecture # 4

Composite Steel-Concrete Construction

Steel Structures

Historical Background

- Steel frames supporting cast in place reinforced concrete slab construction was historically designed on the assumption that the concrete slab acts INDEPENDENTLY of the steel in resisting loads.
- With the advent of WELDING, it became practical to provide mechanical shear connectors to resist the horizontal shear which develops during bending.
- Steel beams encased in concrete were widely used from the early 1900s until the development of lightweight materials for fire protection in the past 50 years

Steel Structures

Non-Composite Action

Non composite action results when a concrete slab is supported by steel beams and there is no provision for shear transfer between the two.

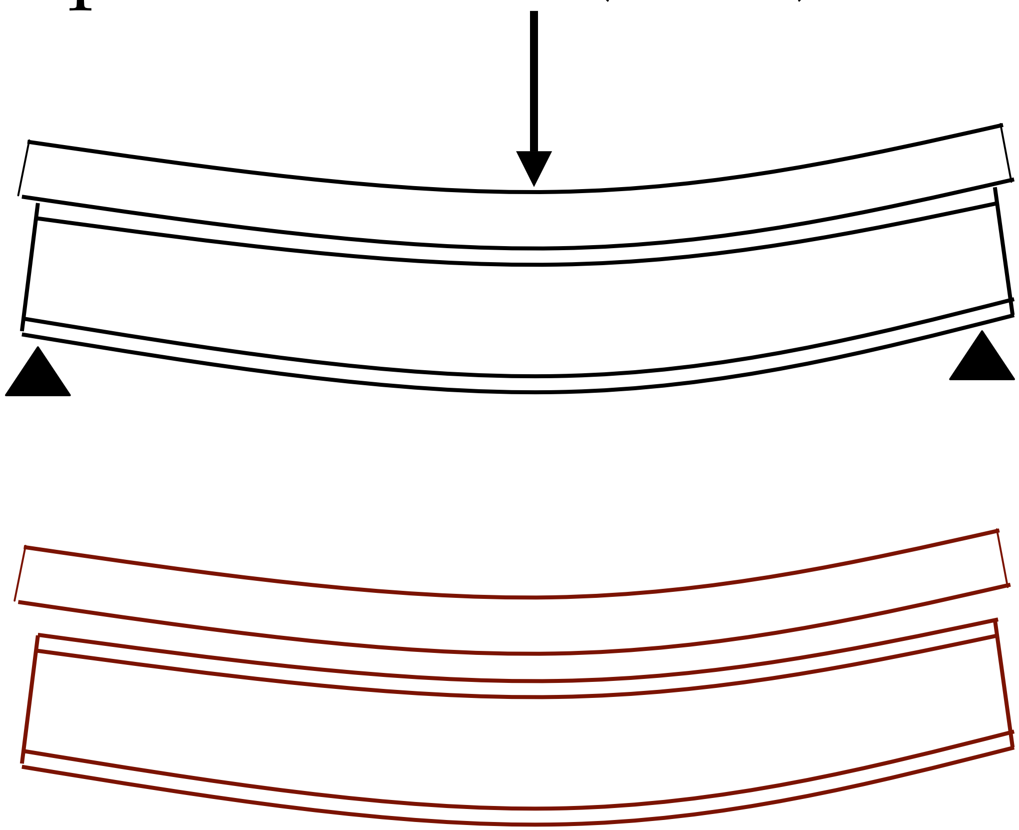
- Beam and slab carry separately a part of load

The total resisting moment is:

$$\Sigma M = M_{slab} + M_{beam}$$

Steel Structures

Non-Composite Action (contd…)



Slip is present

No Horizontal shear is developed

Deflected non-composite beam

Steel Structures

Partial-Composite Action

Lesser number of shear connectors than required results in Partial Composite Action.

- Due to partial interaction the SLIP reduces

The total resisting moment is:

$$\Sigma M = M_{slab} + M_{beam} + C' l_a$$

where C' is the resultant compressive force developed in the slab and ℓ_a is the distance between this force and its balancing tension.

Steel Structures

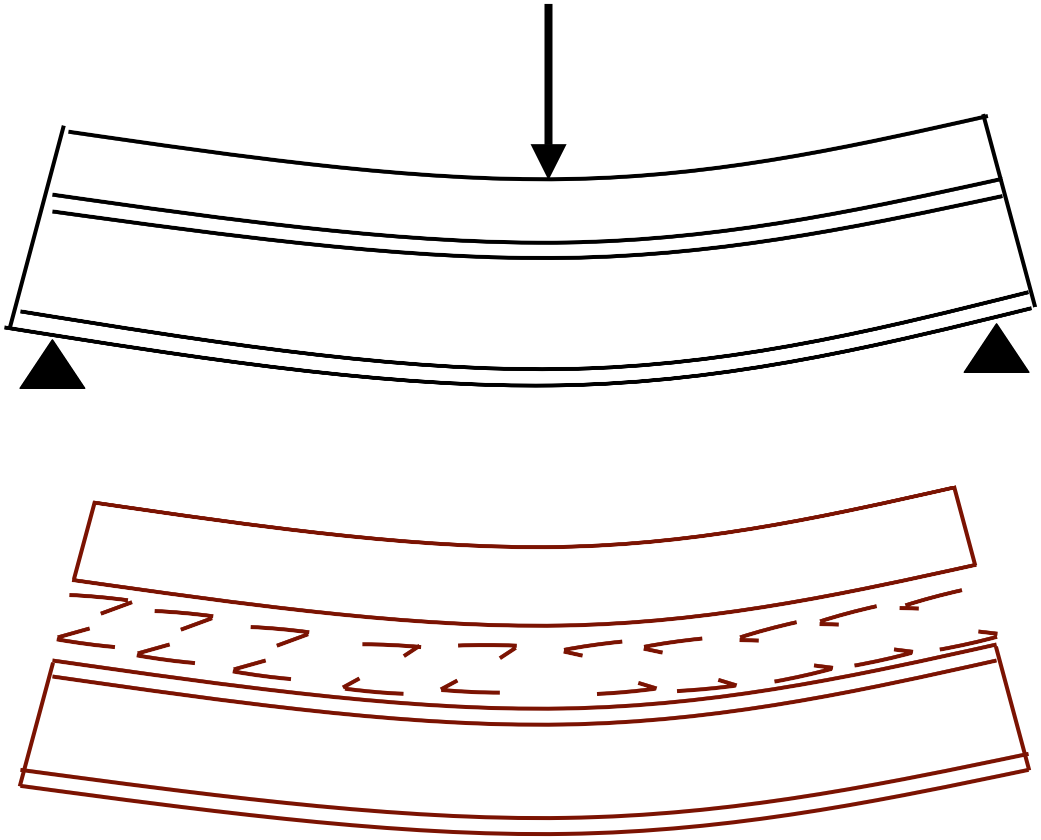
Composite Action

"Composite action is developed when two load carrying structural members, (slab & beam) are integrally connected and deflect as a single unit".

- In composite section strain varies linearly throughout the depth of slab and beam.
- Moment capacity becomes larger than simply the addition of moment capacities for individual members.

Steel Structures

Composite Action (contd…)



No slip at the interface

Deflected composite beam

Steel Structures

Composite Action (contd…)

- No slip occur between beam and slab.
- A single N.A. occurs.

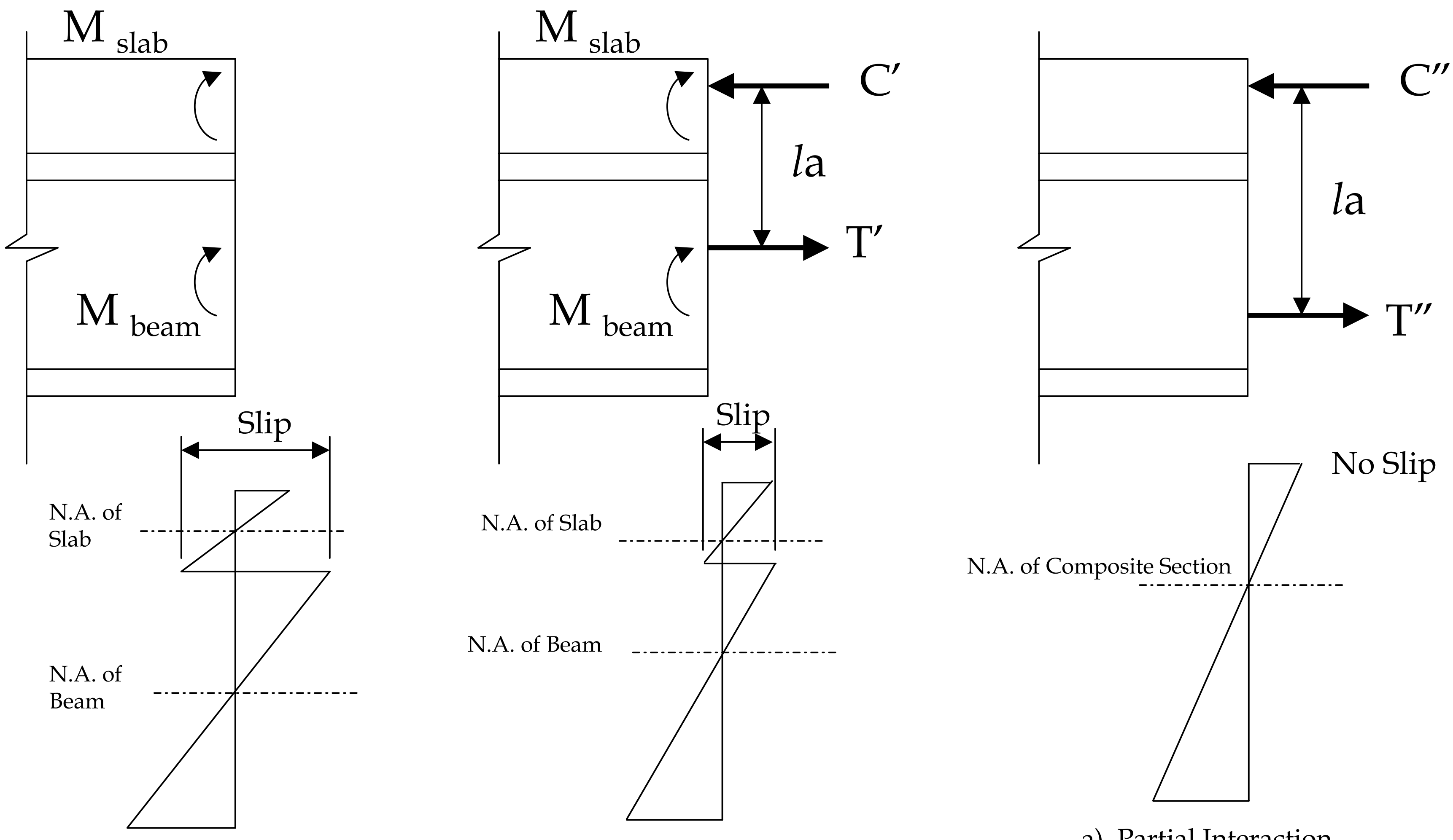
The moment capacity becomes

$$\Sigma M = T'' \times l_a = C'' \times l_a$$

where C'' is the total compression developed over the N.A. and T'' is the corresponding tensile force.

Steel Structures

Strain Variation in Composite Beams



a) No Interaction

a) Partial Interaction

a) Partial Interaction

Steel Structures

Advantages of Composite Construction

1. The nominal flexural strength is greater than their individual sum.
2. High compressive strength of concrete is effectively utilized.
3. Usually 20 to 30% reduction in steel is possible.
4. Relatively shallow depth beams can be used. **(specially beneficial for multistory building)**
5. Stiffness of the floor system increases therefore live load deflections are reduced.

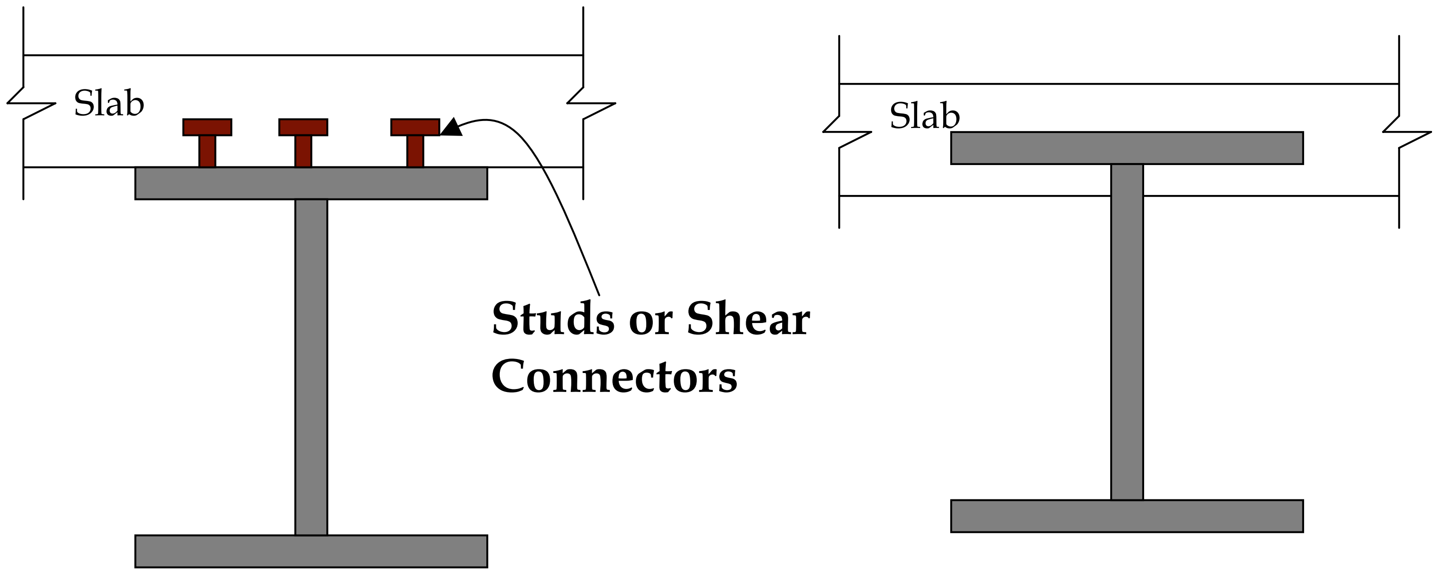
Steel Structures

Advantages of Composite Construction (contd…)

6. Increased span length can be used for a given member.
7. Fire proofing cost is reduced **(steel section encased in concrete)**.
8. Local buckling and lateral torsional buckling is avoided due to continuous bracing.
9. Architectural appearance is better due to encased section

Steel Structures

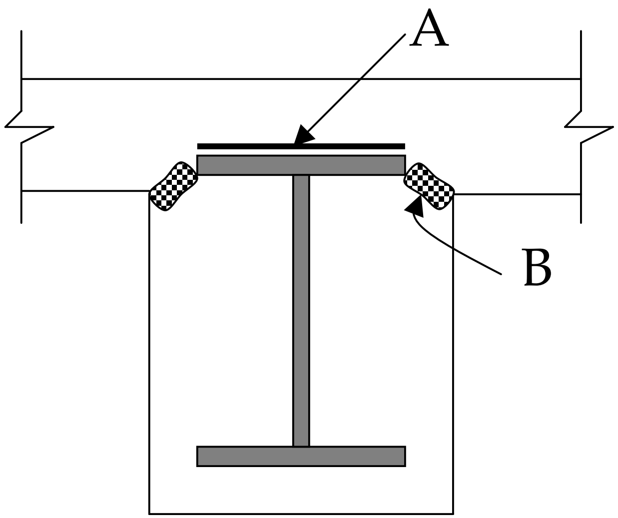
Full composite action may be developed in one of the following ways:



(a) (b)

Steel Structures

How to provide Shear Connection (contd…)

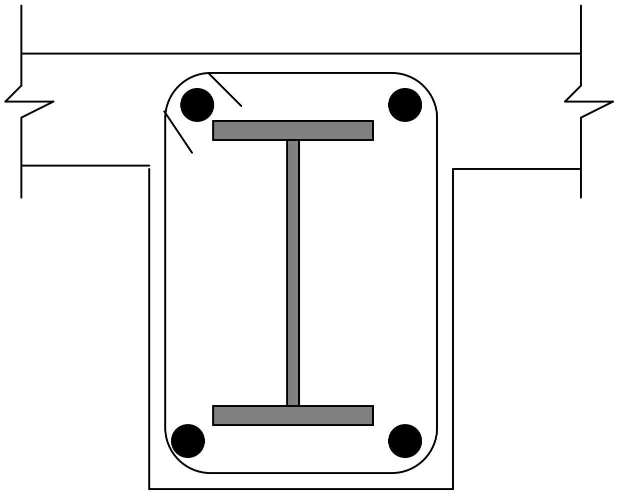


(c) Encased Steel Section

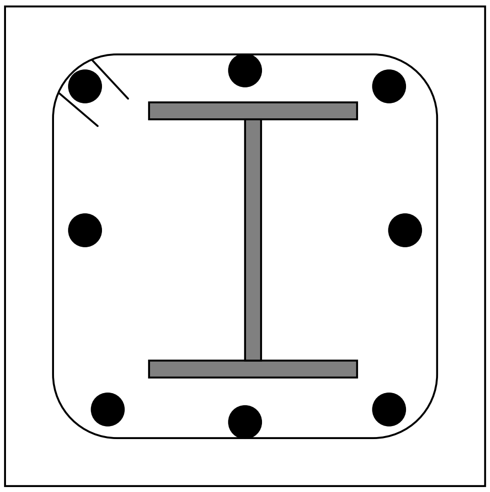
- Surface "A" transfers shear by the bond between steel and concrete.
- At surface "B" shear strength of the concrete is utilized.
- If the shear capacity is low, shear reinforcement can also be provided.

Steel Structures

How to provide Shear Connection **(contd…)**



(d) Encased Steel Section
with Shear Reinforcement

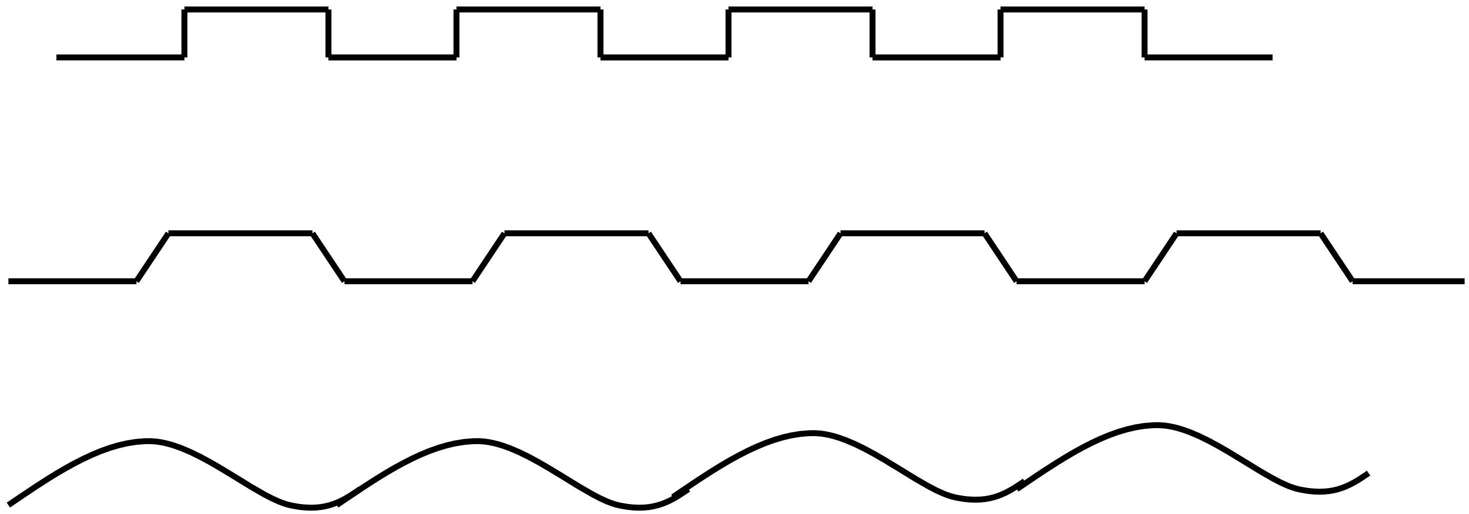


(e) Composite Column
Section (Encased Section)

Steel Structures

How to provide Shear Connection **(contd…)**

Using Formed Steel Deck with Ribs

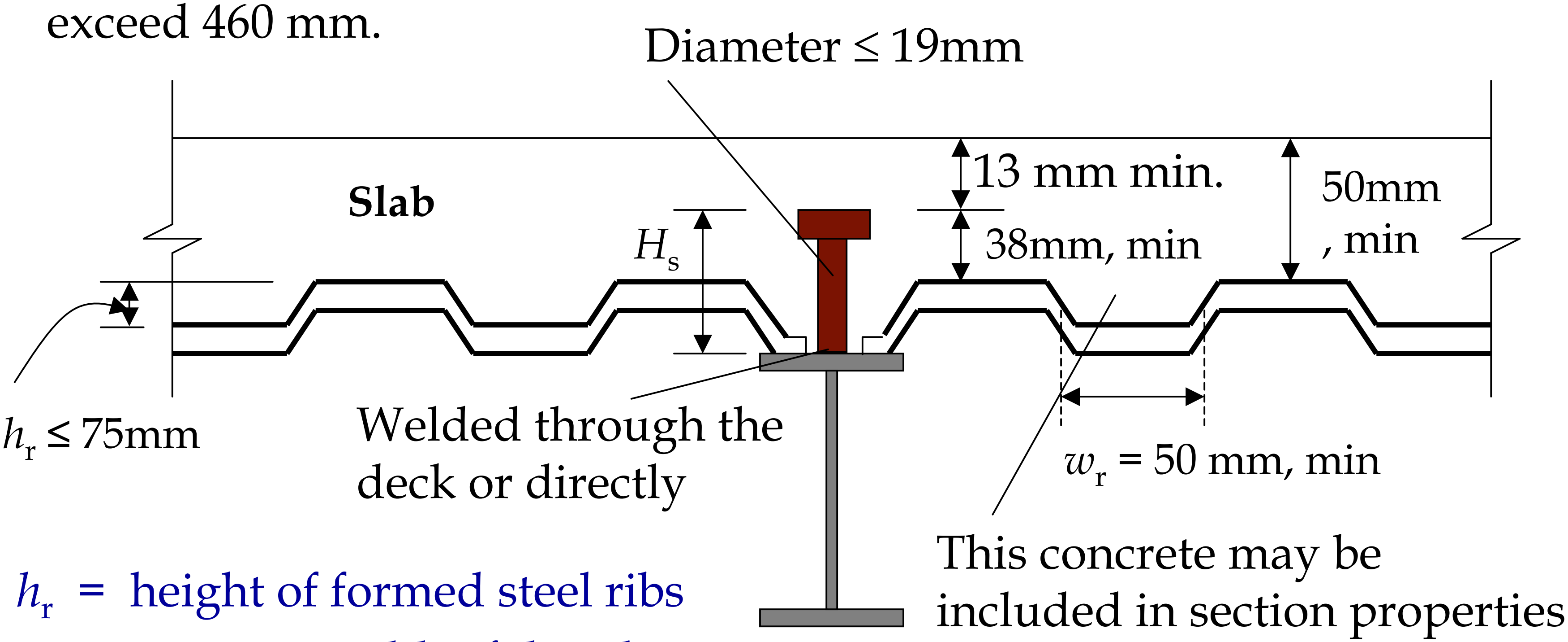


Steel Structures

How to provide Shear Connection (contd…)

(f) Using formed Steel Deck with Ribs Parallel to Beam

Deck must be anchored to all supporting members at a spacing not to exceed 460 mm.



h_r = height of formed steel ribs

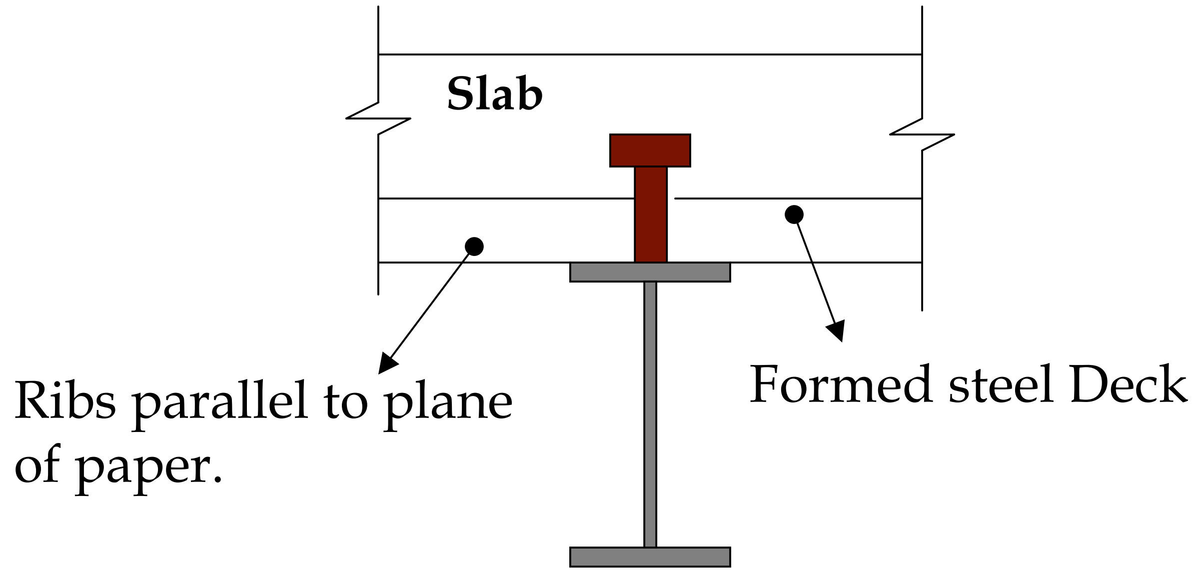
w_r = average width of the ribs

If we use ribbed steel deck, formwork for slab is not required

Steel Structures

How to provide Shear Connection (contd…)

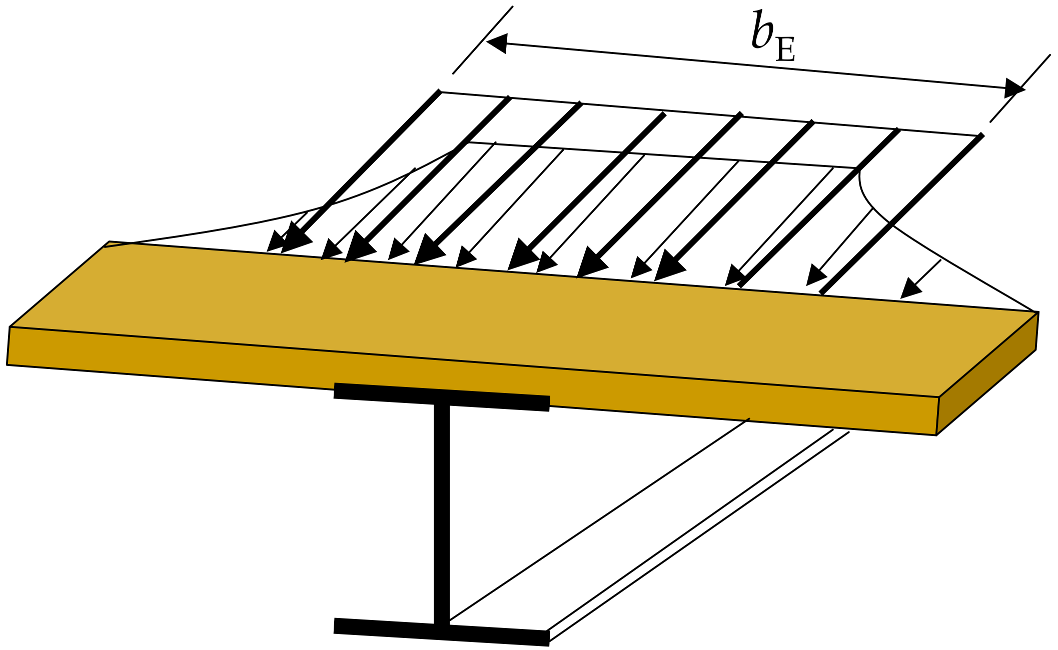
(g) Using formed Steel Deck with Ribs Perpendicular to Beam



Concrete below the top of the steel deck must be neglected in determining the composite section properties.

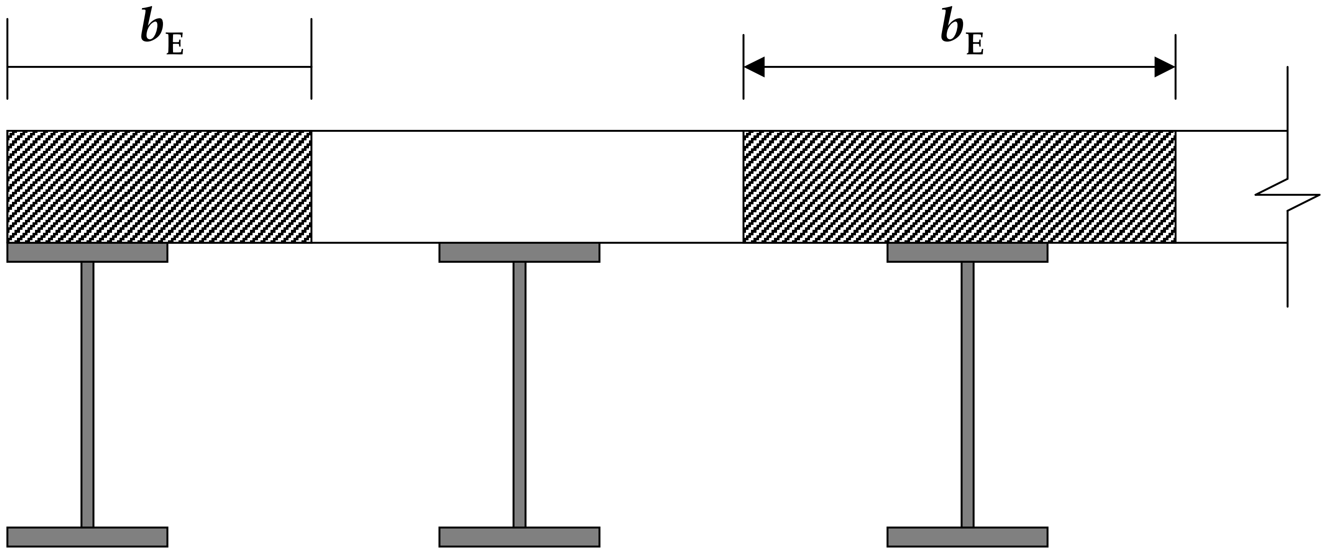
Steel Structures

Effective Width (contd…)



Steel Structures

Effective Width



b_E = **Effective width**

Steel Structures

Effective Width (contd…)

Interior Girder

b_E is smaller of

- L/4
- s

Exterior Girder

b_E is smaller of

- L/8
- s/2 + distance from beam center to edge of slab.

L = Span of girder

s = Spacing between beams

Steel Structures

AICS-I1 General Provisions

Load Effects Determination

In determining load effects in members and connections of a structure that includes composite beams, consideration must be given to the effective sections at the time each increment of load is applied.

Plastic Stress Distribution

All concrete has stress = $0.85 f_c'$ (compression in slab)

All steel has stress = f_y (tension in steel)

Concrete compression in round HSS filled with concrete

= $0.9 f_c'$ (due to concrete confinement)

Steel Structures

Shoring

"Vertical support provided to fresh concrete of slab until it gains strength"

- Weight of the fresh concrete is not transferred to steel beam but is directly transferred to soil through vertical supports.
- No shoring is preferred in bridges, when vertical supports are difficult to be provided.
- When 75% of the 28 days strength is achieved, the composite behavior is developed and composite section is used to resist loads.

Steel Structures

Computation of Elastic Section Properties

"A" for shear strength

"I" for deflection

"S" for flexural strength

Transformed section will be developed by changing concrete area into an equivalent steel area.

Equivalent Steel Area = Concrete Area/n

Equivalent Effective Width = b_E**/n**

n **= modular ratio**

$$n = \frac{E_s}{E_c}$$

Rounded to nearest whole number

Steel Structures

Computation of Elastic Section Properties (contd…)

$$E_c = 0.043 \times w^{1.5} \sqrt{f_c'}$$

E_c and fc′ in MPa

w = density of concrete in kg/m^3

For w = 2300 kg/m^3

$$E_c = 4700 \sqrt{fc'}$$

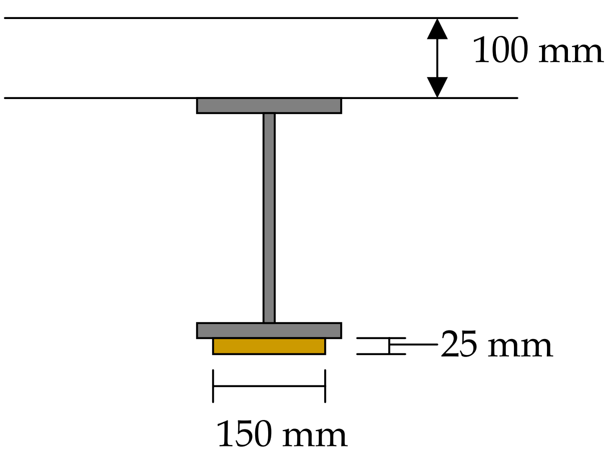
Steel Structures

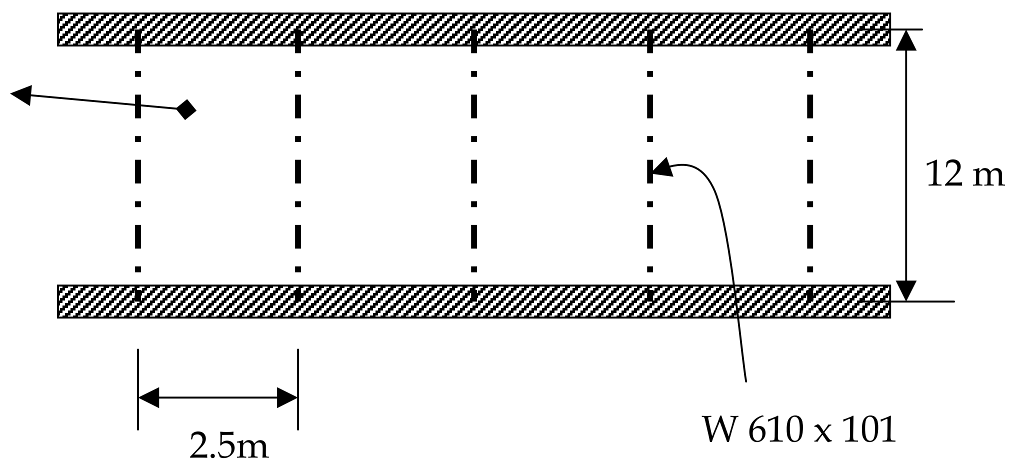
Computation of Elastic Section Properties (contd…)

Example

Compute the elastic section modulus of the given section.

f_c' = 20 MPa, A36 Steel, bottom steel cover plate of size 25 x 150mm is used.





Steel Structures

Computation of Elastic Section Properties (contd…)

Solution

W 610 x 101

$d = 603$ mm

$A = 13000$ mm^2

$b_f = 228$ mm

$t_f = 14.9$ mm

$t_w = 10.5$ mm

$I_x = 76{,}200 \times 10^4$ mm^4

Steel Structures

Computation of Elastic Section Properties (contd…)

Solution

Effective width of concrete slab

b_E is smaller of

- L/4 = 12000/4 = 3000 mm
- s = 2500 mm

So **b_E = 2500 mm**

E_s = 200,000 MPa

$$E_c = 4700\sqrt{f_c'} = 4700\sqrt{20}$$

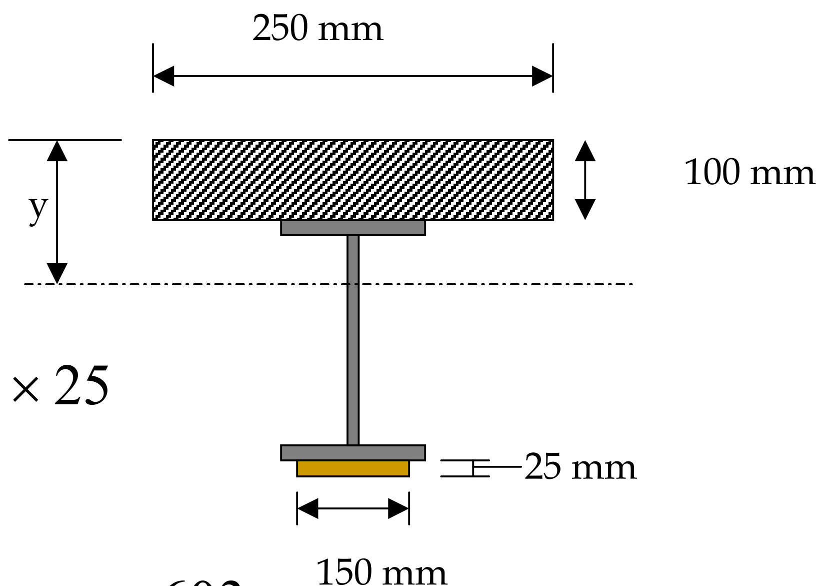
$$= 21019\,MPa$$

$$n = \frac{E_s}{E_c} = 10$$

Steel Structures

Computation of Elastic Section Properties (contd...)

Solution



$$\frac{b_E}{n} = \frac{2500}{10} = 250\,mm$$

$$A = 250 \times 100 + 13000 + 150 \times 25$$

$$= 41{,}750 \text{ mm}^2$$

$$\bar{y} = \frac{(250\times100\times50)+13000\times(100+\frac{603}{2})+25\times150\times(100+603+25/2)}{41750}$$

$$= 219\,mm$$

Steel Structures

Computation of Elastic Section Properties (contd...)

Solution

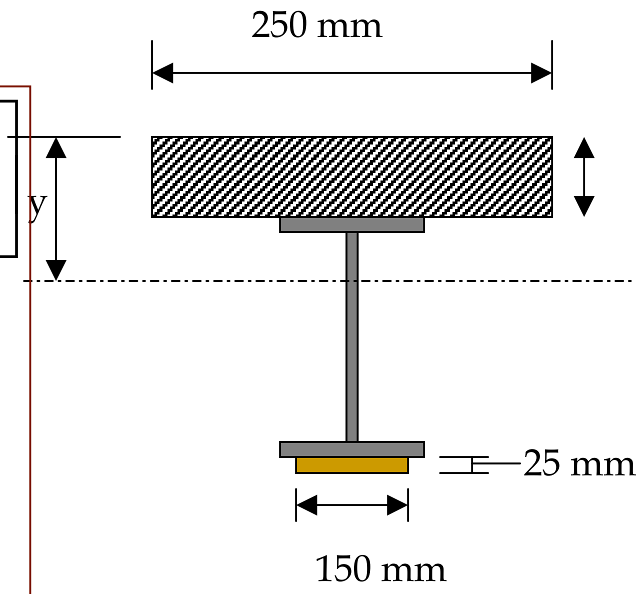
$$I_{tr} = \left[\frac{250 \times 100^3}{12} + 250 \times 100 \times (219 - 50)^2 \right]$$

$$+ \left[76200 \times 10^4 + 13000 \times 182.5^2 \right]$$

$$+ \frac{150 \times 25^3}{12} \qquad \text{(Negligible)}$$

$$+ 150 \times 25 \times (715.5 - 219)^2$$

$$I_{tr} = 285426 \times 10^4 \, mm^4$$



Steel Structures

Computation of Elastic Section Properties **(contd…)**

Solution

$$S_{top} = \frac{I_{tr}}{y_t} = 13033 \times 10^3\, mm^3$$

$$S_{bot} = \frac{I_{tr}}{y_b} = 5608 \times 10^3\, mm^3$$

Steel Structures

Service Load Stresses With & Without Shoring

For construction without shoring, the steel beam acting alone support the weight of forms, construction loads, weight of wet concrete and its self weight.

Once forms are removed and concrete has cured, the section will act in a composite way to resist all dead and live loads placed after the curing of concrete.

The stresses which were generated due to load of slab and self weight of beam before curing of concrete remain as such in the beam and composite action at service stage is not available.

The reason is that the slab has not deformed for these loads applied before the hardening of concrete with the beam, with zero corresponding stresses.

Steel Structures

Service Load Stresses With & Without Shoring

M_s = Moment due to self weight of beam and slab

M_w = Moment due to construction live load ≈ 200 kg/m^2

M_D = Moment due to imposed dead load

M_L = Moment due to live load

Without Shoring

Stage-I: Construction Stage, Resistance by Steel Beam Alone

Before Curing of Concrete

$$f_{\text{top of steel section}} = \frac{M_s + M_w}{S_t\,\text{(steel section alone)}}$$

$$f_{bot} = \frac{M_s + M_w}{S_b\,\text{(steel section alone)}}$$

Steel Structures

Service Load Stresses With & Without Shoring (contd…)

Without Shoring

Stage-II: Service Load Stage, Composite Action Present

After Curing of Concrete

$$f_{\text{top of slab}} = \frac{M_D + M_L}{nS_t\,(\text{composite})}$$

$$f_{\text{top of steel section}} = \frac{M_D + M_L}{I_{tr}/c} + \frac{M_s}{S_t\,(\text{for steel section only})}$$

Where c is the distance of top of steel section from N.A. of composite section

$$f_{bot} = \frac{M_D + M_L}{S_b\,(\text{composite})} + \frac{M_s}{S_b\,(\text{for steel section only})}$$

Steel Structures

Service Load Stresses With & Without Shoring (contd…)

With Shoring

In case of construction with shoring, when this temporary support is released, the dead load is supported by the composite action subjecting the slab to compressive loads.

This sustained load causes substantial creep and shrinkage in concrete parallel to the beams resulting in decrease in the concrete slab stresses with a corresponding increase in steel beam stresses.

Consequently, most of the dead load is again supported by the steel beams only, with the composite action really applicable to live loads.

However, at ultimate stage, plastic redistribution occurs and all loads are resisted by composite action regardless of whether shoring is used or not.

Steel Structures

$$f_{\text{top of slab}} = \frac{M_s + M_D + M_L}{nS_t\,(\text{composite})}$$

$$f_{\text{bot. of whole section}} = \frac{M_s + M_D + M_L}{S_b\,(composite)}$$

Steel Structures

Service Load Stresses With & Without Shoring (contd…)

Example: For the composite beam of previous example, determine the service load stresses considering:

a) Construction without shoring

b) Construction with shoring

The dead and live load moment $M_D + M_L$ to be superimposed after the concrete has hardened is 760 kN-m. The construction live load is 200 Kgs/m^2

Solution:

<u>Composite Section Properties</u>

Already calculated.

Steel Structures

Service Load Stresses With & Without Shoring (contd...)

Non Composite Section Properties

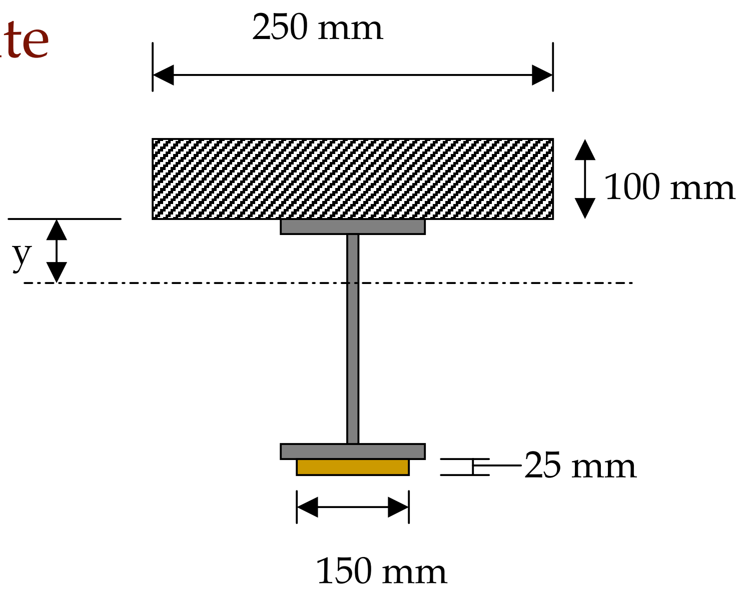
Calculated for the I-section and Steel plate

$$A = 13000 + 150 \times 25 = 16750 \text{mm}^2$$

$$\frac{\text{Wt}}{\text{m}} = \frac{16750}{1000^2} \times 7850 = 131.5 \text{kg/m}$$

$$\bar{y} = \frac{13000 \times {}^{603}\!/_{2} + 150 \times 250 \times (603 + 12.5)}{16750}$$

$$= 371.8 mm$$



Steel Structures

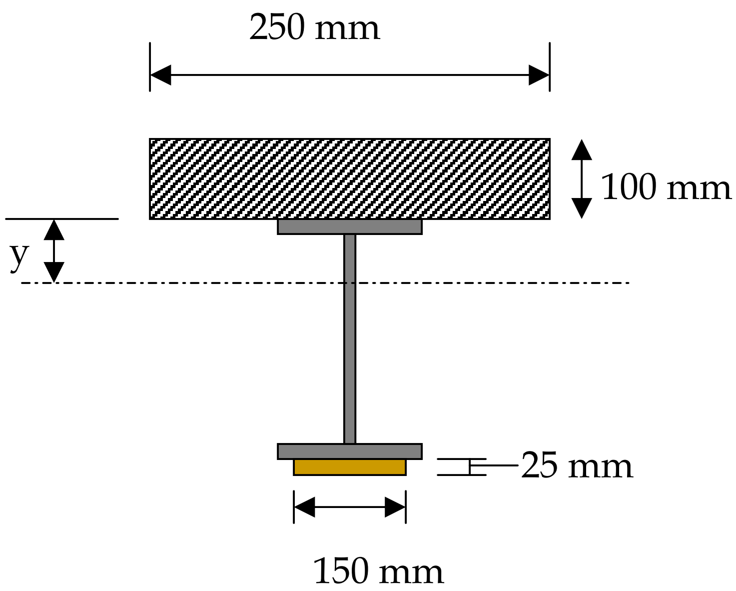
Service Load Stresses With & Without Shoring (contd…)

Non Composite Section Properties

$$I_s = 104896 \times 10^4$$

$$S_{\text{steel top}} = \frac{I_s}{\bar{y}} = 2821 \times 10^3 \, mm^3$$

$$S_{\text{steel bottom}} = \frac{I_s}{(25 + 603 - 371.8)} = 4094 \times 10^3 \, mm^3$$



Weight of concrete to be supported by one beam

$$= \frac{100}{1000} \times 2.5 \times 2400 \times \frac{9.81}{1000} = 5.886 \text{kN/m}$$

Steel Structures

Service Load Stresses With & Without Shoring (contd…)

Non Composite Section Properties

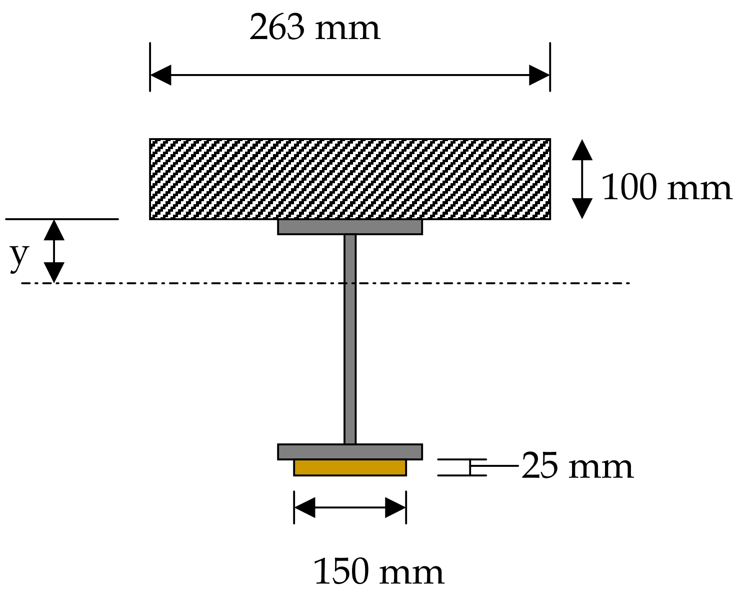
Weight of steel section

$$= 131.5 \times \frac{9.81}{1000} = 1.290\text{kN} / \text{m}$$

Total self weight

$$w_s = 5.886 + 1.290 = 7.176 kN / m$$

$$M_s = \frac{w_s L^2}{8} = \frac{7.176 \times 12^2}{8} = 129.17 kN - m$$



Steel Structures

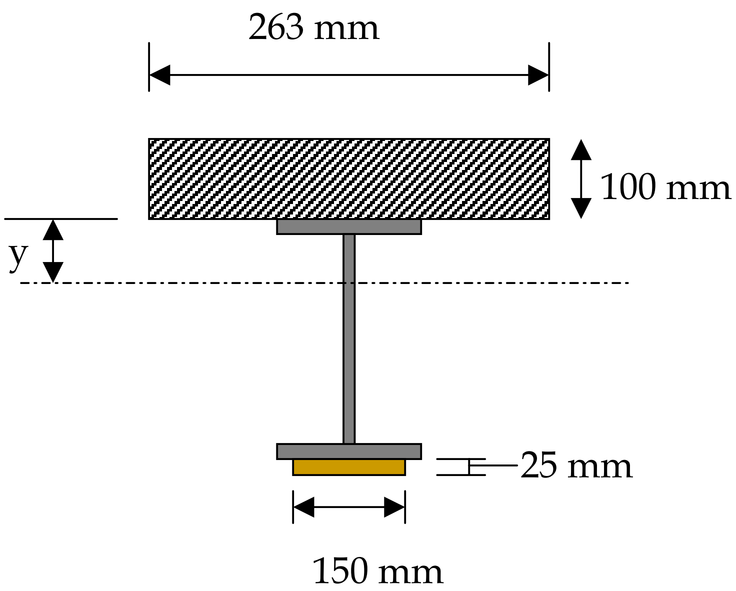
Service Load Stresses With & Without Shoring (contd…)

Non Composite Section Properties

Construction live load

$$w_w = 200 \times 2.5 \times \frac{9.8}{1000} = 4.91 kN/m$$

$$M_w = \frac{w_w L^2}{8} = 88.38 kN - m$$



Steel Structures

Service Load Stresses With & Without Shoring (contd…)

<u>Stresses Without Shoring</u>

Stage-I

$$f_{\text{top of steel section}} = \frac{M_s + M_w}{S_t}$$

$$f_{\text{top of steel section}} = \frac{(129.17 + 88.38) \times 10^6}{2821 \times 10^3} = 77.12 MPa$$

$$f_{\text{bottom of steel section}} = \frac{(129.17 + 88.38) \times 10^6}{4094 \times 10^3} = 53.14 MPa$$

Steel Structures

Service Load Stresses With & Without Shoring (contd…)

Stresses Without Shoring

Stage-II

$$f_{top...of...slab} = \frac{M_D + M_L}{nS_t}$$

$$f_{top...of...slab} = \frac{760 \times 10^6}{9.5 \times 13514 \times 10^3} = 5.92\text{MPa}$$

$$f_{top...of...steel...section} = \frac{M_D + M_L}{I_{tr}/c} + \frac{M_s}{S_t}$$

$$f_{top...of...steel...section} = \frac{760 \times 10^6}{289164 \times 10^4/114} + \frac{129.17}{2821 \times 10^3} = 75.7\text{MPa}$$

Steel Structures

Service Load Stresses With & Without Shoring (contd...)

Stresses Without Shoring

Stage-II

$$f_{\text{top of concrete slab}} = \frac{1}{n}\frac{M_D + M_L}{S_t\,(composite)} = \frac{1}{10}\times\frac{760\times10^6}{13033\times10^3} = 5.83\ \text{MPa}$$

$$f_{\text{bottom of steel section}} = \frac{M_D + M_L}{S_b\,(\text{composite})} + \frac{M_s}{S_b\,(\text{steel})} = \frac{760\times10^6}{5608\times10^3} + \frac{129.17\times10^6}{4094\times10^3} = 167.07\ \text{MPa}$$

$$f_{\text{top of steel section}} = \frac{M_D + M_L}{T_{tr}/c} + \frac{M_s}{S_t\,(\text{steel})} = \frac{760\times10^6}{285426\times10^4/119} + \frac{129.17\times10^6}{2821\times10^3} = 77.47\ \text{MPa}$$

$$167.07MPa > 0.66F_y = 165MPa$$

Not O.K.

Steel Structures

Service Load Stresses With & Without Shoring (contd…)

Stresses With Shoring

$$f_{\text{top (concrete)}} = \frac{M_s + M_D + M_L}{nS_t\,(\text{composite})} = 6.82MPa$$

$$f_{\text{bottom of whole section}} = \frac{M_s + M_D + M_L}{S_b\,(\text{composite})} = 158.55MPa$$

$$f_{\text{top of steel section}} = \frac{M_s + M_D + M_L}{I_{tr}/c} = 37.07MPa$$

Steel Structures

AISC I3-2

Strength of Composite Beams with Shear Connectors

1. Positive Moment Section

The design positive flexural strength, $\phi_b M_n$, and the allowable flexural strength, M_n/Ω_b, is to be determined for the limit state of yielding as given in the next slide.

$\phi_b = 0.9$(LRFD), $\Omega_b = 1.67$ (ASD)

Steel Structures

Design Strength of Fully Composite Section

1. Positive Moment Section

   i. For

$$\frac{h}{t_w} \leq 3.76\sqrt{E/f_{yf}} = 106.5 \quad \text{For A36 Steel}$$

M_n is determined from plastic stress distribution

   ii. For $$\frac{h}{t_w} > 3.76\sqrt{E/f_{yf}}$$

M_n is determined from the superposition of elastic stresses, considering the effects of shoring, for the limit state of yield moment.

Steel Structures

Strength Design (contd…)

Design Strength of Fully Composite Section

2. Negative Moment Section

Design strength is to be determined form steel section alone.

OR

Strength is calculated using plastic stress distribution using ϕ_b =0.9 or Ω_b =1.67, provided that:

- Steel beam is adequately braced compact section.
- Shear connectors connect the slab in the negative moment region
- Slab reinforcement parallel to the steel beam, within effective width of slab, is properly developed.

Steel Structures

Strength Design (contd…)

Positive Moment Strength Based on Plastic Stress Distribution

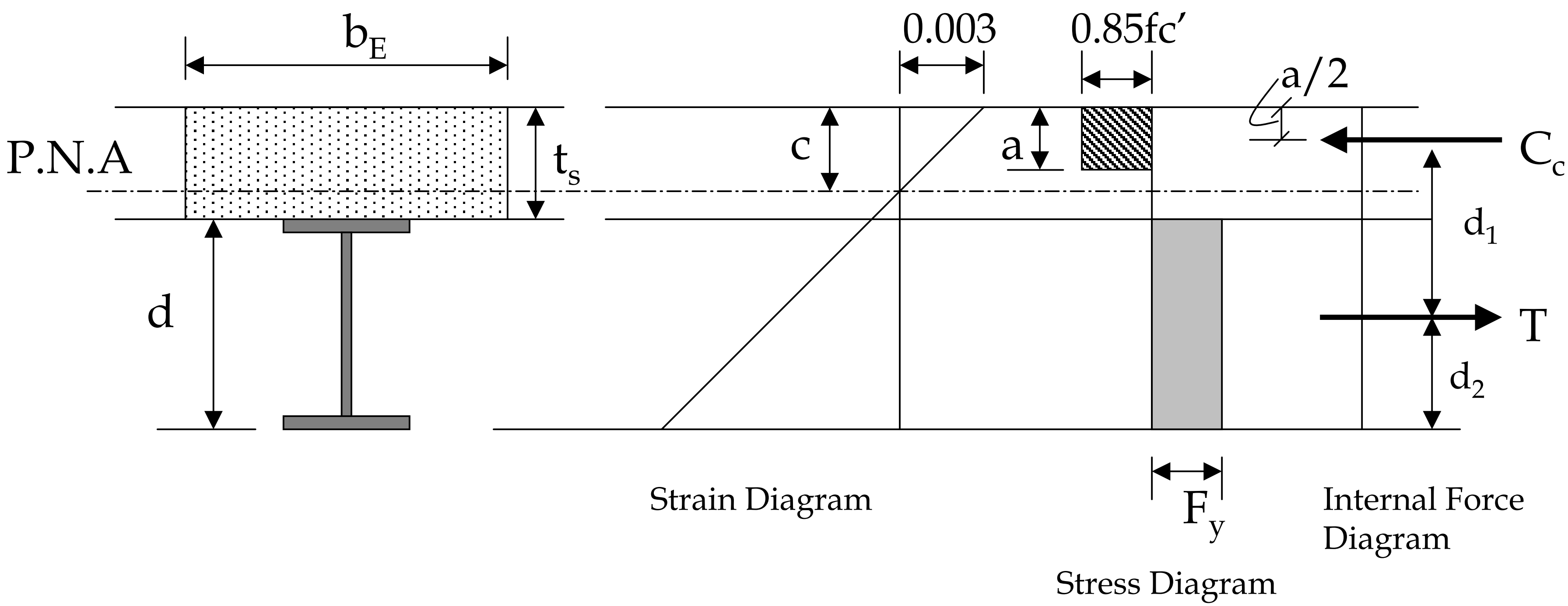
- Plastic N.A with in the slab
- Plastic N.A. within the beam
  - In the flange
  - In the web

Steel Structures

Strength Design (contd…)

Positive Moment Strength Based on Plastic Stress Distribution

Case-I Plastic N.A Within Slab



Steel Structures

Strength Design (contd…)

Positive Moment Strength Based on Plastic Stress Distribution

Case-I Plastic N.A with in the slab

$$C_c = 0.85 f_c' \times b_E \times a$$

$$T = A_s F_y$$

A_s = Area of steel section

Steel Structures

Strength Design (contd…)

Positive Moment Strength Based on Plastic Stress Distribution

For longitudinal equilibrium

$$C_c = T$$

$$0.85 f_c' \times b_E \times a = A_s F_y$$

$$a = \frac{A_s F_y}{0.85 f_c' \times b_E} \quad \text{and} \quad c = \frac{a}{\beta_1}$$

If $c \le t_s$, P.N.A is within the slab

If $c > t_s$, P.N.A is within the beam

Steel Structures

Strength Design (contd…)

Positive Moment Strength Based on Plastic Stress Distribution

$$M_n = C_c \times d_1 \qquad \text{or} \qquad T \times d_1$$

where $d_1 = \left(\frac{d}{2} + t_s - \frac{a}{2} \right)$

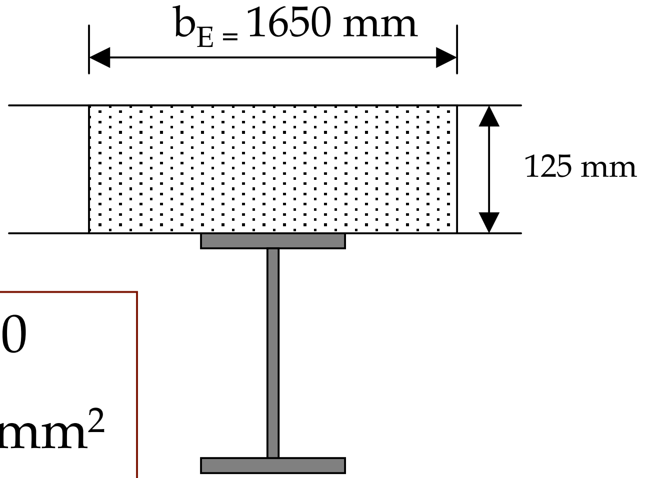
$$\boxed{M_n = A_s F_y \left(\frac{d}{2} + t_s - \frac{a}{2} \right)}$$

Steel Structures

Strength Design (contd…)

Example: Compute the design moment capacity of the given composite section assuming full composite behavior, f_c' = 20 MPa.

Solution



W 460 x 60

A = 7160 mm^2

h/tw = 51.0

d = 455mm

Steel Structures

Strength Design (contd…)

Assuming P.N.A within the slab

$$a = \frac{A_s F_y}{0.85 f_c' b_E}$$

$$= \frac{7610 \times 250}{0.85 \times 20 \times 1650} = 67.8$$

$$c = \frac{67.8}{0.85} \cong 80mm < t_s$$

P.N.A with in slab

Steel Structures

Strength Design (contd…)

$$\frac{h}{t_w} = 51.0 < 106.5$$

Plastic stress distribution can be used

$$\phi_b M_n = \phi_b A_s F_y \left(\frac{d}{2} + t_s - \frac{a}{2} \right)$$

$$\phi_b M_n = 0.9 \times 7610 \times 250 \left(\frac{455}{2} + 125 - \frac{67.8}{2} \right) \Big/ 10^6$$

$$\boxed{\phi_b M_n = 545.5 \ \ kN - m}$$

Concluded