EGCE 406: Bridge Design

Design of Slab for Bridge Deck

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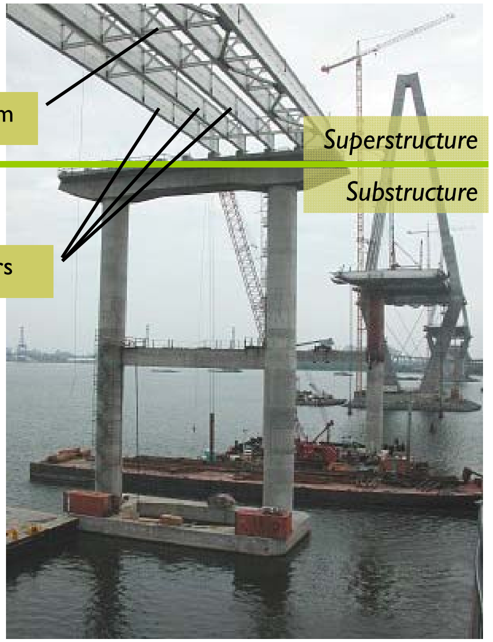
Outline

- Components of bridge Superstructure
- Bridge Deck
  - Types
  - Materials
- Design of RC Deck Slab
  - Slab thickness/ Minimum Cover
  - Analysis and Design Methods
    - Empirical Method
    - Strip Method
      - Analysis for Moment
      - Strip Widths
      - Slab Design for Primary Reinforcement
      - Secondary Reinforcement
      - Temperature and Shrinkage Reinforcement

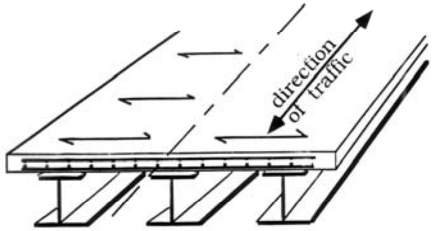
Bridge Superstructure

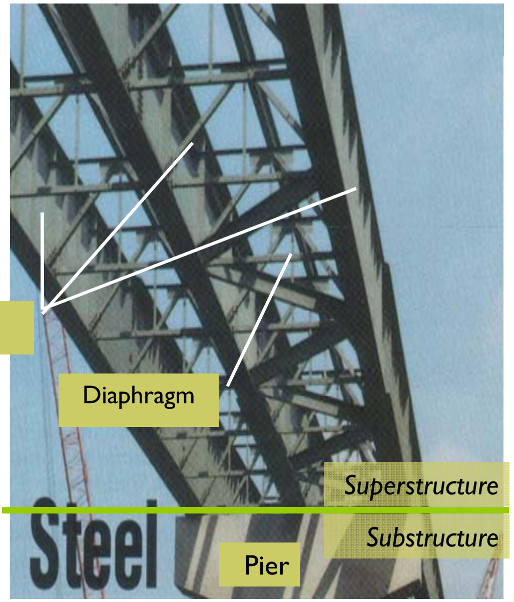
- Bridge superstructures consist of structural and nonstructural components
- Structural Components:
  - Girder (the big beam)
  - Roadway Deck (slab)
  - Floor Beam
  - Stringer
  - Diaphragm
- Nonstructural Components:
  - Asphalt Surface
  - Traffic Barriers
  - Railings
  - Signs, Lighting, Drainage etc…



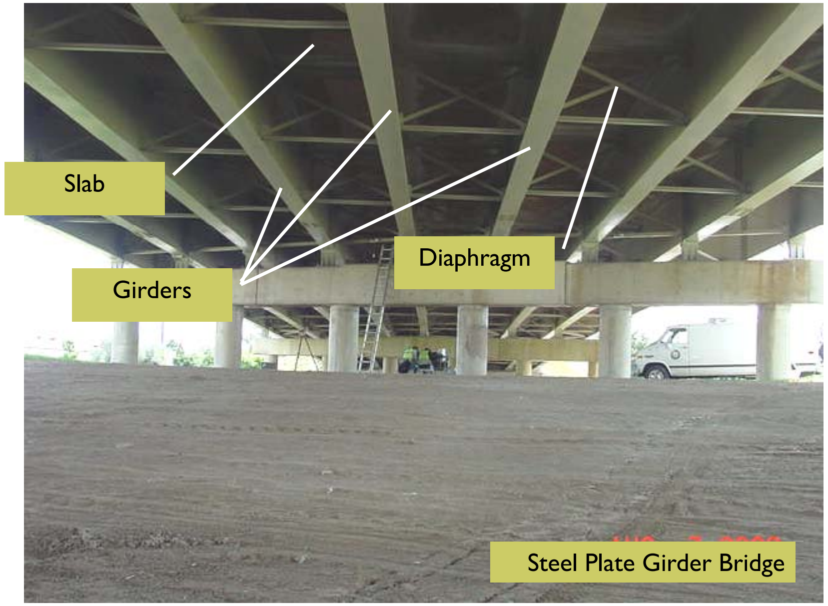
Bridge Superstructure – Girder Bridge

- For girder bridges, all girders rest on the pier – Thus, they all resist the load (almost) equally
- The slabs rest on the top of the girder
- Diaphragms are used to prevent girders from bending out of plane and to transfer lateral loads



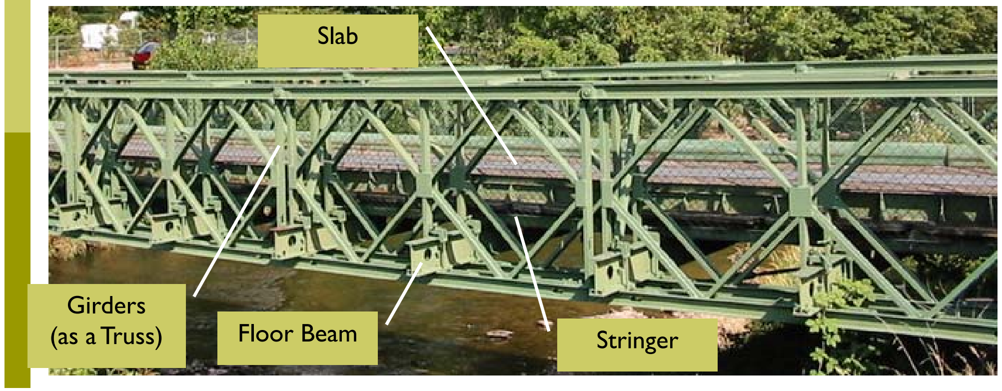


Bridge Superstructure – Girder Bridge

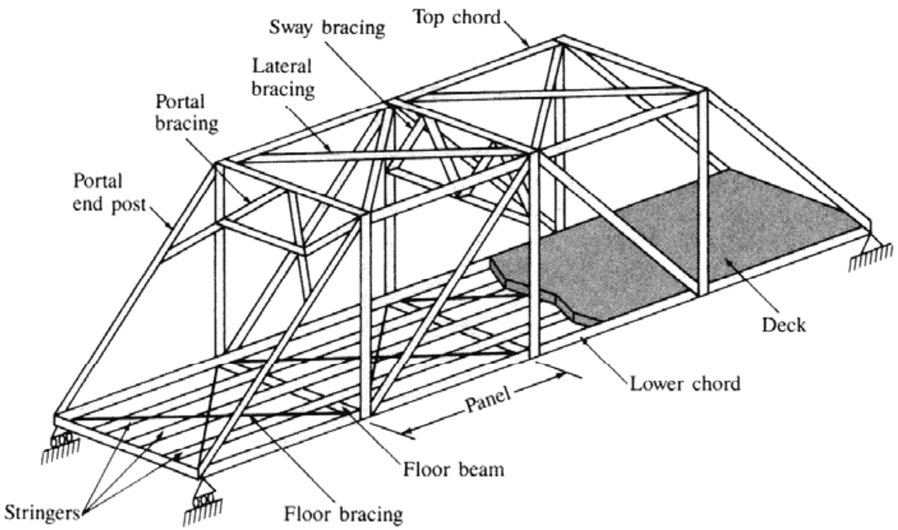


Bridge Superstructure – Truss Bridge

- For some types of bridge such as truss bridges, loads are transferred to the pier through two main structural components locating on the outer sides.
- Therefore, we need something in between to carry the slab (slab cannot span the whole roadway width!!! – it's too wide)
- We need *floor beams* and *stringer*
- Loads are transferred from Slab → Stringer → Floor Beam → Girder → Pier

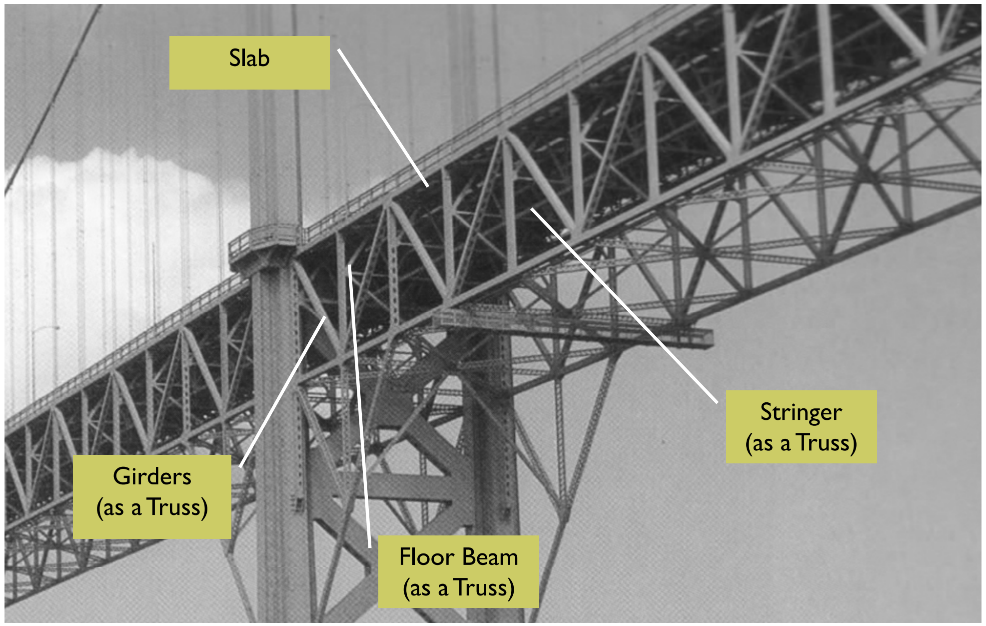


Bridge Superstructure – Truss Bridge



Components of Truss

Bridge Superstructure



Bridge Superstructure

- For some types of bridge (such as segmental construction), the girder and roadway deck are in one piece – We will not consider this type of construction here.

Bridge Deck

Types

Materials

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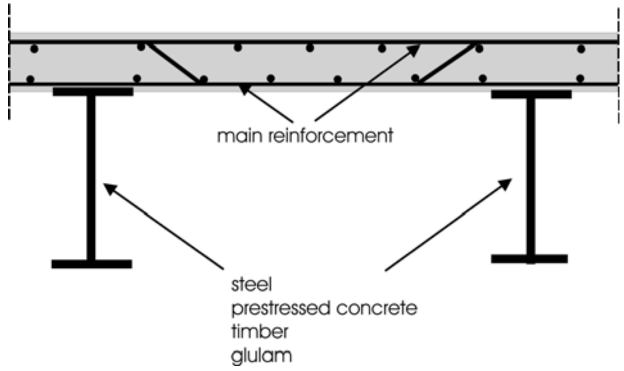
Types of Deck

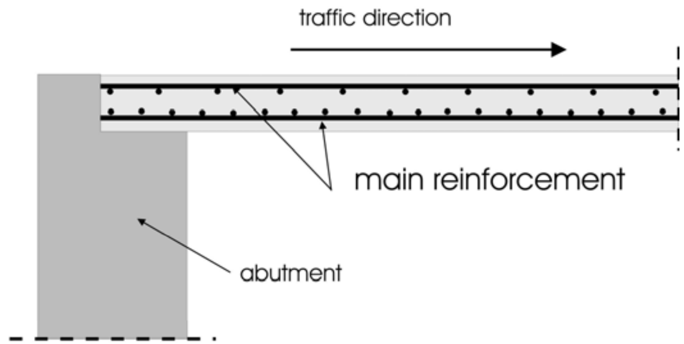
- Conventional reinforced concrete decks supported on girders
- Slab superstructures, cast-in-place, longitudinally reinforced
- Stay-in-place formwork decks

Types of Deck



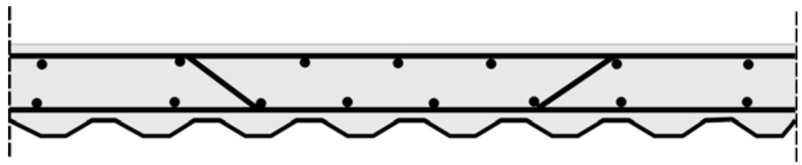
Conventional reinforced concrete decks supported on girders

Types of Deck



Slab superstructures, cast-in-place, longitudinally reinforced

Types of Deck

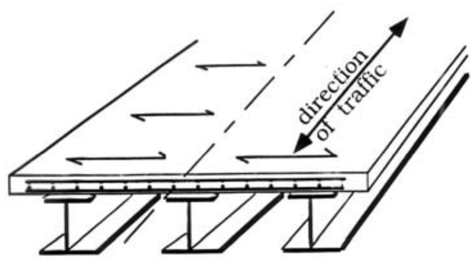


Stay-in-place formwork decks

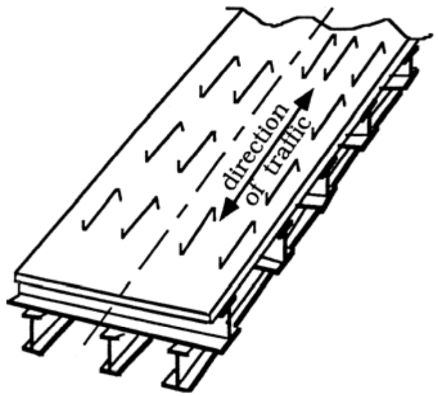
Types of Slab Reinforcement

- The deck slab may be designed as **One-Way Slab** with main reinforcement perpendicular or parallel to the traffic direction

- Main reinforcement perpendicular to traffic
  - Found in girder bridges
  - Girder Spacing must not be too large



- Main reinforcement parallel to traffic
  - Slab on floor beams



Materials: Concrete

- Minimum compressive strength, f'_c = 28 MPa at 28 days (tested on 150 x 300 mm standard cylinders)
- Two classes of concrete specified:
  - Class A (generally used for all structural elements)
  - Class AE (air-entrained, suitable for freeze/thaw cycles, exposure to deicing salts and saltwater)
- Water-Cement Ratio (*W/C*) should not exceed 0.49 for Class A (for both classes)
- Modulus of elasticity, E_c (for concrete unit weight γ_c between 1440-2500 kg/m3)

$$E_c = 0.043\, \gamma_c\, (f'_c)^{0.5}\ ;\ f'_c \text{ in MPa}$$

Materials: Reinforcing Steel

- In general, reinforcing bars shall be deformed (except wires used for spirals, hoops and wire fabric).
- Modulus of elasticity, E_s = 200,000 MPa
- Minimum Yield strength 420 MPa (can be less with approval of the Owner)
- Maximum Yield strengths 520 MPa

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Type	Grade	Fy (ksc) Minimum	Fu (ksc) Minimum	Ultimate Strain (%) Minimum
Round Bar	SR 24	**2400**	3900	21
Deformed Bar	SD 30	**3000**	4900	17
	SD 40	**4000**	5700	15
	SD 50	**5000**	6300	13

Design of RC Deck Slab

Slab Thickness/ Minimum Cover

Empirical Design Method

Strip Method

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Minimum Slab Thickness

- Absolute Minimum Thickness = 175 mm (9.7.1.1)
- Traditionally, the minimum thickness was specified in AASHTO *Standard Specification* for the purpose of deflection control
- However, AASHTO LRFD removes all the requirements for maximum deflection and leaves it to the judgment of the designer. Therefore, the thickness of slab for deflection control is now optional. (2.5.2.6.3)

Table 2.5.2.6.3-1 - Traditional Minimum Depths for Constant Depth Superstructures

Superstructure		Minimum Depth (Including Deck) When variable depth members are used, values may be adjusted to account for changes in relative stiffness of positive and negative moment sections	
Material	Type	Simple Spans	Continuous Spans
Reinforced Concrete	Slabs with main reinforcement parallel to traffic	$\frac{1.2(S+3000)}{30}$	$\frac{S+3000}{30} \geq 165\ mm$
	T-Beams	0.070L	0.065L
	Box Beams	0.060L	0.055L
	Pedestrian Structure Beams	0.035L	0.033L
Prestressed Concrete	Slabs	0.030L ≥ 165 mm	0.027L ≥ 165 mm
	CIP Box Beams	0.045L	0.040L
	Precast I-Beams	0.045L	0.040L
	Pedestrian Structure Beams	0.033L	0.030L
	Adjacent Box Beams	0.030L	0.025L
Steel	Overall Depth of Composite I-Beam	0.040L	0.032L
	Depth of I-Beam Portion of Composite I-Beam	0.033L	0.027L
	Trusses	0.100L	0.100L

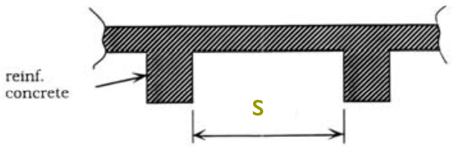
S = slab span (mm)
L = span length (mm)

Reinforced Concrete Slab

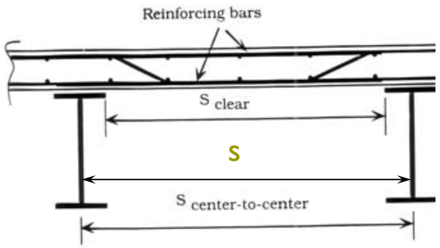
Prestressed Concrete Slab

Slab Span "S"

- Slab span (s) is determined from
  - Face-to-Face distance for slab monolithic with beam (i.e. cast into one piece)

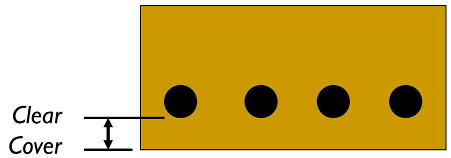


  - For composite slab on steel or concrete girder, the distance between the face of the webs



Minimum Cover of Reinforcement

- The clear cover is the distance from the top or bottom of the section to the outer edge of steel reinforcement (not at the center!)



- Minimum cover is specified so that there is enough concrete to cover the steel and prevent the steel from corrosion
- A large covering is required in corrosive environments

Corrosion of steel in RC bridge deck

Minimum Cover

- Minimum clear cover for reinforcing steel and prestressing steel (5.12.3)
- Adjustments for Water-Cement Ratio:
  - For W/C < 0.4, the concrete tends to be dense; therefore can use only 80% of the value in the table (i.e. multiply by **0.8**)
  - For W/C > 0.5, the concrete tends to be porous; the value in the table must be increase by 20% (i.e. multiply by **1.2**)
- If there is no initial overlay of wearing surface, should add another 10 mm to the clear cover on the **top surface** to allows for some wear and tear

Table 5.12.3-1 - Cover for Unprotected Main Reinforcing Steel (mm)

SITUATION	COVER (mm)
Direct exposure to salt water	100
Cast against earth	75
Coastal	75
Exposure to deicing salts	60
Deck surfaces subject to tire stud or chain wear	60
Exterior other than above	50
Interior other than above	
• Up to No. 36 bar	40
• No. 43 and No. 57 bars	50
Bottom of cast-in-place slabs	
• Up to No. 36 bar	25
• No. 43 and No. 57 bars	50
Precast soffit form panels	20
Precast reinforced piles	
• Noncorrosive environments	50
• Corrosive environments	75
Precast prestressed piles	50
Cast-in-place Piles	
• Noncorrosive environments	50
• Corrosive environments	
- General	75
- Protected	75
• Shells	50
• Auger-cast, tremie concrete, or slurry construction	75

Analysis and Design Methods

- Methods for designing slab
  - Empirical Method (9.7.2)
  - Approximate Method (Strip Method) (4.6.2.1)
  - Refined Method including
    - Classical force and displacement methods
    - Yield Line Method
    - Finite Element Analysis
    - Etc…

Empirical Method

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Empirical Method

- Empirical method is based on the test data (this is why it is called "empirical") that the primary mechanism of the bridge deck under wheel load is **not flexure** but rather complex arch-action and punching shear
- Empirical method of design can be only used for **concrete isotropic decks** (having two identical layers of reinforcement, perpendicular to and in touch with each other) **supported on longitudinal components**.
- If the required conditions are satisfied, we can get the area of steel directly.

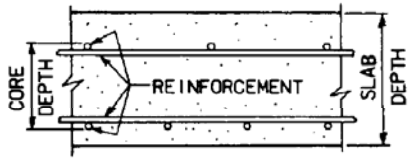
- ***Conditions that must be satisfied in order to use the Empirical Method***

  - cross-frames or diaphragms are used throughout the cross-section at lines of support
  - the supporting components (girders) are made of steel and/or concrete
  - the deck is fully cast-in-place (no precast!) and water cured
  - the deck has uniform depth

Empirical Method

- ***Conditions that must be satisfied in order to use the Empirical Method (Continued)***

  - core depth of the slab is not less than 100 mm



  - the effective length (or slab span "s") ≤ 4.1 m
  - the ratio of effective length (S) to design depth is between 6 and 18
  - the minimum depth of the slab is 175 mm, excluding the wearing surface
  - the specified 28-day f'_c of the deck concrete is > 28 MPa
  - the deck is made composite with the supporting structural components.

Empirical Method

Reinforcement Requirement for Empirical Method

This does not depend on the slab thickness!

- The minimum amount of reinforcement shall be:
  - 0.570 mm^2/mm of steel for each bottom layer
  - 0.38 mm^2/mm of steel for each top layer
- Spacing of steel must be ≤ 450 mm
- 4 layers of isotropic reinforcement (same in all directions) shall be provided

Strip Method

Analysis for Moment
Strip Widths
Slab Design for Primary Reinforcement
Secondary Reinforcement
Temperature and Shrinkage Reinforcement

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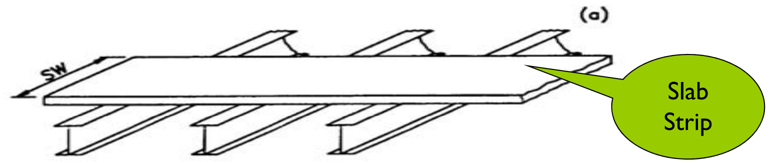
Strip Method

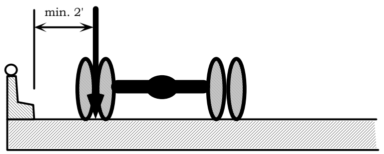
- Strip method is an approximate analysis method in which the deck is subdivided into strips perpendicular to the supporting components (girder)



- The slab strip is now a continuous beam and can be analyzed using classical beam theory and designed as a one-way slab

Strip Method - Procedures

- Slab is modeled as beams and with girders as supports
- Wheel loads are placed (transversely) on this slab to produced the maximum effect



- Determine the maximum moment (M+ and M-) based on classical beam theory
- Determine the width of strip for each M+ and M- case
- Divide the maximum moment by the width of strip to get the moment per 1 unit width of slab
- Design an RC slab for this moment – the reinforcement required will be for 1 unit width of slab (this is for the *primary* direction)
- The reinforcement in the *secondary* direction may be taken as a percentage of those in the primary direction

Strip Method – Width of Strip

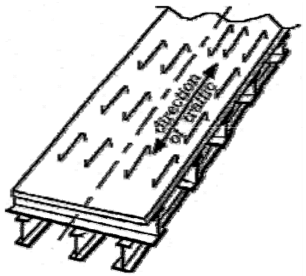
Table 4.6.2.1.3-1 - Equivalent Strips

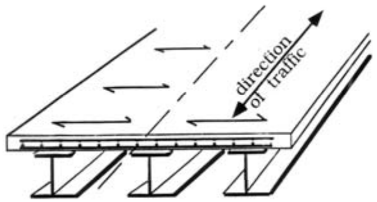
TYPE OF DECK	DIRECTION OF PRIMARY STRIP RELATIVE TO TRAFFIC	WIDTH OF PRIMARY STRIP (mm)
Concrete:		
• Cast-in-place	Overhang	1140 + 0.833X
	Either Parallel or Perpendicular	+M: 660 + 0.55S −M: 1220 + 0.25S
• Cast-in-place with stay- in-place concrete formwork	Either Parallel or Perpendicular	+M: 660 + 0.55S −M: 1220 + 0.25S
• Precast, posttensioned	Either Parallel or Perpendicular	+M: 660 + 0.55S −M: 1220 + 0.25S

S = spacing of supporting components (FT)
X = distance from load to point of support (FT)
+M = positive moment
-M = negative moment

Strip Method – Width of Strip

- We can obtain the width of equivalent interior strips from the table, which depends on the direction of slab relative to traffic (parallel or perpendicular)
  - When deck span is parallel to traffic, strip width must be less than 3600 mm (that's the design lane width!) (if it is greater, then another provision applies, see 4.6.2.3)
  - When deck span is perpendicular to traffic, there is no limit on strip width





- The strips should be analyzed by classical beam theory. The moment obtained is divided by the strip width to get moment per unit width

Strip Method – Analysis for Moments

- Deck slab is designed for maximum positive and negative bending moments
- These moments are considered as representative and may be used for all panels.
- Need to consider LL placement to get the maximum effect
- Primary reinforcement is calculated using these moments

3.6.1.3.3 Design Loads for Decks, Deck Systems, and the Top Slabs of Box Culverts

The provisions of this article shall not apply to decks designed under the provisions of Article 9.7.2, Empirical Design Method.

Where the approximate strip method is used to analyze decks and top slabs of box culverts, force effects shall be determined on the following basis:

- Where primary strips are transverse and their span does not exceed 4600 mm - the transverse strips shall be designed for the wheels of the 145 000 N axle.
- Where primary strips are transverse and their span exceeds 4600 mm - the transverse strips shall be designed for the wheels of the 145 000 N axle and the lane load.
- Where primary strips are longitudinal - the **longitudinal** strips shall be designed for all loads specified in Article 3.6.1.2, including the lane load.

Strip Method – Simplified Procedure

- The previous procedure is quite complex for routine designs (need to consider transverse placements of live loads to get the maximum effect). Therefore, AASHTO offers a simplified procedure to determine maximum M+ and M- directly!!!

- Slab is modeled as beams and with girders as supports
- Determine the maximum M+ and M- from table (see next page) based on the slab span – this is the LL+IM moment per mm! (multiply by 1000 to get per m)
- M+ and M- from DL/DW are relatively small and may be approximated as $M=wl^2/c$ where c ~ 10-12
- Design an RC slab for this moment – the reinforcement required will be for 1 mm of slab (this is for the primary direction)
- The reinforcement in the secondary direction may be taken as a percentage of those in the primary direction

Strip Method – Design Aid

Table A4-1 - Maximum Live Load Moments Per Unit Width, N·mm/mm

		NEGATIVE MOMENT						
S	Positive	Distance from CL of Girder to Design Section for Negative Moment						
mm	Moment	0.0 mm	75 mm	150 mm	225 mm	300 mm	450 mm	600 mm
1300	21130	11720	10270	8940	7950	7150	6060	5470
1400	21010	14140	12210	10340	8940	7670	5960	5120
1500	21050	16320	14030	11720	9980	8240	5820	5250
1600	21190	18400	15780	13160	11030	8970	5910	4290
1700	21440	20140	17290	14450	12010	9710	6060	4510
1800	21790	21690	18660	15630	12930	10440	6270	4790
1900	22240	23050	19880	16710	13780	11130	6650	5130
2000	22780	24260	20960	17670	14550	11770	7030	5570
2100	23380	26780	23190	19580	16060	12870	7410	6080
2200	24040	27670	24020	20370	16740	13490	7360	6730
2300	24750	28450	24760	21070	17380	14570	9080	8050
2400	25500	29140	25420	21700	17980	15410	10870	9340
2500	26310	29720	25990	22250	18510	16050	12400	10630
2600	27220	30220	26470	22730	18980	16480	13660	11880
2700	28120	30680	26920	23170	19420	16760	14710	13110

Strip Method – Design Aid

2800	29020	31050	27300	23550	19990	17410	15540	14310
2900	29910	32490	28720	24940	21260	18410	16800	15480
3000	30800	34630	30790	26960	23120	19460	18030	16620
3100	31660	36630	32770	28890	23970	21150	19230	17780
3200	32500	38570	34670	30770	26880	22980	20380	18910
3300	33360	40440	36520	32600	28680	24770	21500	20010
3400	34210	42250	38340	34430	30520	26610	22600	21090
3500	35050	43970	40030	36090	32150	28210	23670	22130
3600	35870	45650	41700	37760	33810	29870	24700	23150
3700	36670	47250	43310	39370	35430	31490	25790	24140
3800	37450	48820	44880	40940	37010	33070	27080	25100
3900	38230	50320	46390	42460	38540	34600	28330	25550
4000	38970	51790	47870	43950	40030	36110	29570	26410
4100	39710	53190	49280	45370	41470	37570	30770	27850
4200	40420	54560	50670	46770	42880	38990	31960	28730
4300	41120	55880	52000	48130	44250	40380	33130	29570
4400	41800	57150	53290	49440	45580	41720	34250	30400
4500	42460	58420	54580	50740	46900	43060	35380	31290
4600	43110	59620	55800	51980	48160	44340	36700	32360

IM and multiple presence factors are included in this table

Slab Design

- Recall RC Design

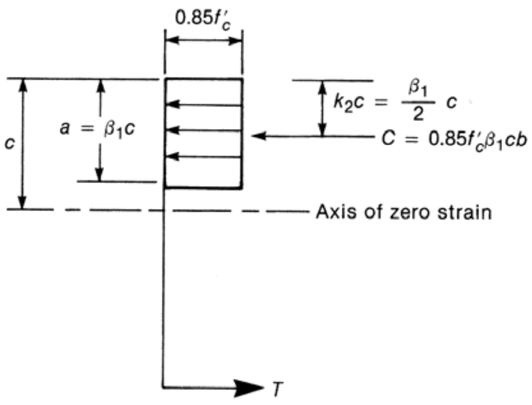


Fig. 4–14
Equivalent rectangular stress block.

- M_n = (C or T)*Moment Arm
- For under-reinforced beams
- $M_n = A_s f_y(d-a/2)$
- $M_n = (0.85f'_c ba)(d-a/2)$
- Note that $A_s f_y = 0.85f'_c ba$
- For over-reinforced beam, the steel does not yield
- $M_n = A_s f_s(d-a/2)$; $f_s=\varepsilon_s E_s$
- $M_n = (0.85f'_c ba)(d-a/2)$

Slab Design

- In the case of deck design only one of five strength load combinations needs to be investigated:
  - STRENGTH I
  - This limit state is the basic load combination relating to normal vehicular use of the bridge (without wind)
- $U = \eta\ [1.25\ DC + +1.5\ DW + 1.75\ (LL + IM)]$
- Resistance factors for strength limit state:
  - 0.90 for flexure and tension of reinforced concrete
  - 1.00 for flexure and tension of prestressed concrete

$$\sum \eta\gamma_i Q_i \leq \Phi R_n$$

Strip Method – Secondary Reinf.

- Reinforcement in the *secondary* direction may be determined as a percentage of that in the *primary* direction

9.7.3.2 DISTRIBUTION REINFORCEMENT

Reinforcement shall be placed in the secondary direction in the bottom of slabs as a percentage of the primary reinforcement for positive moment as follows:

- For primary reinforcement parallel to traffic:

  $1750/\sqrt{S} \leq 50$ percent

- For primary reinforcement perpendicular to traffic:

  $3840/\sqrt{S} \leq 67$ percent

where:

S = the effective span length taken as equal to the effective length specified in Article 9.7.2.3 (mm)

Strip Method

- Note that the primary and secondary reinforcement is per unit width of slab (say 1 m)
- There is also a minimum reinforcement requirement for temperature and shrinkage

$$A_s > 0.75\ A_g/f_y$$

- We can calculate this for a unit width; i.e.
  Ag = 1.00*slab thickness

5.10.8 Shrinkage and Temperature Reinforcement

5.10.8.1 GENERAL

Reinforcement for shrinkage and temperature stresses shall be provided near surfaces of concrete exposed to daily temperature changes and in structural mass concrete. Temperature and shrinkage reinforcement shall be added to ensure that the total reinforcement on exposed surfaces is not less than that specified herein.

5.10.8.2 COMPONENTS LESS THAN 1200 mm THICK

Reinforcement for shrinkage and temperature may be in the form of bars, welded wire fabric, or prestressing tendons.

For bars or welded wire fabric, the area of reinforcement in each direction shall not be less than:

$$A_s \geq 0.75\ A_g/f_y \quad (5.10.8.2\text{-}1)$$

where:

A_g = gross area of section (mm^2)

f_y = specified yield strength of reinforcing bars (MPa)

The steel shall be equally distributed on both faces; however, for members 150 mm or less in thickness, the steel may be placed in a single layer.

Shrinkage and temperature reinforcement shall not be spaced farther apart than 3.0 times the component thickness or 450 mm.