UNIT 19 BRIDGES

Structure

19.1 Introduction
Objectives

19.2 IRC Loading
19.2.1 Class AA Loading
19.2.2 Class 70R Loading
19.2.3 Class A Loading
19.2.4 Class B Loading
19.2.5 Impact Effect
19.2.6 Selection of Loading for the Design of a Bridge
19.2.7 Arrangement of Live Load on a Bridge

19.3 Components of Culverts and T-beam Bridges

19.4 Analysis of Slabs Carrying Wheel Loads
19.4.1 Effective Width Method
19.4.2 Pigeaud's Coefficients

19.5 Culverts

19.6 T-beam Bridges
19.6.1 Proportioning
19.6.2 Analysis of Longitudinal Girder

19.7 Summary

19.8 Answers to SAQs

19.1 INTRODUCTION

A bridge is a structure providing passage over an obstacle without closing the way beneath. The required passage may be for a road, a railway, pedestrians, a canal or a pipe line. The obstacle to be crossed may be a river, a road, a railway or a valley.

According to the material of construction of the super-structure, bridges can be classified as timber, masonry, steel, reinforced concrete, prestressed concrete, composite, or aluminium bridges. Reinforced Concrete (RC) is now a universally used material for the construction of bridges because of its durability, economy, ease of construction, and its adaptability to create pleasing designs. Reinforced concrete is well suited for the construction of highway bridges in the small and medium span range. The usual types of reinforced concrete bridges are :

- Slab bridges (culverts),
- Girder and slab (T-beam) bridges,
- Hollow girder bridges,
- Balanced cantilever bridges,
- Rigid frame bridges,
- Arch bridges, and
- Bow-string girder bridges.

The selection of type of bridge for a certain location depends mostly on cost considerations and also on natural conditions, e.g. nature of foundations, water-way to be provided and difficulties of construction. Experience is invaluable in selecting the proper type of bridge. Generally speaking, the cost of a bridge will be least when the length of spans is so chosen that the cost of main girders in one span is equal to the cost of pier and its foundation.

First two types of RC bridges will be covered in this unit. The design will be confined only to the design of super-structure. The design criteria as laid down by the Indian Road

Congress (IRC) Code of Practice will be generally followed. The relevant extracts of the code are given in the text.

Objectives

After studying this unit you should be able to design

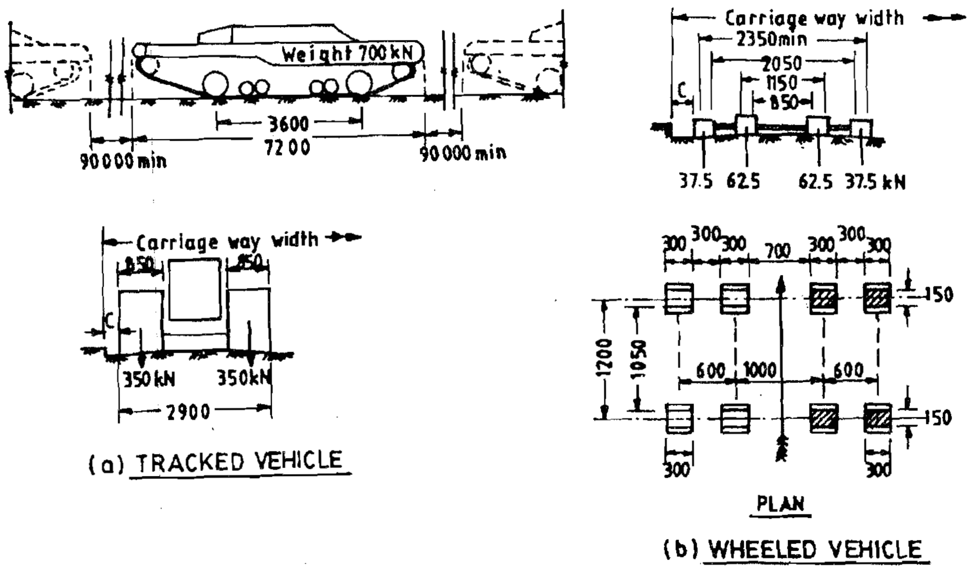
- reinforced concrete deck slab of slab culverts for IRC loading, and
- the super-structure of reinforced concrete T-beam bridges for IRC loading.

19.2 IRC LOADING

Vehicles crossing a bridge are the live loads that are transient in nature. These loads can not be estimated precisely, they may also change in future, and the designer has very little control over them once the bridge is opened to traffic. However, hypothetical loadings that are reasonably realistic need to be evolved and specified to serve as design criteria. IRC, for these reasons, has standardized the live loads to be considered in the design of a highway bridge. The loads have been classified under four categories namely Class AA, Class 70R, Class A, and Class B loading. For simplifying the analysis, the contact area of wheels with the pavement has been assumed to be rectangular. The four categories of IRC live loads are described in the subsequent sub-sections.

19.2.1 Class AA Loading

There are two sub categories in this loading namely tracked vehicle of 700 kN and wheeled vehicle of 400 kN with dimensions shown in Figure 19.1. The tracked vehicles represent battle tanks that move on chains.



Clear Carriage Way	Minimum Value of C (cm)
Single Lane Bridge	
3.8 moment and above	30
Multiple Lane Bridge	
Less than 5.5·moment	60
5.5 m and above	120

C→ Minimum clear distance of wheel from inner edge of the kerb

Figure 19.1 : IRC Class AA Loading

19.2.2 Class 70R Loading

This loading consists of a tracked vehicle of 700 kN or a wheeled vehicle of total load of 1000 kN. The tracked vehicle as shown in Figure 19.2 is similar to that of Class AA. The wheeled vehicle as shown in Figure 19.2 is 15.22 m long and has seven axles with loads totaling 1000 kN.

This loading was originally included in the Appendix to the bridge code for use for the rating of existing bridges. In recent years, there is an increasing tendency to specify this loading in place of Class AA loading.

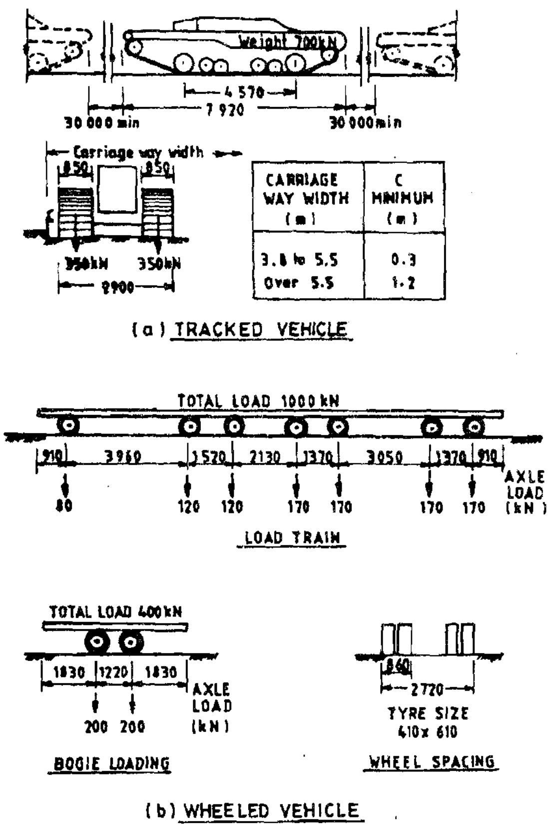


Figure 19.2 : IRC Class 70R Loading

19.2.3 Class A Loading

Class A loading consists of a train of wheel loads carrying a driving vehicle and two trailers as shown in Figure 19.3.

19.2.4 Class B Loading

This loading also comprises a driving unit and two trailers similar to that of Class A loading but with smaller axle loads as shown in Figure 19.3.

19.2.5 Impact Effect

Moving vehicles produce higher stresses than those which would be caused if the vehicles are stationary. It is mainly because of the impact caused by vehicles during motion on an uneven surface of the road. In order to take into account the increase in stresses due to dynamic action and still proceed with the simpler statistical analysis, an impact allowance is made for impact.

The impact allowance is expressed as a function of the percentage of the applied live load, and is computed as below :

(a) For IRC Class A or B Loading

$I = 0.5$ for $L \leq 3$ m

$I = \dfrac{4.5}{6 + L}$ for $3 \text{ m} \leq L \leq 45$ m

$I = 0.088$ for $L \geq 45$ m

where, I is the impact fraction factor, and L is the span in meters.

(b) For IRC Class AA or 70R Loading

Tracked Vehicles :

$I = 0.25$ for $L \leq 5$ m

$I = 0.1 + 0.0375\,(9 - L)$ for $5\text{ m} \leq L \leq 9\text{ m}$

$I = 0.088 + (45 - L)/3000$ for $9\text{ m} \leq L \leq 45\text{ m}$

$I = 0.888$ for $L \geq 45$ m

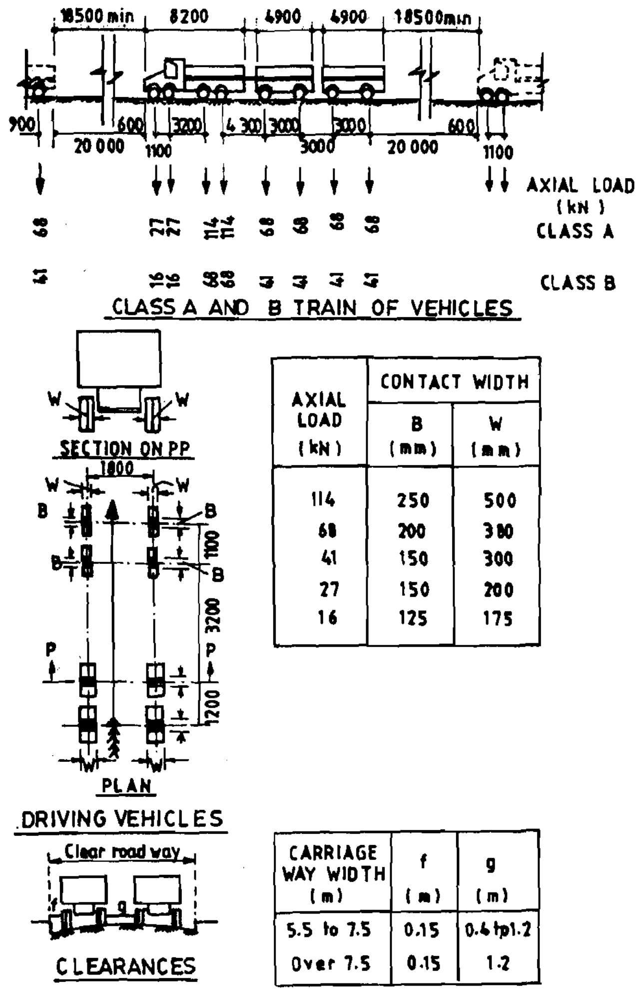
Wheeled Vehicles :

$I = 0.25$ for $L \leq 12$ m

$I = \dfrac{4.5}{6 + L}$ for $12\text{ m} \leq L \leq 45\text{ m}$

$I = 0.088$ for $L \geq 45$ m

The impact fraction factor, I, can alternatively be read from Figure 19.4.



AXIAL LOAD (kN)	CONTACT WIDTH B (mm)	CONTACT WIDTH W (mm)
114	250	500
68	200	380
41	150	300
27	150	200
16	125	175

CARRIAGE WAY WIDTH (m)	f (m)	g (m)
5.5 to 7.5	0.15	0.4 to 1.2
Over 7.5	0.15	1.2

Figure 19.3 : IRC Class A and B Loadings

19.2.6 Selection of Loading for the Design of a Bridge

The following points should be considered while deciding the loading to be considered in the design of a bridge.

- The Class AA or 70R loading is to be adopted for bridges located within certain specified municipal localities and along specified highways. Normally structures on National Highways and State Highways are provided for these loading. Structures designed for Class AA or 70R loading should also be checked for Class A loading, since under certain conditions, more severe stresses may be obtained under Class A loading. Class 70R loading should only be considered when it is specifically specified.

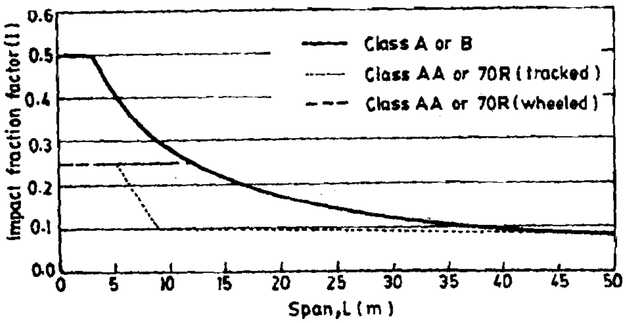


Figure 19.4 : Impact Fraction Factor for RC Highway Bridges

- Class A loading is to be normally adopted on all roads on which permanent bridges or culverts are constructed.
- Class B loading is to be adopted for temporary structures, timber bridges, and for bridges in specified areas.

19.2.7 Arrangement of Live Load on a Bridge

The loading should be so arranged as to produce maximum BM and SF in the component under consideration. In deciding the arrangement of vehicles on a bridge, the following guidelines should be followed :

- The vehicles are to be aligned so as to travel parallel to the length of the bridge.
- When these vehicles are on the bridge, no other live load need be considered as acting over the unoccupied area.
- Vehicles in adjacent lanes are to be assumed moving in a direction producing maximum stresses.
- For multi-lane bridges and culverts, single train of Class AA tracked or wheeled vehicles shall be considered for every two-lane width.

SAQ 1

(a) List the IRC codes to be used while designing road bridges on a National Highway.

(b) Describe the IRC standard loadings and indicates the conditions under which each should be used.

(c) What is the significance of Impact Factor and how is it estimated?

19.3 COMPONENTS OF CULVERTS AND T-BEAM BRIDGES

The components of a culvert with reinforced concrete deck slab are the following :

- Deck slab
- Wearing coat, kerbs, hand rails etc.
- Abutments and wing walls
- Foundations

The super-structure of a T-beam bridge consists of the following components :

- Deck slab
- Wearing coat, kerbs, hand rails, footpaths, if provided

- Cantilever portion
- Longitudinal girders
- Cross beams

Standard details are used for kerbs and hand rails. Wearing coat can be of asphaltic concrete or cement concrete of 1 : 1.5 : 3 mix with an average thickness of 75 mm.

19.4 ANALYSIS OF SLABS CARRYING WHEEL LOADS

The live load on a bridge consists of wheel loads acting on the contact area of wheels of a standard IRC vehicle with the surface of the road. This type of loading is not easy to deal with while analysing bending moment and shear force in the deck slab because of its highly indeterminate nature. The use of elastic theory for varying position of a wheel load acting on a slab results in equations whose solution is very time consuming and impracticable. The analysis is done in a semi-empirical manner by modifying the results of elastic analysis suitably. There are, in general, three approaches employed for this purpose, namely

(a) effective width method,

(b) use of Pigeaud's coefficients, and

(c) Westergaard's method.

The first two approaches, normally used in practice, have been described here.

19.4.1 Effective Width Method

This method is applicable for the following two support conditions of a rectangular slab :

- Slab simply supported on two opposite edges
- Slab supported on all four edges and aspect ratio (B / L) very large

When a point load acts on a slab, it deflects forming a saucer. Since the slab gets curvature in the plane of the span as well as at right angles to it, it is obvious that bending moments in the slab are created in the plane of span as well as normal to it. It is not only the strip of the slab immediately below the load that bears it but even strips on either side of the load take part in supporting the load. The bending moments are, therefore, much smaller than they would be if only the strip of slab below the load was acting singly. It is therefore assumed that the load is supported by a certain width of slab, known as the effective width and the load is assumed to be distributed over this entire width thus converting the indeterminate problem into a determinate one. If the effective width is known, then bending moments along the span can be easily calculated statically. However, Bending Moment (BM) at right angles to the span are not given by this method but taken empirically as the sum of 20% of the BM due to dead load and 30% of the BM due to live load calculated along the span.

The Indian Road Congress has recommended certain formulae to obtain effective width of slabs as given below.

(a) **Slabs Supported on Opposite Edges**

For a single load, the effective width 'b' is given by

$$b = Kx\left(1 - \frac{x}{L}\right) + a \qquad \ldots (19.1)$$

where, x = distance of the centroid of wheel load from any support,

L = effective span for Simply Supported (SS) slabs,

= clear span for continuous slabs,

a = contact length of wheel with the surface of road parallel to supports after dispersion through wearing coat = $(g + 2h)$,

g = length of area of contact of the wheel with the road surface parallel to supports,

h = thickness of wearing coat,

K = a constant depending on the ratio B/L and is given in Table 19.1, and

B = width of slab.

The effective width shall not exceed the actual width of slab. In case of a load near to the unsupported edge of a slab, the effective width shall not exceed the above value nor it will be more than $b/2$ plus the distance of the c.g. of the load from the unsupported edge.

Table 19.1 : Value of Parameter *K* for Simply Supported (SS) and Continuous Slabs

B / L	SS Slab	Cont. Slab	B / L	SS Slab	Cont. Slab
0.1	0.40	0.40	1.1	2.60	2.28
0.2	0.80	0.80	1.2	2.64	2.36
0.3	1.16	1.16	1.3	2.72	2.40
0.4	1.48	1.44	1.4	2.80	2.48
0.5	1.72	1.68	1.5	2.84	2.48
0.6	1.96	1.84	1.6	2.88	2.52
0.7	2.12	1.96	1.7	2.92	2.52
0.8	2.24	2.08	1.8	2.96	2.60
0.9	2.36	2.16	1.9	3.00	2.60
1.0	2.48	2.24	2.0 & more	3.00	2.60

B = Width of Slab; L = Span of Slab

For two or more concentrated loads in a line in the direction of span, the bending moments per unit effective width of slab at any section shall be calculated separately for each load and then added.

For two or more loads in a line normal to span, if the effective width of slab for one load overlaps that of an adjacent load, the resultant effective width for the loads will be the sum of the respective widths for each load minus the width of overlap. In such a case, the slab should also be tested for each load acting separately.

(b) **Cantilever Slabs**

For cantilever slabs, the effective width can be calculated by the following formula :

$$b = 1.2x + a \qquad \ldots (19.2)$$

where, $a = (g + 2h)$, same as described above; x is the distance of the centroid of wheel load from the face of support, provided the effective width shall not exceed one third the length of cantilever slab measured parallel to support. And provided further that when the wheel load is placed near one of the two extreme ends of the length of cantilever, the effective width shall not exceed the above value nor shall it exceed b/2 plus distance of the load from the end.

19.4.2 Pigeaud's Coefficients

This approach of analysis for the determination of bending moment in a slab panel is employed for slabs simply supported on all its four edges with corners held down. It is to be noted here that a slab simply supported on two opposite edges is a special case of slab supported on all four edges with infinite (very large) transverse span (i.e., B / L = ∞). If wheel load is placed close to the unsupported edge of slab, the effective width method may be used.

Using Pigeaud's coefficients obtained from the curves (Figurs 19.5 to 19.16), bending moment at the centre of a slab panel carrying a wheel load placed at the centre of the slab can be calculated using the following formulae :

$$M_1 = (\alpha + 0.15\,\beta)\,P \qquad \ldots (19.3)$$

$$M_2 = (0.15\,\alpha + \beta)\,P \qquad \ldots (19.4)$$

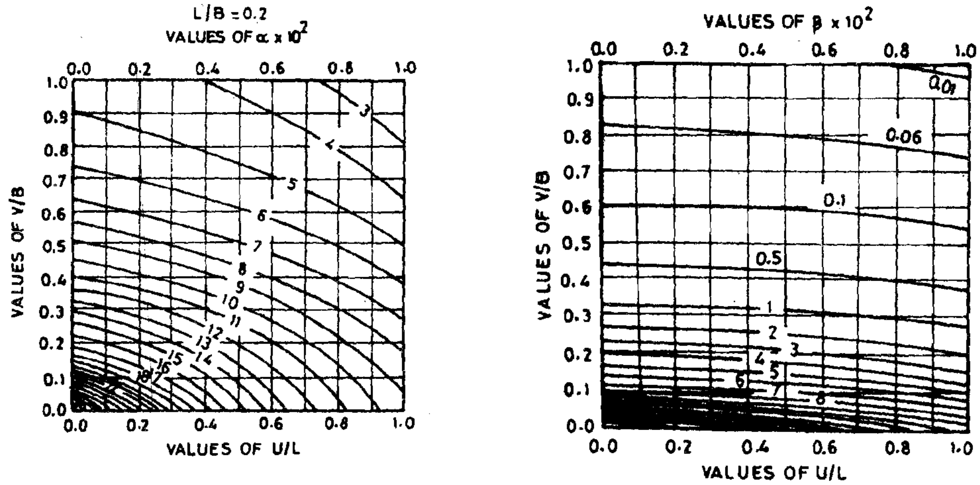


Figure 19.5 : Pigeaud's Coefficients

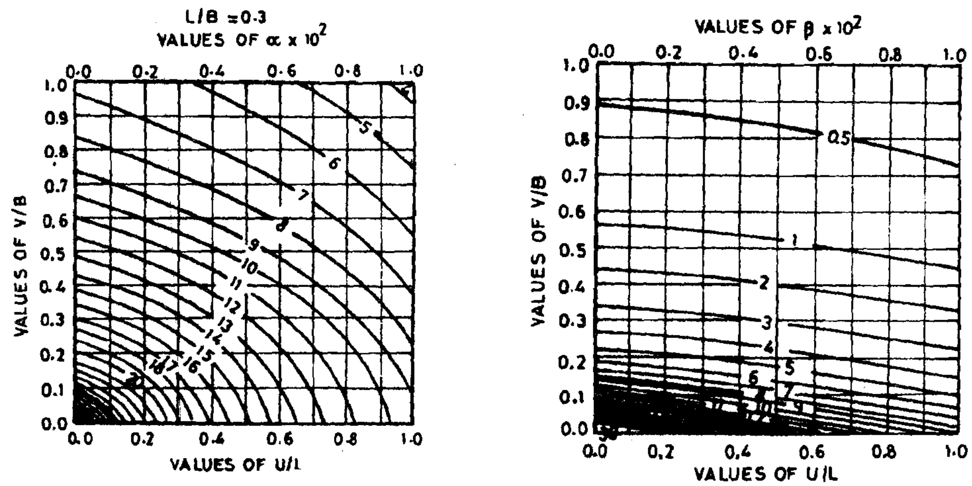


Figure 19.6 : Pigeaud's Coefficients

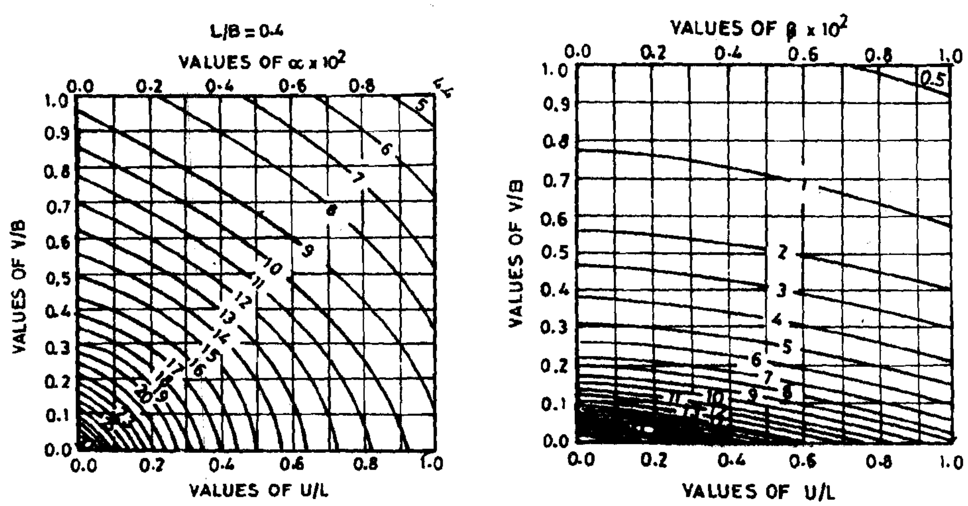


Figure 19.7 : Pigeaud's Coefficients

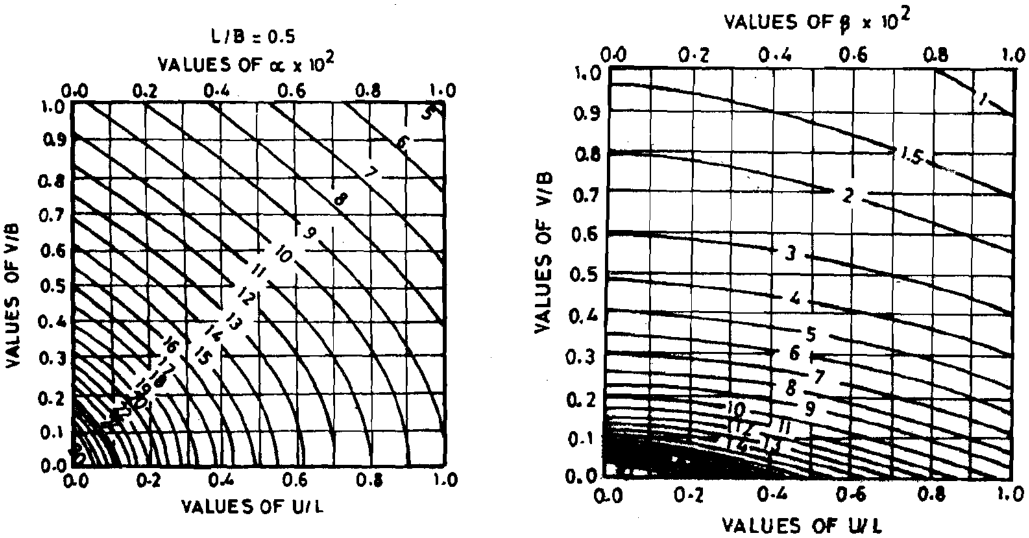


Figure 19.8 : Pigeaud's Coefficients

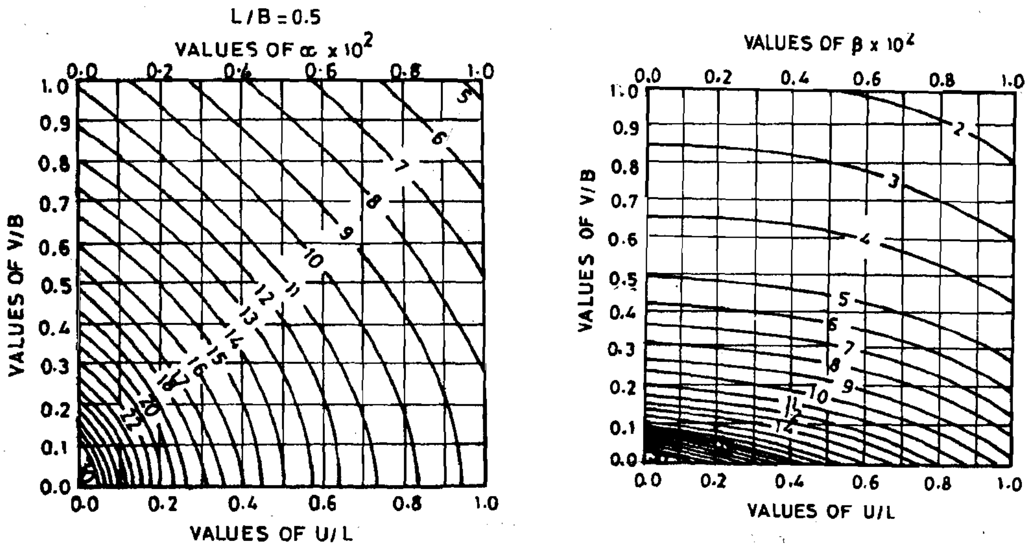


Figure 19.9 : Pigeaud's Coefficients

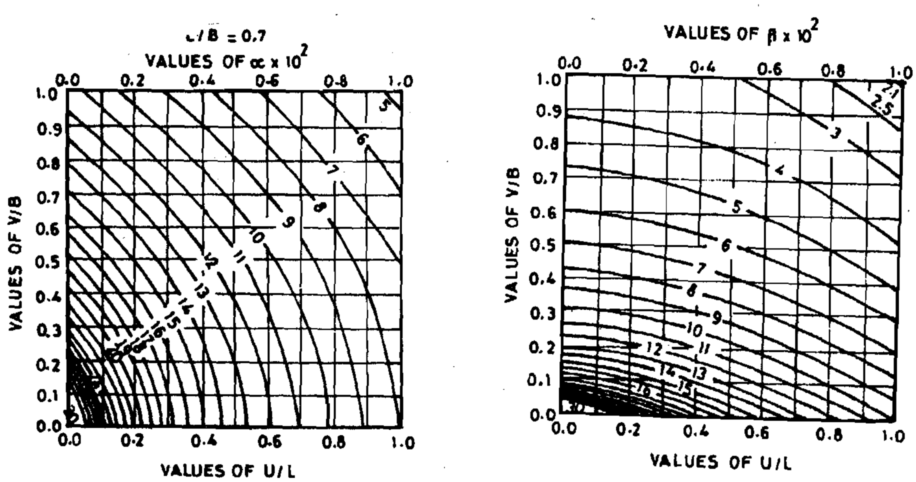


Figure 19.10 : Pigeaud's Coefficients

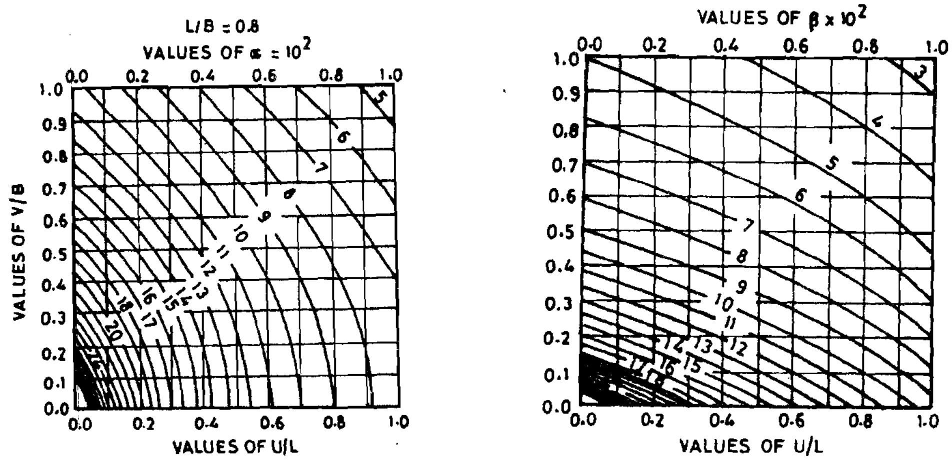


Figure 19.11 : Pigeaud's Coefficients

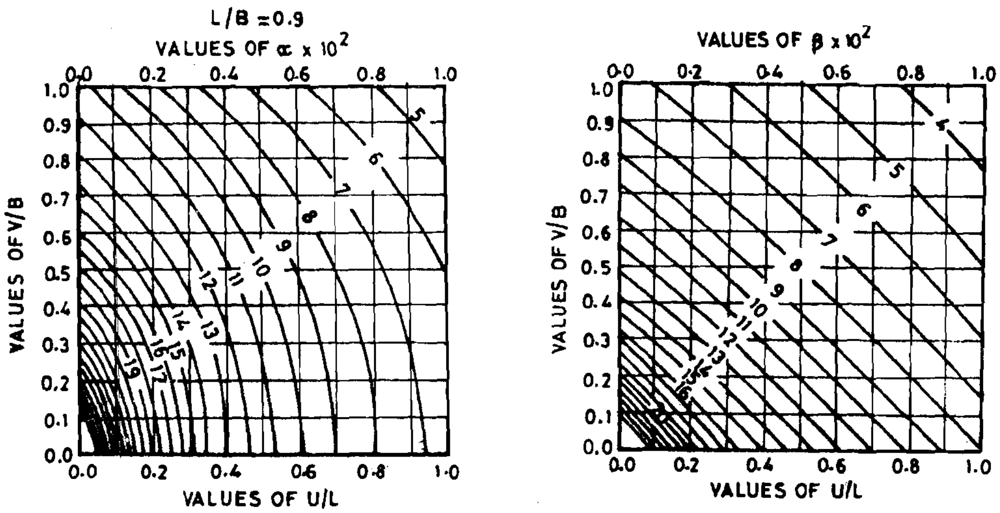


Figure 19.12 : Pigeaud's Coefficients

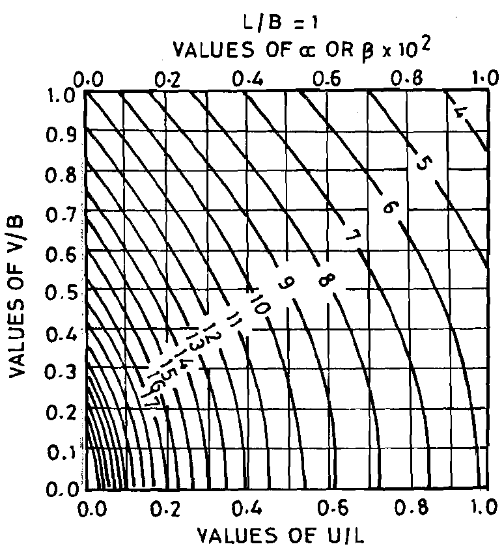


Figure 19.13 : Pigeaud's Coefficients

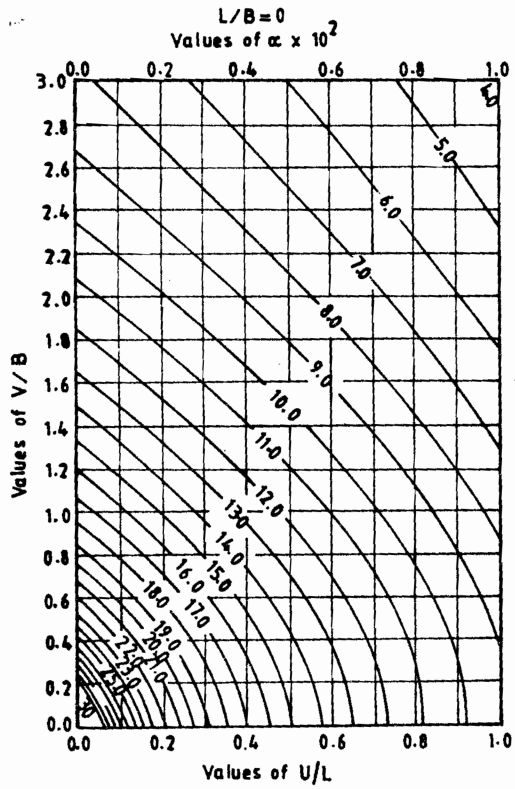


Figure 19.14 : Pigeaud's Coefficients

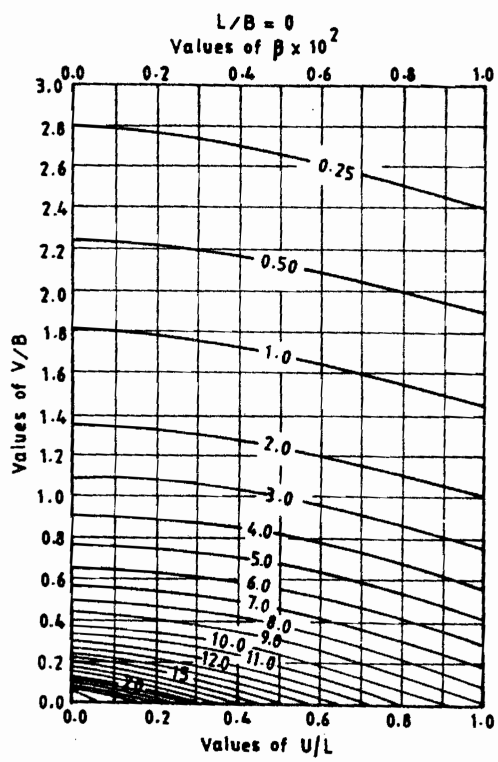


Figure 19.15 : Pigeaud's Coefficients

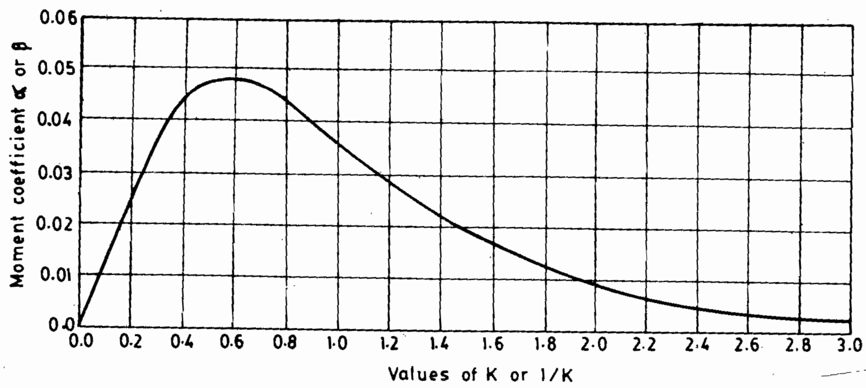


Figure 19.16 : Moment Coefficients for Slab Completely Loaded with Uniformly Distributed Load (Coefficient is α for K and B for 1/K)

where, M_1 and M_2 are the bending moments in the two transverse direction; α and β are the Pigeaud's coefficients to be read from the curves corresponding to the values of u/L, v/B, and L/B; $u \times v$ is the contact area of wheel after dispersion through wearing coat and slab as shown in Figure 19.17. If the unit of P is kN then the units of M_1 and M_2 will be kN-m/m.

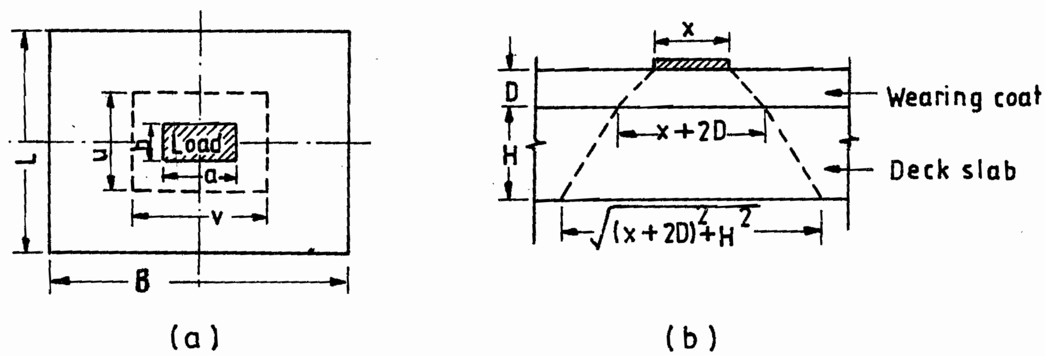


Figure 19.17 : Dispersion of Live Load through Deck Slab

The calculation of bending moment presented above is confined to a single wheel load placed at the centre of slab panel. In practice, however, there may be two or more loads in the same line along short span or long span of the slab. For an eccentrically placed wheel load with eccentricity only in one direction (Figure 19.18), the bending moment at the centre of span can be calculated by considering an imaginary symmetrically placed load as shown in Figure 19.18 The bending moment for this case can be calculated as given below :

BM due to loaded area $ABA'B'$ = (BM due to loaded area $ABCD$ – BM due to loaded area $A'B'C'D'$)/2

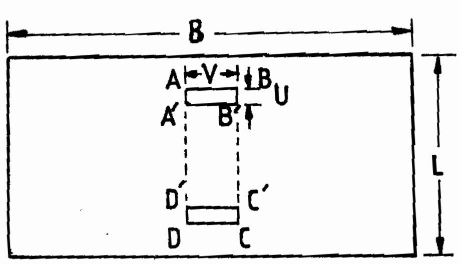


Figure 19.18 : Two Loads along Short Span

The load intensity taken in the above calculation shall be same as for the original wheel load.

The bending moment due to various positions of wheel loads can be calculated at the centre of span and then superimposed to obtain the net bending moment. Sometimes slabs may be continuous over the supports. In such cases, the positive or sagging bending negative or hogging bending moment over the supports may be taken equal to the positive bending moment thus calculated.

SAQ 2

Describe how would you compute the maximum bendingmoment caused by a concentration load acting on a bridge slab by all possible methods for the following cases :

(i) simply supported on two opposite sides,

(ii) cantilever beyond an adjacent supporting beam, and

(iii) continuous on all four edges.

19.5 CULVERTS

Culverts are cross drainage works with clear span less than 8 meters in any highway or railway project, the majority of cross drainage works fall under this category. Hence these structures collectively are important in any project, though the cost of individual structures may be relatively small. Based on the construction of the structure, the culverts can be of the following types :

- Reinforced concrete slab culvert
- Pipe culvert
- Box culvert
- Stone arch culvert
- Steel girder culvert for railways

The reinforced concrete slab culverts are economical upto spans of about 8 m. The thickness of slab of culverts and hence the dead load are quite considerable. However, the construction is relatively simpler due to easier fabrication of formwork and reinforcement and easier placing of concrete.

Design Example 19.1 : Slab Culvert

(1) *Given Data*

Location of culvert	National Highway
Carriageway	Two-lane width
Materials	M20 grade concrete
Clear span, L_c	5.5 m

(2) *Design of Deck Slab*

(i) *Preliminary dimensions* :

Slab thickness (assumed) = 500 mm (Between L_c / 10 and L_c / 12 for M20 grade concrete)

Assuming ϕ 25 mm main bars and 25 mm clear cover,

Effective depth, $d = 500 - (25 + 12.5)$

$= 462.5$ mm

Width of bearing = 400 mm (say)

Effective span, $L = \underset{(L_c)}{5.5} + \underset{\text{(bearing)}}{0.4} = 5.9$ m

Lesser of the two

OR $= \underset{(L_c)}{5.5} + \underset{(d)}{0.4625} = 5.9625$ m

$\therefore L = 5.9$ cm

Unit weight of lightly reinforced concrete = 24 kN/m³

(ii) *Dead Load BM & SF* :

Factored Weight of slab and wearing coat = $1.5\,(0.5 + 0.075) \times 24$

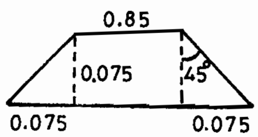
$= 20.7\ \text{kN/m}^2$

Factored Dead Load BM, $M_{ud} = \dfrac{20.7 \times 5.9^2}{8} = 90.1\ \text{kNm/m}$

Factored Dead Load SF (on clear span), $V_{ud} = \dfrac{20.7 \times 5.5}{2} = 56.9\ \text{kN/m}$

(iii) *Live Load BM & SF (Class AA – Tracked Vehicles)* :

Impact factor $= 0.1 + 0.0375\,(9 - 5.9) = 0.216$



0.85 + 2 x 0.075
= 1.0 m

Placing the vehicle closest to the kerb, i.e. at 1.2 m clear distance from the kerb (See Figure 19.19). Assuming the width of kerb as 600 mm, distance of the centre of outer track from the edge of slab will be 2.225 m. The contact area of each track with the pavement is 0.85 m × 3.6 m which after dispersion through wearing coat (at 45°) becomes 1.0* m × 3.75 m. The c/c distance between the two tracks is 1.2 + 0.85 = 2.05 m.

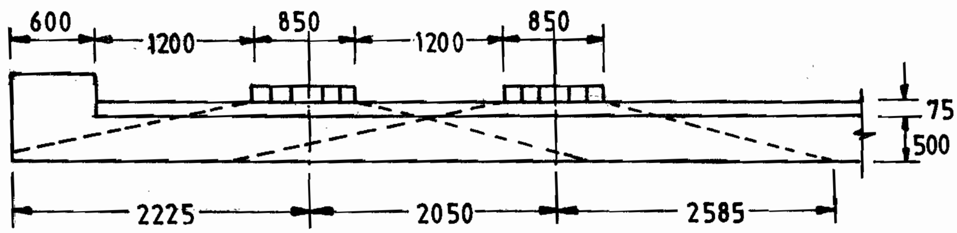


Figure 19.19 : Disposition of Tracked Vehicle along the Carriageway

For maximum BM, tracked vehicle shall be placed symmetrically on the span as shown in Figure 19.20.

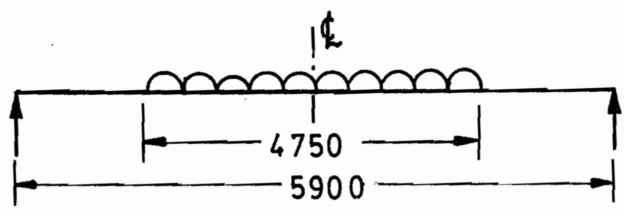


Figure 19.20 : Longitudinal Placement of Track for Maximum BM

Effective length of the load $= 3.6 + 2\,(0.50 + 0.075)$

$= 4.75\ \text{m}$

*Effective width formula is for a wheel load whose length along the span is small in comparison to the span of the slab, but for the present case it is not ture. Better results can be obtained by dividing the load into some portions (say, 4) and then treating each as a wheel load. Students are advised to calculate it by considering four parts and then compare the results with those

Effective width of slab for each track can be approximately* calculated using Eq. (19.1)

$$b = Kx\left(1 - \frac{x}{L}\right) + a$$

where, $x = \dfrac{5.9}{2} = 2.95\ \text{m}$

$L = 5.9\ \text{m}$

$a = 0.85 + 2 \times 0.075 = 1.0\ \text{m}$

B = width of slab = [clear carriageway + 2 × (width of kerb) for two-lane bridge]

$= 7.5 + 2 \times 0.6 = 8.7\ \text{m}$

$K = 2.828$ (From Table 19.1 for B / L = 1.47)

$\therefore b = 2.828 \times (1 - 0.5) + 1.0 = 5.17\ \text{m}$

As the effective width is greater than 2.05 m (the c/c distance between two tracks), the effective widths of the two tracks overlap. Also, half of the effective width is more than the distance of the centre of outer track (i.e., left track in Figure 19.19) from the edge of the slab, i.e. 2.225 m, therefore, available width of slab will be taken, i.e., 2.225 m in the calculation of combined effective width. The combined effective width for the two tracks will be 2.225 + 2.05 + 5.17 / 2 = 6.86 m (as shown in Figure 19.19).

Total factored load of the two tracks including impact

$$= 1.5 \times (1 + 0.216) \times 700$$
$$= 1276.8 \text{ kN}$$

$$\text{Average factored load intensity} = \frac{1276.8}{4.75 \times 6.86} = 39.2 \text{ kN / m}^2$$

Factored maximum BM due to class AA tracked vehicle (From Figure 19.20)

$$= \frac{39.2 \times 4.75}{2} \times \frac{5.9}{2} - \frac{39.2 \times 4.75^2}{8}$$
$$= 164.1 \text{ kN m / m}$$

For maximum SF due to class AA tracked vehicle, track is placed in such a way that the longitudinal dispersed zone will just be at the face of the support as shown in Figure 19.21.

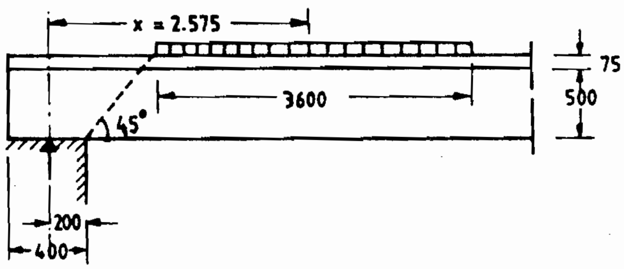


Figure 19.21 : Placement of Track for Maximum SF

Effective width of slab for each track,

$$b = 2.828 \times 2.575 \left(1 - \frac{2.575}{5.9}\right) + 1.0$$
$$= 5.10 \text{ m}$$

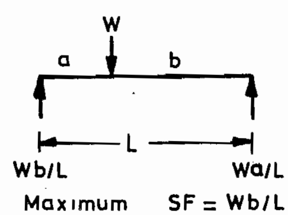
Here $x = \frac{3600}{2} + (75 + 500) + 200$
$= 2575 \text{ mm}^2$
$= 2.575 \text{ m}$

Combined effective width of the two tracks as calculated above will be 2.225 + 2.05 + 5.10 / 2 = 6.825 m.

$$\text{Average factored load intensity} = \frac{1276.8}{4.75 \times 6.825} = 39.4 \text{ kN / m}^2$$

Factored maximum SF (From Figure 17.21)

$$= (39.4 \times 4.75) \times \frac{(5.9 - 2.575)}{5.9} = 105.5 \text{ kN / m}$$



(iv) *Live Load BM & SF (Class AA - Wheeled Vehicle)* :

Impact factor = 0.25

The vehicle will be placed at minimum clear distance from the face of kerb i.e., 1.2 m. (As there are two axles in the vehicle, there will be two wheels in the direction of span). For deciding the placement of vehicle along the span for maximum BM, one shall determine the width of dispersion parallel to span. If the area of dispersion of the wheels overlap, then the two wheel loads will be considered as one and this load will be placed at the centre of span. On the other hand, if they do not overlap, maximum BM will be under one of the wheel load which is close to the mid span and the two wheel loads can be approximately placed such that the resultant of the two wheel loads and one of the wheel loads are equidistant from the mid of span.

Width of dispersion parallel to span

$$= \underset{\text{(width of wheel)}}{150} + \underset{\text{(depth of slab + wearing coat)}}{2\,(500 + 75)}$$

$$= 1300 \text{ mm} > 1200 \text{ mm}$$

The two wheel loads overlap after dispersion and therefore the placement for maximum BM will be as shown in Figure 19.22.

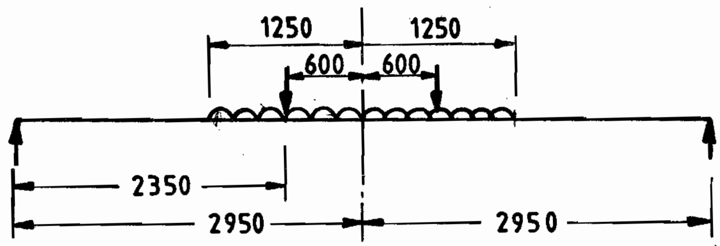


Figure 19.22 : Placement of Class AA Wheeled Vehicle for Maximum BM

Length of load along the span = 1.2 + 1.30 = 2.50 m

Effective width of slab for load W,

$$b = 2.828 \times 2.35 \left(1 - \frac{2.35}{5.9}\right) + (0.3 + 2 \times 0.075)$$

$$= 4.45 \text{ m}$$

The placement of vehicle along the carriageway is shown in Figure 19.23. The combined effective width for all the four wheels of an axle is $1.95 + 0.6 + 1.0 + 0.6 + 4.45 / 2 = 6.375$ m

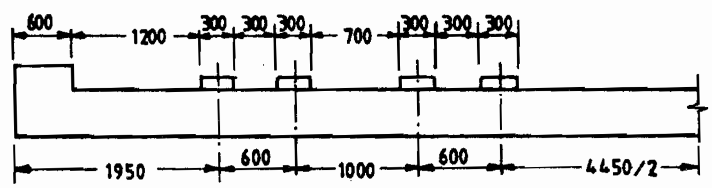


Figure 19.23 : Placement of Class AA Wheeled Vehicle along the Carriageway

Factored Intensity of loading including impact

$$= \frac{1.5 \times 1.25 \times 400}{6.375 \times 2.50} = 47.06 \text{ kN / m}^2$$

Maximum factored BM at the centre of span

$$= \frac{48.5 \times 2.50}{2} \left(2.95 - \frac{2.50}{4}\right)$$

$$= 140.95 \text{ kN m / m}$$

For maximum SF, the two axles are placed as shown in Figure 19.24.

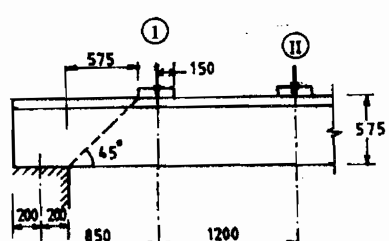


Figure 19.24 : Placement of Class AA Wheeled Vehicle for Maximum SF

$$\text{Effective Width for a wheel of axle I} = 2.828 \times 0.85 \left(1 - \frac{0.85}{5.9}\right) + 0.45$$

$$= 2.51 \text{ m}$$

Referring to Figure 19.23, combined effective width of the four wheels of axle I will be 0.6 + 1.0 + 0.6 + 2.51 = 4.71 m.

$$\text{Effective width for a wheel of axle II} = 2.828 \times 2.05 \left(1 - \frac{2.05}{5.9}\right) + 0.45$$

$$= 4.23 \text{ m}$$

Again referring to Figure 19.23, combined effective width for wheels of axle II will be 1.95 + 0.6 + 1.0 + 0.6 + 4.23 / 2 = 6.265 m.

SF per unit effective width at support

$$= 1.5 \times 1.25 \times 200 \left[\frac{(5.9 - 0.85)}{5.9 \times 4.71} + \frac{(5.9 - 2.05)}{5.9 \times 6.265}\right] = 107.2 \text{ kN / m}$$

(v) *Live Load BM (Class A two-lane loading)* :

$$\text{Impact factor} = \frac{4.5}{6 + 5.9} = 0.378$$

The most heavily loaded axles are the two rear axles of the driving unit of vehicle. Axle load of these axles is 114 kN each. For maximum BM, these axles will be placed on the span. The wheels of the two Class A vehicles are placed across the width of the deck as shown in Figure 19.25.

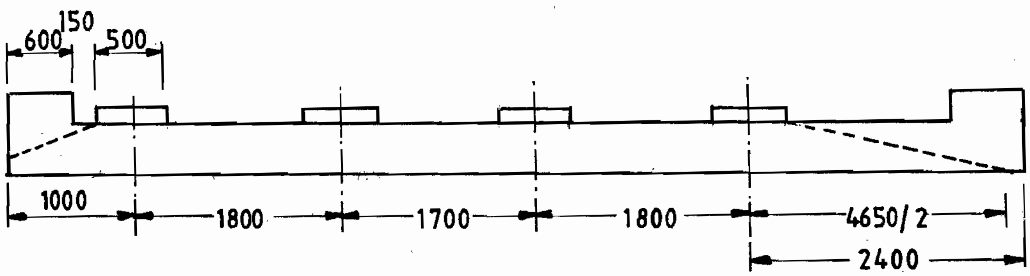


Figure 19.25 : Disposition of Two Class A Vehicles across the Carriageway

Width of a wheel after dispersion parallel to span = 250 + 2 (500 + 75)

= 1400 mm > 1200 mm

The areas of dispersion of two axles overlap, therefore, the two axles will be placed symmetrically as in case of Class AA wheeled vehicle.

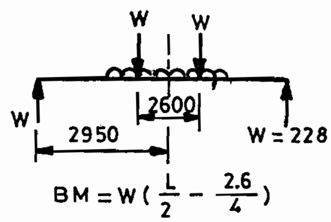
Length of load along the span = 1.2 + 1.400 = 2.60 m

$$\text{Effective width of slab,} \quad b = 2.828 \times 2.35 \left(1 - \frac{2.35}{5.9}\right) + (0.5 + 2 \times 0.075)$$

$$= 4.65 \text{ m}$$

The combined effective width for all four wheels will be 8.625 m $\left(= 1.0 + 1.8 + 1.7 + 1.8 + \frac{4.65}{2}\right)$

Maximum factored BM at the centre of span



$$= \frac{1.5 \times 1.378 \times 228}{8.625} \left(2.95 - \frac{2.60}{4}\right)$$

$$= 125.67 \text{ kN m / m}$$

Maximum SF can be calculated as done earlier for Class AA wheeled vehicle. It will be smaller than that calculated for Class AA tracked and wheeled vehicles. Students are supposed to verify it.

(vi) *Design of Deck Slab for Flexure* :

Among the three load cases, BM produced by Class AA tracked vehicle is the greatest. Hence it will be adopted for design as the live load BM.

Design factored maximum BM,

$$M_u = M_{ud} + M_{ul} = 90.1 + 164.1 = 254.2 \text{ kN m / m}$$

Effective depth required, $d = \sqrt{\dfrac{M_u}{0.138\, b f_{ck}}} = \sqrt{\dfrac{254.2 \times 10^6}{0.138 \times 20 \times 1000}}$

$$= 303.5 \text{ mm} < 46.2 \text{ mm} \quad \text{(OK)}$$

Area of steel can be calculated from the formula

$$M_u = 0.87 f_y A_{st} \left(d - \frac{f_y A_{st}}{f_{ck}\, b} \right)$$

or, $254.2 \times 10^6 = 0.87 \times 415\, A_{st} \left(462.5 - \dfrac{415\, A_{st}}{20 \times 1000} \right)$

or, $A_{st} = 1644 \text{ mm}^2$

Providing ϕ 25@ 290 c/c, giving an area of 1692 mm^2, i.e. 0.366%.

BM in transverse direction $= 0.2\, M_{ud} + 0.3\, M_{ul} = 0.2 \times 90.1 + 0.3 \times 164.1$

$$= 67.25 \text{ kN m / m}$$

using ϕ 12 bars, effective depth $= 500 - 25 - 25 - 6 = 444$ mm

$$67.25 \times 10^6 = 0.87 \times 415\, A_{st} \left(444 - \frac{415\, A_{st}}{20 \times 1000} \right)$$

or, $A_{st} = 428 \text{ mm}^2$

Provide ϕ 12 @ 250 c/c.

(vii) *Check in Shear* :

Among the three loads, maximum SF is produced by Class AA wheeled vehicle.

Maximum factored SF, $V_u = V_{ud} + V_{ul}$

$$= 56.9 + 107.2 = 164.1 \text{ kN / m}$$

Nominal shear stress,

$$\tau_v = \frac{V_u}{bd} = \frac{164.1 \times 10}{1000 \times 462.5} = 0.344 \text{ MPa} < 0.416 \text{ MPa for } 0.366\% \text{ steel}$$

(viii) *Check for Development Length at Support* :

Cutting alternate bars at 470 mm (i.e., 0.08 L) from support.

Moment of resistance of remaining bars at support, $M_1 \approx \dfrac{1}{2} \times 254.2$

$$= 127.1 \text{ kN m / m}$$

Development length of ϕ 25 bars, $L_d = 56\, \phi$

Anchorage length of 90° bend, $L_o = 8\, \phi = 8 \times 25 = 200$ mm

$$L_d \le \frac{1.3\, M_1}{V_u} + L_o$$

$$56\, \phi \le \frac{1.3 \times 1.27 \times 10^6}{159 \times 10^3} + 200$$

or, $\phi \le 22$ mm

Instead of ϕ 25 bars, providing ϕ 20 @ 120 c/c with 50% curtailment at 470 mm from support.

(ix) *Design of Kerb* :

The kerbs on either side of the carriageway are to be designed for a live load of 4 kN / m^2 and horizontal load applied at the top of kerb of 7.5 kN / m. Assuming width of kerb as 600 mm and overall height as 800 mm (i.e., 300 mm over the slab).

Dead load of kerb = $0.6 \times 0.8 \times 24$ = 11.5 kN / m

Weight of parapet = 6.0 kN / m (say)

Live load = 4×0.6 = 2.4 kN / m

Total load = 19.9 kN / m

$$\text{Maximum factored BM} = 1.5 \times \frac{19.9 \times 5.9^2}{8} = 129.9 \text{ kNm}$$

BM due to live load (vehicle loading) = 0.6×164.1

= 98.5 kNm

Total factored design BM, M_u = 129.9 + 98.5 = 228.4 kNm

$$\text{Effective depth required,} \quad d = \sqrt{\frac{228.4 \times 10^6}{0.138 \times 20 \times 600}} = 371.4 \text{ mm}$$

Effective depth provide = 800 − (25 + 10) = 765 mm (OK)

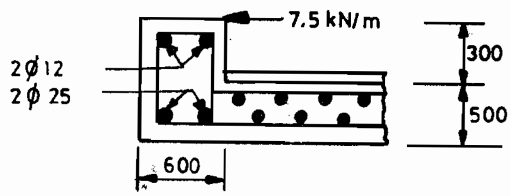
$$228.4 \times 10^6 = 0.87 \times 415 A_{st} \left(\frac{765 - 415 A_{st}}{20 \times 600} \right)$$

or, A_{st} = 856 mm^2

Providing 2 ϕ 25 giving 980 mm^2

For vertical cantiliver, BM at top of slab due to horizontal force

= 7.5×0.3 = 2.25 kNm



Effective Depth available = 600 − (25 + 5) = 570 mm

providing ϕ 8 loops @ 300 mm c/c as nominal steel.

The reinforcement detail is shown in Figure 19.26.

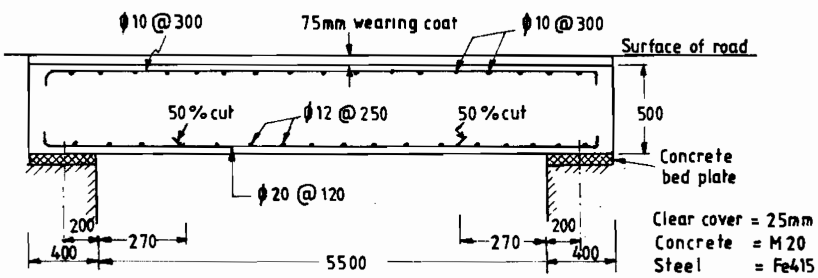
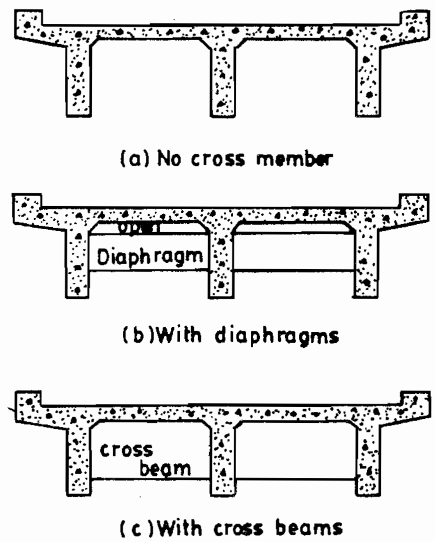


Figure 19.26 : Reinforcement in Slab Culvert
(All dimension in mm)

19.6 T-BEAM BRIDGES

The T-beam Bridge is by far the most commonly adopted type in the span range of 10 to 25 m. The bridge is so named because the main longitudinal girders are designed as T-beams. The T-beam action is due to its monolithic construction with deck slab.

The super-structure may be arranged to conform to one of the following three types, as shown in Figure 19.27 :



(a) No cross member

(b) With diaphragms

(c) With cross beams

Figure 19.27 : Typical Cross-section of T-Beam Bridges

- **Girder and slab type**, in which the deck slab is supported on and cast monolithically with the longitudinal girders. No cross beams are provided. The system does not possess much torsional rigidity and the longitudinal girders can spread laterally at the bottom level.

- **Girder, slab and diaphragm type**, wherein the slab is supported on and cast monolithically with the longitudinal girders. The diaphragms connecting the longitudinal girders are provided at supports and at one or more intermediate locations within a span. The diaphragms do not extend upto the deck slab. This type of super-structure possesses a greater torsional rigidity than the girder and slab type.

- **Girder, slab and cross beam type**, in which the system has atleast three cross beams extending upto and cast monolithically with the deck slab. The panels of deck slab are supported along the four edges by longitudinal and cross beams. The provision of cross beams stiffens the structure to a considerable extent, resulting in better distribution of wheel loads among the longitudinal girders. Through experimental investigation also, this type of construction has been found to be better than the previous two and hence this type has been adopted in practice.

19.6.1 Proportioning

The number of longitudinal girders greatly affects the cost of a T-beam bridge. Hence in any particular design, the comparative estimates of several alternate arrangements of girders should be studied before adopting a final design. With more number of girders, the thickness of deck slab decreases resulting in smaller cost of materials. But the cost of form work will increase due to larger number of girder forms, vertical supports and bracings. Relative economy of two arrangements with different number of girders depends upon the relative cost of materials and form work. The aim of the design should be to adopt a system which results in minimum cost. For Indian conditions, a three girder system is usually more economical than a four girder system for a bridge of two lane carriage way without footpaths.

Cross beams are provided mainly to stiffen the girders and to reduce torsion in the exterior girders. These are essential over the supports to prevent lateral spread of the girders at the bearings. Another function of the cross beams is to equalise the deflection of the girders carrying heavy loading with those of the girder with less loading. This is particularly important when the design loading consists of concentrated wheel load, such as Class AA wheeled vehicle, to be placed in the most unfavourable position. The current Indian practice is to use one cross beam at each support and to provide atleast three intermediate cross beams. The spacing of cross beams should be slightly less than about

1.5 times the spacing of longitudinal girders. But, some of the designers provide even less number of cross beams with a minimum of three.

The cantilever portion of the deck slab is normally kept as half of the spacing of longitudinal girders.

19.6.2 Analysis of Longitudinal Girder

If a wheel load is placed on a T-beam bridge, all the longitudinal girders undergo deflection because they are connected with each other through the deck slab and more importantly through cross beams. The distribution of load among various longitudinal girders will not only depend on its position on the deck but also on the transverse stiffness of deck which is mainly because of the presence of cross beams. Though the load distribution among longitudinal girders can be calculated by considering equal deflection of each longitudinal girder and hence employing the moment distribution method, but the consideration of unequal deflection of girders which is actually the case results in an economical design. This consideration, however, imposes bending moments in cross beams and they shall be capable of resisting them. The problem of analysis of this load distribution is very complex for which any of the following three simplified methods can be adopted :

- Courbon's Method .
- Hendry-Jaegar Method
- Morris and Little Method

The first two methods normally used in practice are described here.

(a) **Courbon's Method**

This method is applicable only when the following conditions are satisfied :

- The ratio of span to width of the bridge is greater than 2 but less than 4.
- The longitudinal girders are interconnected by at least five symmetrically spaced cross girders.
- The cross girders extend to a depth of atleast 75% of the depth of the longitudinal girders.

These conditions are usually satisfied for a majority of modern T-beam bridges. According to this method, load transferred to ith longitudinal girder for a known system of loading on a bridge can be calculated from the equation:

$$R_i = \frac{I_i P}{\sum I_j}\left[1 + \frac{\sum I_j}{\sum I_j d_j^2} d_i e\right] \qquad \ldots (19.5)$$

where, I = moment of inertia of a longitudinal girder, assumed to be same for each girder,

d_i = distance of ith longitudinal girder from the axis of the bridge,

e = eccentricity of live load from the axis of the bridge,

P = total live load, and

n = number of longitudinal girders.

When all the longitudinal girders have same value of moment of inertia, the above equation simplifies to the following :

$$R_i = \frac{P}{n}\left[1 + \frac{n}{\sum d_j^2} d_i e\right] \qquad \ldots (19.6)$$

(b) **Hendry-Jaeger Method**

In this method, cross beams are replaced by a uniform continuous transverse medium of equivalent stiffness. According to this method, the distribution of loading in an interconnected bridge deck system depends on the following three dimensionless parameters.

$$A = \frac{12}{\pi^4}\left(\frac{L}{h}\right)^3 \frac{n\,E\,I_T}{E\,I} \qquad \ldots (19.7)$$

$$F = \frac{\pi^2}{2n}\left(\frac{h}{L}\right)\frac{CJ}{EI_T} \qquad \ldots (19.8)$$

$$c = \frac{EI_1}{EI_2} \qquad \ldots (19.9)$$

where, L = span of the bridge,

h = spacing of longitudinal girders,

n = number of cross beams,

EI, CJ = flexural and torsional rigidities respectively of a longitudinal girder,

EI_1, EI_2 = flexural rigidities of outer and inner longitudinal girders, and

EI_T = flexural rigidity of a cross beam.

Normally for a reinforced concrete T-beam bridge, the flexural rigidities of the outer and the inner longitudinal girders will be nearly equal therefore, the value of parameter c will be unity. The parameter A is the most important of all the three parameters because it contains cube of the ratio of span to the spacing of longitudinal girders. The second parameter F is a measure of the relative torsional rigidities of longitudinal girders, and is difficult to determine accurately, due to uncertainties in the estimation of the value of CJ. For T-beam bridges having 3 or 4 longitudinal girders with a number of cross beams, it is usually permissible to employ the distribution coefficients for $F = \infty$. The torsional rigidity of the transverse system will thus be neglected. The coefficients for intermediate values of F may be obtained by interpolation from equation :

$$m_F = m_o + (m_\infty - m_o)\sqrt{\frac{F\,A}{3 + F\sqrt{A}}} \qquad \ldots (19.10)$$

where m_F is the required distribution coefficient m_o and m_∞ are respectively the coefficients for $F = 0$ and $F = \infty$. For reinforced concrete T-beam bridges, F will generally be more than 1.25. In such cases, it would be admissible to use the coefficients for $F = \infty$ in design, as the effective difference in the final moments will be small.

Typical graphs for distribution coefficients for a three girder system for $F = 0$ and $F = \infty$ are given in Figures 19.28 to 19.31. The distribution coefficient read from these graphs will be the load on longitudinal girder i due to unit load on girder j.

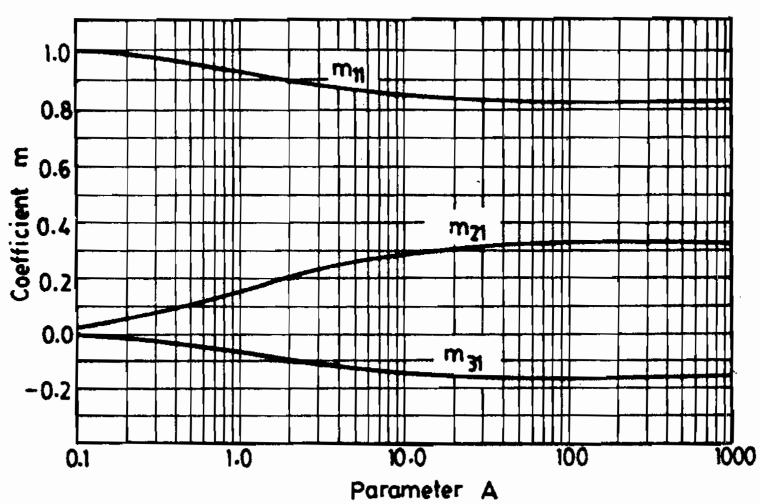


Figure 19.28 : Distribution Coefficients for Three-girder Bridge with Load on Girder No. 1, $F = 0$

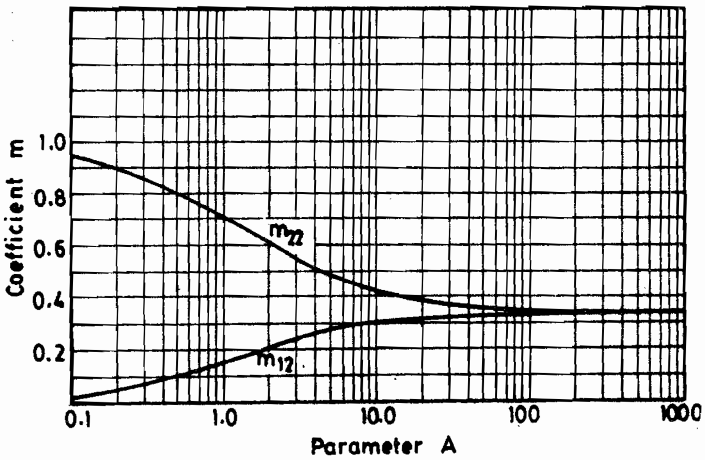


Figure 19.29 : Distribution Coefficients for Three-girder Bridge with Load on Girder No. 2, $F = 0$

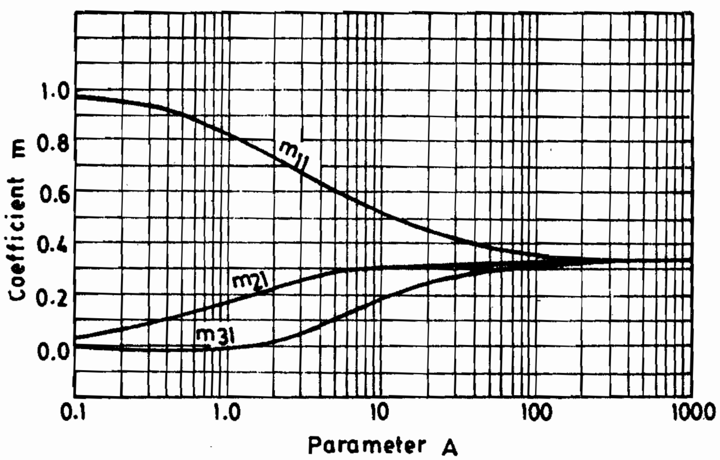


Figure 19.30 : Distribution Coefficients for Three-girder Bridge with Load on Girder No. 1, $F = \infty$

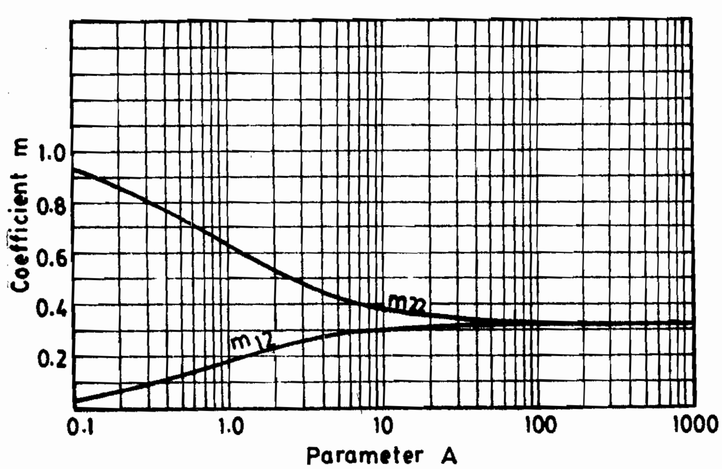


Figure 19.31 : Distribution Coefficients for Three-girder Bridge with Load on Girder No. 2 $F = \infty$

SAQ 3

Discuss the relative merits of the following three arrangements of a T-beam bridge :

(i) without any cross beam or diaphragm,

(ii) with cross beams,

(iii) with diaphragms.

SAQ 4

Indicate the different component of the superstructures of T-beam bridge.

SAQ 5

Describe the various methods of load distribution among the longitudinal girders of a T-beam bridge.

Design Example 19.2 : T-beam Bridge

(1) *Given Data*

Location of Bridge	National Highway
Carriage way	Tow-lane width
Materials	M20 grade concrete
Effective span	14.0 m

(2) *Preliminary Proportioning*

Clear road way = 7.5 m

Assuming three longitudinal giders, preliminary dimensions may be assumed (based on experience) as shown in Figure 19.32. These will be checked and modified, if necessary.

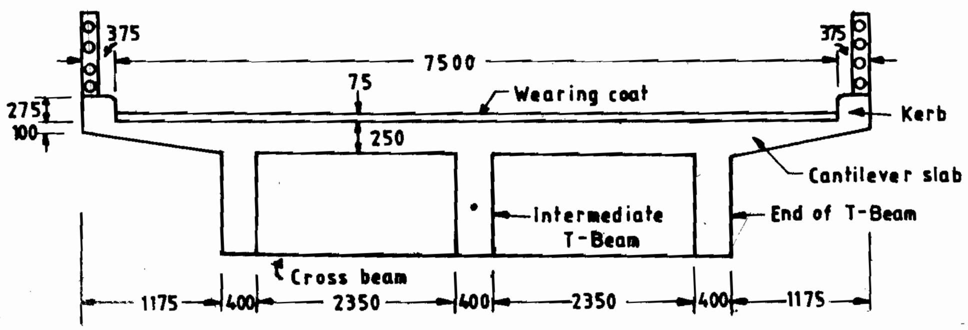


Figure 19.32 : Section of T-Beam Bridge

Providing three cross-beams, one each at the ends and one at the mid of span. Keeping the width of cross beams as 300 mm and as deep as the main beams.

(3) *Cantilever Slab*

(i) BM due to Deal load (Referring to Figure 19.33)

BM due to hand rails (0.6 kN / m) $= 0.6 \times 1.1 = 0.66$ kN m / m

BM due to wearing coat $= (0.075 \times 24) \times \dfrac{0.8^2}{2} = 0.576$ kN m / m

BM due to weight of kerb= $(0.375 \times 0.275 \times 24) \times \left(1.175 - \dfrac{0.375}{2}\right)$

$= 2.444$ kN m / m

BM due to weight of slab = $(0.1 \times 24) \times \dfrac{1.175^2}{2} = 1.657$ kN m / m

$= (0.15 \times 24) \times \dfrac{1.175^2}{6} = 0.828$ kN m / m

Total factored BM due to DL = $1.5 \times 6.165 = 9.25$ kNm / m

Total factored SF due to DL $= 1.5 \times (0.6 + 0.075 \times 24 \times 0.8$

$+ 0.375 \times 0.275 \times 24 + 0.1 \times 24 \times 1.175$

$+ 0.15 \times 24 \times \frac{1.175}{2}) = 14.18$ kN / m

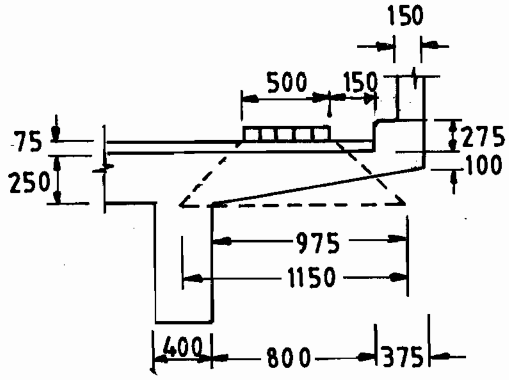


Figure 19.33 : Cantilever Slab with Class A Wheel

(ii) *BM due to Live Load*

Class AA loading can not cover any portion of the cantilever as it has to be 1.2 m away from the kerb. Class A loading can be placed at 150 mm clear from the kerb. One of the wheel of 114 kN axle on cantilever is shown in Figure 19.33. It can be seen from Figure 19.33 that the wheel spreads to 1150 mm out of which 975 mm is on the cantilever.

Factored including impact on cantiliver $= 1.5 \times 1.5 \times \frac{114}{2} \times \frac{0.975}{1.15}$

$= 108.7$ kN

Effective width of cantilever, $b = 1.2\, x + a$ (Impact factor for Class A = 0.5)

$= 1.2 \times \frac{0.975}{2} + (0.25 + 0.15)$

$= 0.985$ m

BM due to live load = $108.7 \times \frac{0.975}{2} \times \frac{1}{0.985} = 53.8$ kN m / m

SF due to live load $= \frac{108.7}{0.985} = 110.4$ kN / m

(iii) *Design of Slab for Flexure*

Total factored BM due to dead and live loads $= 9.25 + 53.8 = 63.05$ kN m / m

Effective depth required, $d = \sqrt{\frac{63.05 \times 10^6}{0.138 \times 20 \times 1000}} = 151.1$ mm

Effective depth provided $= 250 - (25 + 8) = 217$ mm > 151.1 mm (O. K.)

Area of steel required can be calculated from

$$63.05 \times 10^6 = 0.87 \times 415\, A_{st} \left(217 - \frac{415\, A_{st}}{20 \times 1000}\right)$$

or, $A_{st} = 879$ mm^2

Providing 16 @ 220 mm c/c giving a total area of 914 mm^2 (0.42%)

BM in transverse direction = $0.2 \times 9.25 + 0.3 \times 53.8 = 18.00$ kN m / m

(20% of BM due to *DL*) + (30% of BM due to *LL*)

$$18.0 \times 10^6 = 0.87 \times 415\, A_{st} \left(203 - \frac{415\, A_{st}}{20 \times 1000}\right)$$

or, $A_{st} = 253$ mm^2

Providing ϕ 10 @ 300 c/c

(iv) *Check in Shear*

Total factored SF due to dead and live loads, $V_u = 14.18 + 110.4 = 124.58$ kN

Nominal shear stress, $\tau_v = \frac{V_u}{bd} = \frac{124.58 \times 10^3}{1000 \times 217} = 0.57$ MPa > 0.442 MPa (unsafe for 0.42% steel)

Providing a fillet 100 mm × 100 mm in all the three longitudinal girders, slab will then be safe in shear. The inner slab panels will also be safe in shear therefore, they have not to be checked for it. Students should verify it.

(v) *Deck Slab*

The slab is supported on four sides by beams.

Effective span of slab panel in transverse direction = 2.35 m (Figure 19.32)

Effective span of slab panel in longitudinal direction $= \frac{14}{2} - 0.3 = 6.7$ m

(i) *BM due to Dead Load* :

Total factored dead load = $1.5 \times (0.25 + 0.075) \times 24 = 11.7$ kN / m^2

As the slab is supported on all four edges and is continuous, Pigeaud's curves can be used for computing BM.

$$\text{Ratio } k = \frac{\text{Short span}}{\text{Long span}} = \frac{2.35}{6.70} = 0.35, \ \frac{1}{k} = 2.86$$

From Pigeaud's curve (Figure 19.16), $\alpha = 0.042$ and $\beta = 0.0035$

Total factored dead load of panel, $W = 11.7 \times 2.35 \times 6.7 = 184.2$ kN

BM along short span

$= (\alpha + 0.15\,\beta)\, W = (0.042 + 0.15 \times 0.0035) \times 184.2 = 7.8$ kN m / m

BM along long span

$= (\beta + 0.15\,\alpha)\, W = (0.0035 + 0.15 \times 0.042) \times 184.2 = 1.8$ kN m / m

(ii) *Live Load BM due to Class AA Tracked Vehicle* :

Impact factor = 0.25 for 2.35 m span of slab panel

For maximum BM one of the track will be placed at the centre of the slab panel as shown in Figure 19.34. The other track will then be on the adjacent slab panel.

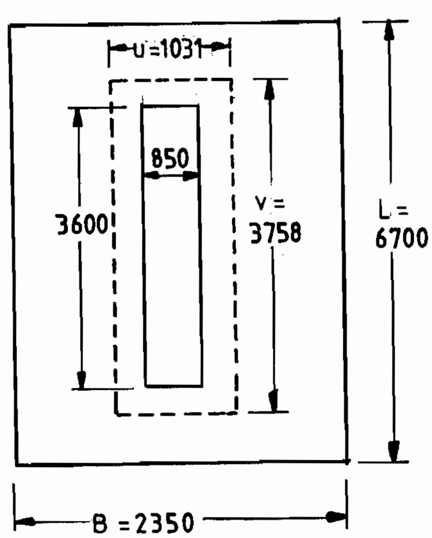


Figure 19.34 : A Track of Class AA Vehicle on Slab Panel

Width of load spread along short span,

$$u = \sqrt{(0.85 + 2 \times 0.075)^2 + 0.25^2}$$

$$= 1.031 \text{ m}$$

Width of load spread along long span,

$$v = \sqrt{(3.6 + 2 \times 0.075)^2 + 0.25^2} = 3.758 \text{ m}$$

$$k = 0.35, \ \frac{u}{B} = \frac{1.031}{2.35} = 0.44, \ \frac{v}{L} = \frac{3.758}{6.7} = 0.56$$

From Pigeaud's curves,

$$\alpha = 0.098, \ \beta = 0.014$$

Total factored load of track including impact = $1.5 \times 1.25 \times 350 = 656.3$ kN

BM along shorter span = $(0.098 + 0.15 \times 0.014) \times 656.3 = 65.7$ kN m / m

BM along longer span = $(0.014 + 0.15 \times 0.098) \times 656.3 = 18.8$ kN m / m

(iii) *Live Load BM due to Class AA Wheeled Vehicle* :

Impact factor = 0.25

For maximum BM in slab, 62.5 kN wheel will be placed at the centre of slab panel. Only three wheels per axle, i.e., a total of six wheels, can be accommodated on the panel as shown in Figure 19.35. BM at the centre of panel due to each wheel load will be calculated separately and then added up.

Contact dimensions of each wheel with pavement is 300×150 mm

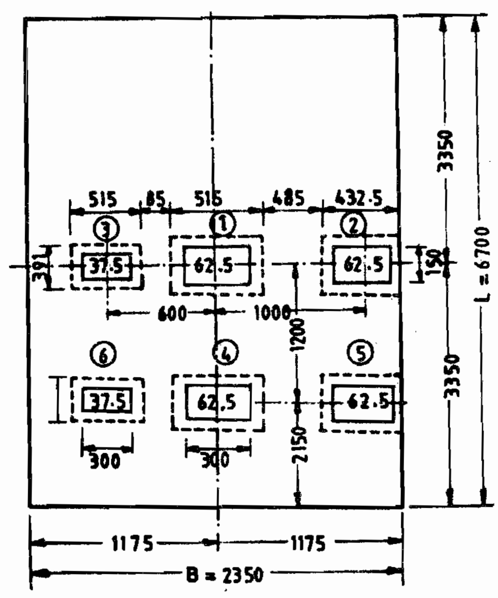


Figure 19.35 : Disposition of Class AA Wheeled Vehicle for Maximum BM

(a) Wheel 1 of 62.5 kN

Dimensions of dispersed area of wheel,

$$u = \sqrt{(0.3 + 2 \times 0.075)^2 + 0.25^2} = 0.515 \text{ m}$$

$$v = \sqrt{(0.15 + 2 \times 0.075)^2 + 0.25^2} = 0.391 \text{ m}$$

$$k = 0.35, \ \frac{u}{B} = \frac{0.515}{2.35} = 0.22, \ \frac{v}{L} = \frac{0.391}{6.7} = 0.058$$

From Pigeaud's curves, $\alpha = 20.7 \times 10^{-2}$ and $\beta = 15.5 \times 10^{-2}$

Factored wheel load including impact,

$$W = 1.5 \times 1.25 \times 62.5 = 117.2 \text{ kN}$$

BM along short span

$$= (20.7 + 0.15 \times 15.5) \times 117.2 \times 10^{-2} = 27.0 \text{ kN m / m}$$

BM along long span

$$= (15.5 + 0.15 \times 20.7) \times 117.2 \times 10^{-2} = 21.8 \text{ kN m / m}$$

(b) Wheel 2 of 62.5 kN

This wheel load (*abcd*) does not lie at the centre of slab panel but pigeaud's curves can be used only when the load is at the centre. Therefore, considering an imaginary load $b'\,a'\,d'\,c'$ as shown in Figure 19.36 and then BM shall be found due to two loads $b'\,b\ d'\,d$ and $a'\,a\ c'\,c$. The BM due to wheel 2 will be 50%, of the difference of BM due to these two loads.

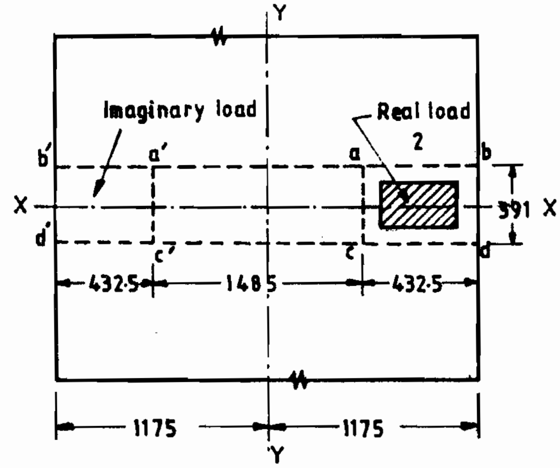


Figure 19.36 : Calculation of BM due to Wheel 2

Factored load intensity including impact $= 1.5 \times 1.25 \times \dfrac{62.5}{0.515 \times 0.391}$

$$= 582.0 \text{ kN / m}^2$$

For loaded area $b'\,b\ d'\,d$ (larger load) :

$$k = 0.35, \ \frac{u}{B} = 1, \ \frac{v}{L} = 0.058$$

$$\alpha = 9.5 \times 10^{-2} \text{ and } \beta = 7.0 \times 10^{-2}$$

Factored BM along short span

$$= (9.5 + 0.15 \times 7.0) \times 10^{-2} \times 582.0 \times 2.35 \times 0.391$$

$$= 56.4 \text{ kN m / m}$$

Factored BM along long span

$$= (7.0 + 0.15 \times 9.5) \times 10^{-2} \times 582.0 \times 2.35 \times 0.391$$

$$= 45.1 \text{ kN m / m}$$

For loaded area $a'\,a\ c'\,c$ (smaller load) :

$$k = 0.35, \ \frac{u}{B} = \frac{1.485}{2.35} = 0.63, \ \frac{v}{L} = 0.058$$

$$\alpha = 13.0 \times 10^{-2} \text{ and } \beta = 10.0 \times 10^{-2}$$

Factored BM along short span

$$= (13.0 + 0.15 \times 10.0) \times 10^{-2} \times 582.0 \times 1.485 \times 0.391$$

$$= 49.0 \text{ kN m / m}$$

Factored BM along long span

$$= (10.0 + 0.15 \times 13.0) \times 10^{-2} \times 582.0 \times 1.485 \times 0.391$$

$$= 40.4 \text{ kN m / m}$$

Net factored BM along short span = $\frac{1}{2}(56.4 - 49.0) = 3.7$ kN m / m

Net factored BM along long span = $\frac{1}{2}(45.1 - 40.4) = 2.4$ kN m / m

(c) Wheel 3 of 37.5 kN

By similar procedure as followed for wheel 2;

Factored load intensity including impact

$$= 1.5 \times 1.25 \times \frac{37.5}{0.515 \times 0.391} = 349.2 \text{ kN / m}^2$$

For larger load (1.715 m × 0.391 m)

$$\frac{u}{B} = \frac{1.715}{2.35} = 0.73, \ \frac{v}{L} = 0.058$$

$$\alpha = 11.8 \times 10^{-2} \text{ and } \beta = 10.5 \times 10^{-2}$$

Factored BM along short span

$$= (11.8 + 0.15 \times 10.5) \times 10^{-2} \times 349.2 \times 1.715 \times 0.391$$

$$= 31.3 \text{ kN m / m}$$

Factored BM along long span

$$= (10.5 + 0.15 \times 11.8) \times 10^{-2} \times 349.2 \times 1.715 \times 0.391$$

$$= 28.7 \text{ kN m / m}$$

For smaller load (0.685 m × 0.391 m) :

$$\frac{u}{B} = \frac{0.685}{2.35} = 0.29, \ \frac{v}{L} = 0.058$$

$$\alpha = 19.0 \times 10^{-2} \text{ and } \beta = 15.0 \times 10^{-2}$$

Factored BM along short span

$$= (19.0 + 0.15 \times 15.0) \times 10^{-2} \times 349.2 \times 0.685 \times 0.391$$

$$= 19.9 \text{ kN m/m}$$

Factored BM along long span

$$= (15.0 + 0.15 \times 19.0) \times 10^{-2} \times 349.2 \times 0.685 \times 0.391$$

$$= 16.7 \text{ kN m / m}$$

Net factored BM along short span = $\frac{1}{2}(31.3 - 19.9) = 5.7$ kN m / m

Net factored BM along long span = $\frac{1}{2}(28.7 - 16.7) = 6.0$ kN m / m

(d) Wheel 4 of 62.5 kN

BM will be calculated by following similar procedure as for wheel 2 and 3.

Factored load intensity including impact = 582 kN / m^2

For larger load (0.515 m × 2.791 m) :

$$\frac{u}{B} = \frac{0.515}{2.35} = 0.22, \ \frac{v}{L} = \frac{2.791}{6.7} = 0.42$$

$$\alpha = 13.6 \times 10^{-2} \text{ and } \beta = 2.8 \times 10^{-2}$$

$$M_1 = (13.6 + 0.15 \times 2.8) \times 10^{-2} \times 582 \times 0.515 \times 2.791$$
$$= 117.3 \text{ kN m / m}$$
$$M_2 = (2.8 + 0.15 \times 13.6) \times 10^{-2} \times 582 \times 0.515 \times 2.791$$
$$= 40.5 \text{ kN m / m}$$

For smaller load (0.515 m × 2.009 m)

$$\frac{u}{B} = 0.22, \ \frac{v}{L} = \frac{2.009}{6.7} = 0.30$$
$$\alpha = 15.8 \times 10^{-2} \text{ and } \beta = 4.2 \times 10^{-2}$$
$$M_1 = (15.8 + 0.15 \times 4.2) \times 10^{-2} \times 582 \times 0.515 \times 2.009$$
$$= 98.9 \text{ kN m / m}$$
$$M_2 = (4.2 + 0.15 \times 15.8) \times 10^{-2} \times 582 \times 0.515 \times 2.009$$
$$= 39.6 \text{ kN m / m}$$

Net factored BM along short span = $\frac{1}{2}(117.3 - 98.9) = 9.2$ kN m / m

Net factored BM along long span = $\frac{1}{2}(40.5 - 39.6) = 0.5$ kN m / m

As compared to wheel 1, the above BM is 34.1% and 2.3% along short and long directions. This is due to the load being placed away from the centre of panel.

(e) Wheels 5 and 6

The effect of wheels 5 and 6 at the centre of slab panel is expected to be very small. As an approximation, their effect can be proportioned out from that of wheel 2 and 3 respectively.

∴ Factored BM along short span due to wheels 5 and 6

$$= 0.341 \times (3.7 + 5.7)$$
$$= 3.2 \text{ kN m / m}$$

∴ Factored BM along long span due to wheels 5 and 6

$$= 0.023 \times (2.4 + 6.0)$$
$$= 0.2 \text{ kN m / m}$$

(f) Total BM due to all Wheels on Slab Panel

The total effect of all wheels can be computed as summation of individual effects

Total factored BM along short span

$$= 27.0 + 3.7 + 5.7 + 9.2 + 3.2 = 48.8 \text{ kN m / m}$$

Total factored BM along long span

$$= 21.8 + 2.4 + 6.0 + 0.5 + 0.2 = 30.9 \text{ kN m / m}$$

(iv) *Design of Deck Slab for Flexure*

Class A vehicle has not been considered because it will give lesser BM (verify it !). Along short span, Class AA tracked vehicle gives heavier BM. But, along long span, Class AA wheeled vehicle gives more severe effect. The loads causing maximum effects are adopted for design BM.

The above computation of BM assumed that the slab is simply supported on all the four edges. In fact, the deck slab is continuous. To allow for continuity, the computed BMs are multiplied by a factor 0.8.

Factored design BM along short span

$$= (7.8 + 65.7) \times 0.8 = 58.8 \text{ kN m / m}$$

Factored design BM along long span

$$= (1.8 + 30.9) \times 0.8 = 26.2 \text{ kN m / m}$$

Effective depth required, $d = \sqrt{\dfrac{58.8 \times 10^6}{0.138 \times 20 \times 1000}} = 145.96$ mm

Effective depth provided

$$= 250 - 25 - 8 = 217 \text{ mm} > 145.96 \text{ mm O.K.}$$

Area of steel (A_{st}) along short span :

$$58.8 \times 10^6 = 0.87 \times 415 A_{st} \left(217 - \frac{415 A_{st}}{20 \times 1000}\right) \text{ (assuming } \phi \text{ 16 bars)}$$

or, $A_{st} = 814 \text{ mm}^2$ (ϕ 16 @ 220 mm c/c, steel = 0.43%)

Area of steel (A_{st}) along long span :

$$26.2 \times 10^6 = 0.87 \times 415 A_{st} \left(203 - \frac{415 A_{st}}{20 \times 1000}\right) \text{ (assuming } \phi \text{ 12 bars)}$$

or, $A_{st} = 372 \text{ mm}^2$ (ϕ 12 @ 300 mm c/c)

(5) *Intermediate Longitudinal Girder*

(i) *Data*

Effective span	= 14.0 m
Thickness of slab	= 250 mm
Width of rib of beam	= 400 mm
Spacing of main beams	= 2750 mm
Overall depth of beam	= 1500 mm

(ii) *BM due to Dead Load*

Weight of Deck slab and wearing coat

$$= 2.75 \times (0.25 + 0.075) \times 24 = 21.5 \text{ kN / m}$$

Weight of T-rib

$$= 0.4 \times 1.25 \times 24 = 12.0 \text{ kN / m}$$

Total Uniformly Distributed Load (Udl), $w = 33.5$ kN / m

Factored Udl, $w_u = 1.5\, w = 1.5 \times 33.50 = 50.3$ kN / m

Factored weight of cross beam acting as point load at mid of span,

$$W_u = 1.5 \times (0.3 \times 1.25 \times 2.35 \times 24) = 31.7 \text{ kN}$$

Maximum factored BM due to $DL = \dfrac{50.3 \times 14^2}{8} + \dfrac{31.7 \times 14}{4}$

$$= 1343.3 \text{ kNm}$$

(iii) *BM due to Live Load*

Maximum live load BM will occur under Class A two-lane loading.

Impact factor $= \dfrac{4.5}{6 + 14} = 0.225$

The loading is arranged in transverse direction as shown in Figure 19.37, allowing minimum clearance near the left kerb. All the four wheel loads are of equal magnitude. Courbon's method has been employed for the distribution of wheel loads among the three longitudinal girders. The conditions of the applicability of Courbon's method are satisfied approximately.

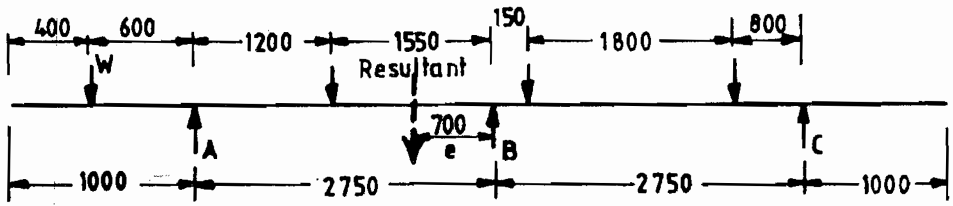


Figure 19.37 : Transverse Disposition of Two Trains of Class A Loading for Determination of Reactions on Longitudinal Beams

$$\text{Reaction for girder } i,\ R_i = \frac{P\,I_i}{\sum I_j}\left(1 + \frac{\sum I_j}{\sum I_j\, d_j^2}\, e d_i\right)$$

where, $P = 4\,W,\ n = 3,\ e = 0.7$ m

Assuming that the values of I for all the three girders are equal.

$$\text{Reaction for girder } A,\ R_a = \frac{4W}{3}\left[1 + \frac{3I}{2\,(I \times 2.75^2)} \times 0.7 \times 2.75\right]$$

$$= 1.84\ W$$

$$\text{Reaction for girder } B,\ R_b = \frac{4W}{3}\ (1 + 0) = 1.33\ W$$

$$\text{Reaction for girder } C,\ R_c = 4W - \left(R_a + R_b\right)$$

$$= 0.83\ W$$

The first six loads of Class A train can be accommodated on the span.

Distance of resultant (209 kN) of the six wheel loads from the first wheel (Figure 19.38).

$$= \frac{1}{209}\,[13.5 \times 1.1 + 57 \times (4.3 \times 2 + 1.2) + 34 \times (2 \times 9.8 + 30)]$$

$$= 6.42 \text{ m}$$

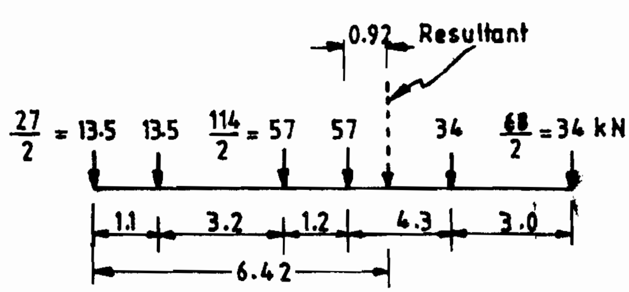


Figure 19.38 : Position of Resultant of First Six Wheels of Class A Vehicle

BM will be maximum under the fourth load when this and the resultant are equidistant from the mid of span as shown in Figure 19.39.

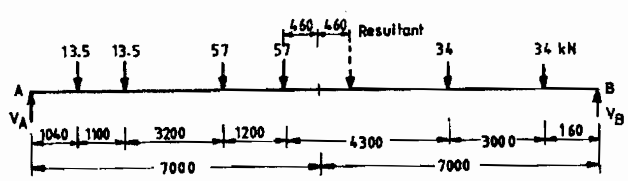


Figure 19.39 : Arrangement of Wheel Loads on Span for Maximum BM

The loads shown in Figures 19.38 and 19.39 are the wheel loads, i.e. half of the axle loads. These loads will have to be multiplied by load factor (i.e., 1.5), impact factor (i.e., 1.225), and reaction factor for intermediate girder (i.e., 1.33). This combined multiplication factor will be $1.5 \times 1.225 \times 1.33 = 2.444$.

$$\text{Reactions, } V_B = 2.444 \times 209 \times \frac{746}{14} = 272.2 \text{ kN}$$

Factored BM under fourth load = $272.2 \times 7.46 - 2.444 \times 34 \times (7.3 + 4.3)$

$= 1066.7$ kNm

(iv) *Design of Beam Section*

Factored Design BM, $M_u = 1343.3 + 1066.7$

$= 2410$ kNm

Effective depth of beam, $d = 1500 - 140$ (eff. cover) $= 1360$ mm

Effective width of flange of T-beam section, as per Cl. 305.12.2 of IRC Bridge Code :

(a) $\frac{L}{4} = \frac{14.0}{4} = 3.5$ m

(b) Distance between centre of rib of T-beams = 2.75 m

(c) Width of rib + 12 times the thickness of flange

$= 0.4 + 12 \times 0.25 = 3.4$ m

Hence the effective width of flange, $b_f = 2.75$ m

Assuming N. A. to lie in the flange, Area of steel (A_{st})

$$2410 \times 10^6 = 0.87 \times 415 A_{st} \left(1360 - \frac{415 A_{st}}{20 \times 2750}\right)$$

or, $A_{st} = 5050 \text{ mm}^2$

Providing 12 ϕ 25 ($A_{st} = 5880 \text{ mm}^2$, 1.08%) in three rows of four bars each.

Depth of N. A. for required area of steel,

$$X_u = \frac{0.87 f_y A_{st}}{0.36 f_{ck} b_f} = \frac{0.87 \times 415 \times 5050}{0.36 \times 20 \times 2750}$$

$= 92 \text{ mm} < 250 \text{ mm}$ (O.K.)

So, the assumption that the N. A. lies in the flange is correct. Curtailment of reinforcement can be made after evaluating maximum BM and corresponding shear at different sections. Shear reinforcement can be calculated by calculating maximum SF at different sections.

(6) *End Longitudinal Girder*

The procedure of the design of end longitudinal girders will be same as for intermediate longitudinal girder.

Factored BM due to deal load ≈ 1343.3 kNm

Reaction factor for end beam = 1.84 (calculated above)

Hence maximum factored BM due to LL = $1066.7 \times \frac{1.84}{1.33} = 1475.7$ kNm

Total factored design BM, $M_u = 1343.3 + 1475.7 = 2819$ kNm

Area of steel (A_{st}) :

$$2819 \times 10^6 = 0.87 \times 415 A_{st} \left(1360 - \frac{415 A_{st}}{20 \times 2750}\right)$$

or, $A_{st} = 5937 \text{ mm}^2$

Providing 14 ϕ 25, the reinforcement detail is shown in Figure 19.40.

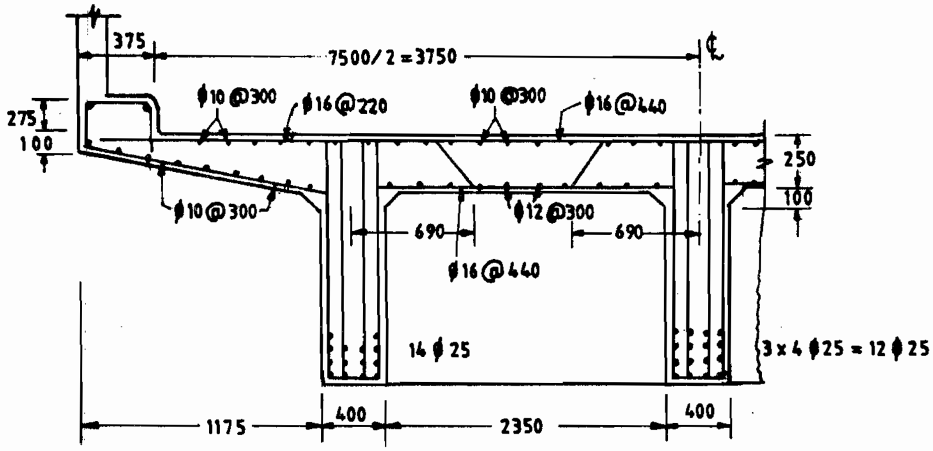


Figure 19.40 : Reinforcement in Cross-section of T-Beam Bridge

19.7 SUMMARY

Slab bridges (culverts), girder and slab (T-beam) bridges, hollow girder bridges, rigid frame bridges, arch bridges and bow-string girder bridges are the usual type of reinforced concrete bridges. The selection of type of bridges for a certain location depends mostly on cost considerations and also on natural conditions.

Live loads as standardized by the Indian Road Congress (IRC) has to be considered in the design of a highway bridge. The loads have been classified under four categories namely Class AA, Class 70 R, Class A and Class B loading. The loading should be so arranged as to produce maximum bending moment and shear force in the component under consideration. Slabs carrying wheel loads can be analysed by use of Pigeaud's Coefficients, effective with method or by Westgard's method.

Effective width method is applicable for the following two support conditions of a rectangular slab :

(i) slab simply supported on two opposite edges,

(ii) slab supported on all four edges and aspect ratio (B/L) very large.

Pigeaud's Coefficients method of analysis is employed for slabs simply supported on all its four edges with corners hold down.

19.8 ANSWERS TO SAQs

Refer the relevant preceding text in the unit or other useful books on the topic listed in the section "Further Reading" to get the answers of the SAQs.