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GUIDELINES FOR THE ANALYSIS AND DESIGN OF CAST-IN-PLACE VOIDED SLAB SUPERSTRUCTURE

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GUIDELINES FOR THE ANALYSIS AND DESIGN OF CAST-IN-PLACE VOIDED SLAB SUPERSTRUCTURE

1. INTRODUCTION

1.1. The Reinforced, Prestressed and Composite Concrete Committee (B-6) of the Indian Roads Congress was reconstituted in 2003 with the following personnel:

Ninan Koshi	...	*Convenor*
Addl. DGBR	...	*Co-Convenor*
T. Viswanathan	...	*Member-Secretary*

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Secretary, IRC
(R.S. Sharma)

Corresponding Members

Ashok Basa
C.V. Kand

1.2. At its first meeting on 29th April, 2003, the Committee felt that in the light of the massive construction programme that was under execution in the highway sector, it was necessary to bring out guidelines on certain topics which were not adequately covered in the existing IRC Codes and Standards. The design and construction of cast-in-place voided slab superstructures was one of the topics selected. It was decided that while highlighting the special design and detailing requirements in each case, the guidelines would be generally in line with IRC:18 and IRC:21 with additional inputs from BS:5400, EURO and AASHTO codes, wherever necessary.

1.3. The initial draft of the guidelines was prepared by Shri T. Viswanathan and Dr. N. Rajagopalan with some inputs from Shri C.V. Kand. The draft was discussed by the B-6 Committee at several meetings and finalized in its meeting held on 3rd September, 2004. The draft document was approved by the Bridges Specifications and Standards Committee in its meeting held on 2nd December, 2004 and by the Executive Committee on 18th December, 2004. The document was considered by IRC Council in its 173rd meeting held on 8th January, 2005 in Bangalore and approved with certain modifications.

The required modifications were accordingly carried out by the Convenor, B-6 Committee before sending the document for publication.

2. SCOPE

The guidelines provide the basic approach for analysis of voided slab superstructures by different methods, design of various members and information on general reinorcement detailing. The designer is advised to consult relevant specialist literature on the subject, if further information is required.

3. CROSS-SECTION DIMENSIONS

3.1. The voids can be rectangular or circular.

3.1.1. For slabs provided with circular voids, the centre-to-centre spacing of the voids should not be less than the total depth of the slab.

3.1.2. In case of circular voids, the ratio of the diameter of void to the total depth of slab shall not exceed 75 per cent in order to avoid transverse distortional effect.

3.1.3. The thickness of the web shall be as per Clause 9.3.1.1 of IRC:18-2000 for prestressed concrete slabs and as per Clause 305.2 of IRC: 21-2000 for reinforced concrete slabs.

3.1.4. For reinforced concrete slabs: The thickness of concrete above the void shall not be less than 200 mm and that below the void shall not be less than 175 mm.

3.1.5. For prestressed concrete slabs: If the cables are not located in the flanges, the thickness of flange shall be governed by provision as in para 3.1.4. If the cables are located in the flanges (not in the web region), the thickness of flanges shall be in accordance with the Clause 16.1 of IRC:18-2000.

3.1.6. For rectangular voids, in addition to the above the transverse width of the void shall not exceed 1.5 times the depth of the void.

3.2. The portion of the slab near the supports in the longitudinal direction on each side, shall be made solid for a minimum length equivalent to the depth of slab or 5 per cent of the effective span whichever is greater.

3.3. Materials used for Void Formers

Void formers are required to possess the necessary rigidity and integrity of dimensions in addition to being water tight.

The void formers may be manufactured from materials, such as, steel sheets, card board, fibre reinforced cement, timber, expanded polystyrene, HDPE, etc. They are generally corrugated for rigidity. Special machines are available for manufacture of corrugated steel void formers, identical to those used for manufacture of pre-stressing cable ducts.

4. ANALYSIS OF STRUCTURE

4.1. The structure shall be analysed both for longitudinal as well as transverse structural actions.

4.1.1. Where the voids conform to the dimensional requirements given above and the void ratio does not exceed 40 per cent, the structure may be analysed as a solid slab for bending moments and shear forces due to longitudinal actions. Other transverse structural actions can be evaluated using the procedure outlined in para 5.2.3.

Void ratio is the ratio of area of the voids to the total area of the slab without deducting the area of voids.

This method is applicable to right and skew bridges with skew angle upto 20°.

4.1.2. If the void ratio exceeds 40 per cent, the structure shall be analysed by any one of the following methods:

(i) Orthotropic Plate
(ii) Grillage Analogy
(iii) Three Dimensional Continuum

4.1.3. If the dimensional parameters mentioned in para 3.1.1., 3.1.2 and 3.1.6 above are not satisfied, any other appropriate method of analysis shall be carried out for taking into account the distortional effect.

5. ORTHOTROPIC PLATE METHOD

The effects of live load can be obtained by adopting the orthotropic plate theory. This method is applicable to right and skew bridges with skew angle upto 20°.

5.1. Analysis & Design for Longitudinal Action

The design forces (bending moment and shear) for longitudinal structural action shall be calculated using the parameters given in ***Appendix-1***, and normal design procedure may be followed.

5.2. Analysis & Design for Transverse Action

5.2.1. Evaluation of Q_y : The shear force Q_y in the transverse direction due to 20T axle load can be evaluated by using the graph shown in ***Appendix-2***. For any other axle load, the value Q_y can be eavaluated by multiplying Q_y obtained from the graph by the ratio of heaviest axle load in tonnes to 20 tonnes.

5.2.2. Design of compression and tension flanges : The transverse moment M_y may be obtained as shown below for the different methods of analysis outlined in para 4 and the moment M_y will be further resolved as axial forces in the compression and tension flanges by using centre-to-centre distance of flanges as lever arm.

(i) Solid Slab Analysis :

M_y shall be taken as 0.3 times the moment in the longitudinal direction due to live load plus 0.2 times the moment in the longitudinal direction due to dead load.

(ii) Orthotropic Plate Analysis :

M_y shall be the same as obtained from the global analysis.

(iii) Grillage (Analogy) Analysis

M_y is the moment obtained for the transverse beam of the grillage system.

(iv) Three Dimensional Constinuum Analysis :

M_y need not be eavaluated. However, the compressive and tensile axial forces in the flanges shall be arrived by integrating the normal stresses in the y-direction on the compression and tension flanges.

The tension flange shall be designed for an axil tensile force of $\frac{M_y}{h_e}$ and reversible bending moment of $M_y = \frac{Q_y}{2} x \frac{d}{4}$ and the compression flange shall be designed for an axial compressive force of $\frac{M_y}{h_e}$ and a reversible bending moment of $M_y = \frac{Q_y x d}{4}$ where Q_y is the transverse shear, d is the diameter of the void, h_e is the centre-to-centre distance of compession and tension flange. In case of rectangular void, the compression flange shall be designed for a reversible moment $M_y = \frac{Q_y x S}{4}$ of along with the axial compressive force and the tension flange shall be designed for a reversible moment of $M_y = \frac{Q_y x S}{4}$ along with the axial tensile force where S is distance between centre-to-centre of void.

5.2.3. Design of web

5.2.3.1. Rectangular voids : In case of rectangluar voids, the web shall be designed for local bending moment of $M_y = \frac{Q_y S}{4}$. This reinforcement requirement shall be provided in the form of links, however, only one leg of such link may be considered to contribute to the required area of reinforcement. This area should be added to that required to resist the longitudianl shear to give the total required area of link reinforcement.

5.2.3.2. Circular voids : In case of circular voids, the occurance of cracks initiating from the inside of void has to be prevented by limiting the maximum tensile stresses at the surface of the voids. The maximum tensile stresses shall be computed using the graph shown in ***Appendix-3*** and it shall be ensured that the tensile stresses shall not exceed the allowable value of $0.36 \sqrt{f_{ck}}$

where f_{ck} and the allowable tensile stress both are in MPa. Following two cases have to be considered:

(i) Tensile stresses less than allowable tensile stresses

Cracking at the inside of a void would not occur in this situation and vertical reinforcement in the webs should be provided to resist the bending moment of $\left(Q_y \, {S}/{h_e}\right) \times \left({d}/{4}\right)$.

This reinforcement requirement shall be provided in the form of links; however, only one leg of such link may be considered to contribute to the required area of reinforcement. This area should be added to that required to resist the longitudinal shear to give the total required area of link reinforcement.

(ii) Tensile stresses more than allowable limits

In this case, cracking would occur at the inside of the void and inclined reinforcement shall be provided. The inclined reinforcement shall be provided to resist the tensile force of $T = \dfrac{Q_y S}{2 h_e \cos\alpha}$, where α is the slope of the inclined reinforcement (to the horizontal). This reinforcement shall be provided in the form of links or bars and in case it is provided in the form of bars, it shall be anchored by lapping the compression and tension flange reinforcement.

Alternative to inclined reinforcement, one additional layer of horizontal reinforcement may be provided to resist the bending moment of $M_v = Q_y d \sin {\phi}/{2}$ at a distance of $d \sin {\phi}/{2}$.

6. GRILLAGE ANALOGY

Standard grillage programme can be used to analyse the structure. This method can be adopted for right, skew and curved bridges. The boundary conditions for the grillage elements shall be properly introduced based on the direction of placement of bearing.

The bending moment and shear forces will be taken as it is for longitudinal structural action. For transverse structural action, the corresponding design forces, such as, transverse shear, bending moment and axial forces in the flanges and bending moment and shear in the web shall be evaluated as outlined under the orthotropic plate method.

7. THREE DIMENSIONAL CONTINUUM ANALYSIS

Three dimensional continuum analysis shall take care of all structural action both in longitudinal and transverse directions with appropriate structural properties. This can be achieved by performing finite element analysis using stiffness approach by discretising the structure into number of elements and having the displacement evaluated using the appropriate boundary conditions and loading. Discretisation of the elements can be left to the designer. However, it shall only be surface element, such as, plate element, plate shell element, solid brick element with or without shear deformations.

The bending moment and shear forces will be taken as it is for longitudinal structural action. For transverse structural action, the corresponding design forces, such as, transverse shear, bending moment and axial forces in the flanges and bending moment and shear in the web shall be evaluated as outlined under the orthotropic plate method.

8. MINIMUM TRANSVERSE REINFORCEMENT IN FLANGES

The transverse reinforcement in flanges shall be provided in two layers, one layer closer to the crown of the void and other closer to the outer surface. The area of transverse reinforcement in compression flange should be lesser of 1000 mm^2/m (500 mm^2/m in each layer) or 0.7 per cent of the minimum flange area. The tension flange shall be provided with transverse reinforcement of 1500 mm^2/m (750 mm^2/m in each layer) or 1 per cent of the minimum flange area whichever is lower.

For the purpose of calculating the reinforcement, the minimum flange area of each layer of concrete shall be arrived at by taking the thickness of concrete layer equal to twice the relevant cover plus the bar diameter.

9. MINIMUM LONGITUDINAL REINFORCEMENT

9.1. RCC Slabs

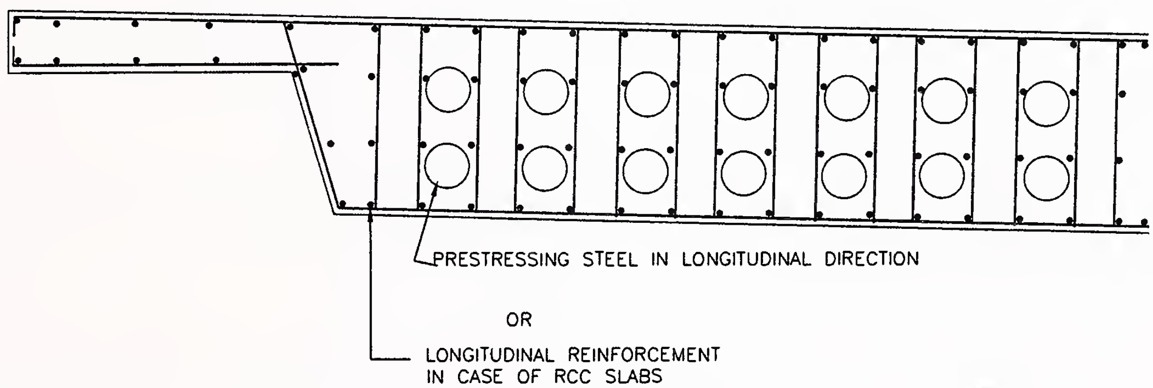
The minimum longitudinal reinforcement in slabs shall be as per Clause 305.19 of IRC:21-2000. The minimum reinforcement shall be provided according to method of analysis adopted. Curtailment of reinforcement shall be as per Clause 305.7 of IRC:21-2000.

9.2. Prestressed Slabs

The minimum reinforcement shall be provided as per Clause 15.1 of IRC:18-2000.

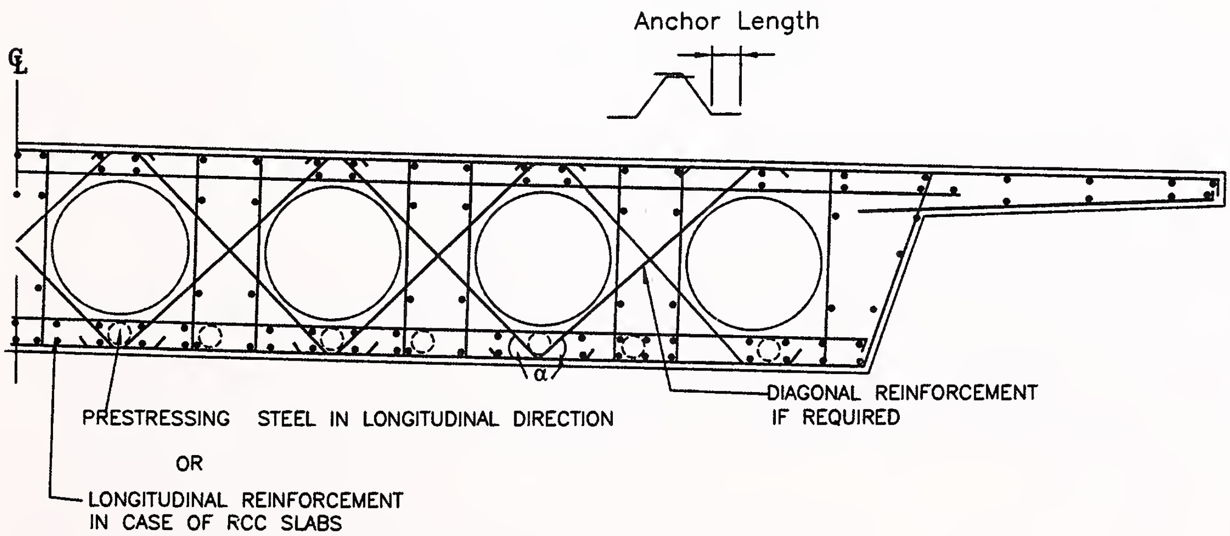
10. DETAILING

Typical reinforcement detailing for voided slab is shown in Fig. 1. and Fig. 2.



Notes : *1. Reinforcements are as per design requirements.*
2. The Sketch is indicative only.

Fig. 1. Detailing of Reinforcement at Solid Section near Support



Notes : *1. Reinforcements are as per design requirements.*
2. The Sketch is indicative only.

Fig. 2. Detailing of Reinforcement at Voided Section

11. REFERENCES

In this publication reference to the following IRC, AASHTO Standards has been made. At the time of publication, the editions indicated were valid. All Standards are subject to revision and the parties to agreements based on these guidelines are encouraged to investigate the possibility of applying the most recent editions of the Standards.

11.1. Codes and Specifications

1. IRC:18-2000 Design Criteria for Prestressed Concrete Road Bridges (Post-Tensioned Concrete (Third Revision)
2. IRC:21-2000 Standard Specifications and Code of Practice for Road Bridges, Section-III, Cement Concrete Plain and Reinforced (Third Revision)
3. AASHTO LRFD Bridge Design Specifications: 1999 (Interim)

11.2. Papers & Publications

1. Baidar Bakht & Leslie G. Jaeger 'Bridge Analysis Simplified'
2. Derrick Beckett 'An Introducation to Structural Design'
3. Edmund C. Hambly 'Bridge Deck Behaviour'
4. L.A. Clark 'Concrete Bridge Design to BS:5400'
5. G. Elliot, L.A. Clark and R.H. Symmons 'Test of Quarter Scale Reinforced Concrete Voided Slab Bridge' (Cement and Concrete Association, London)
6. L.A. Clark and P. Thorogood 'Transverse Shear in RC Circular Voided Slabs' Institution of Structural Engineers (UK), 21st June, 1994.

Appendix-1

ANALYSIS BY ORTHOTROPIC PLATE METHOD

Flexural Parameter

$$\theta = {}^{b}\!/\!_{L}\left(\frac{D_x}{D_y}\right)^{0.25}$$

Torsional Parameter

$$\alpha = \frac{D_{xy} + D_{yx} + D_1 + D_2}{2(D_x D_y)^{0.5}}$$

$$D_x = E_c\left(\frac{t^3}{12} - \frac{\pi t_v^4}{64 P_y}\right)$$

$$D_y = \frac{E_c\, t^3}{12}\left[1 - 0.95\left(\frac{t_v}{t}\right)^4\right]$$

$$D_{yx} = D_{xy} = \frac{G_c\, t^3}{6}\left[1 - 0.84\left(\frac{t_v}{t}\right)^4\right]$$

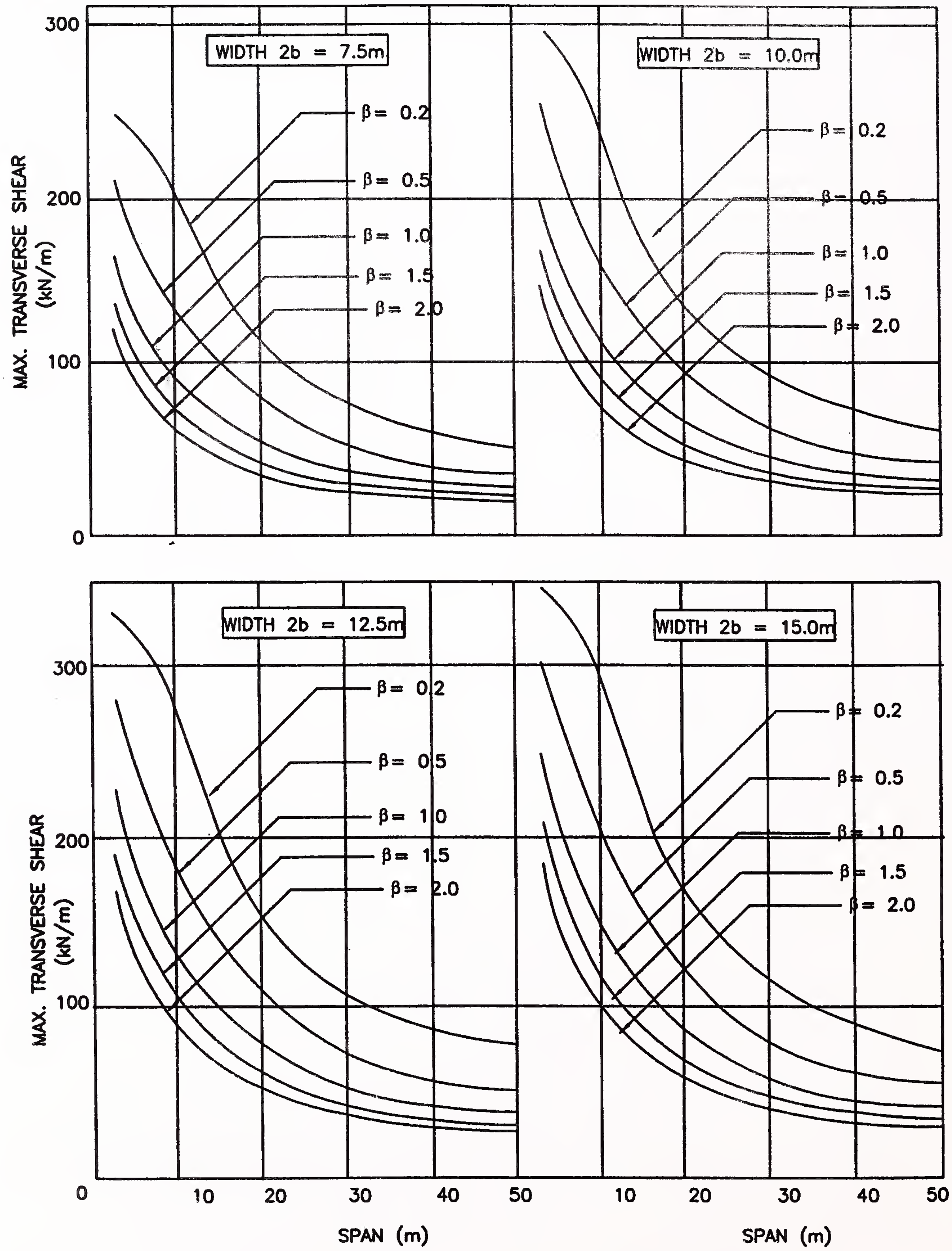
$$D_1 = \mu_c D_y ; D_2 = \mu_c D_y$$

θ	=	Flexural parameter
α	=	Torsional parameter
b	=	½ the width of the equivalent orthotropic plate
L	=	Effective span
D_x	=	The longitudinal flexural rigidity per unit width
D_y	=	The transverse flexural rigidity per unit length
D_{xy}	=	The longitudinal torsional rigidity per unit width
D_{yx}	=	The transverse torsional rigidity per unit length
t	=	The thickness of slab
t_v	=	The diameter of the void
P_y	=	Spacing of the void
μ_c	=	Poission's ratio
D_1	=	The longitudinal coupling rigidity (which is the contribution of transverse flexural rigidity to longitudinal torsional rigidity through Poission's ratio) per unit width
D_2	=	The transverse coupling rigidity per unit length
E_c	=	Modulus elasticity of concrete
G_c	=	Shear modulus of concrete

In the absence of more accurate methods, the above expressions may also be used for those voided slab bridges in which the circular voids are not symmetrically placed between the top and bottom surfaces.

Appendix-2

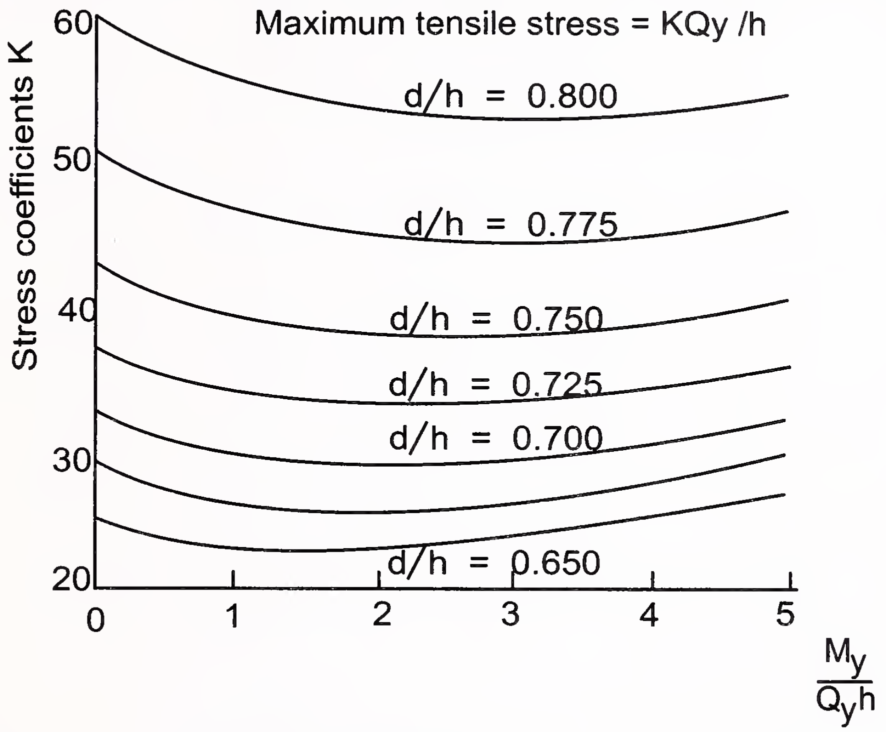
MAXIMUM TRANSVERSE SHEAR FOR DIFFERENT PLATE WIDTHS



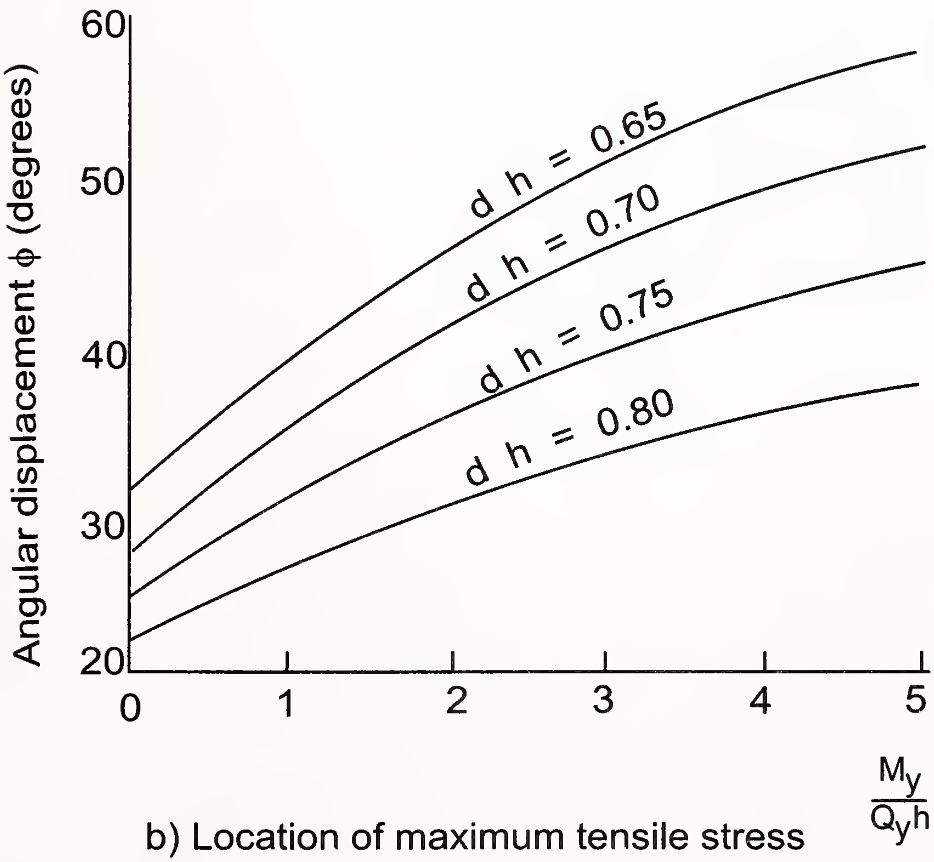
Maximum Transverse Shear Intensity due to 20-Tonne Axle Load

$$\beta = \pi \left(\frac{2b}{L}\right) \left(\frac{D_x}{D_{xy}}\right)^{0.5}$$

MAXIMUM TENSILE STRESS AT DIFFERENT LOCATIONS



a) Maximum tensile stress at face of void



b) Location of maximum tensile stress

d = diameter of the void

h = height of the slab

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