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Autor: Kupfer, Herbert / Bulicek, Hans

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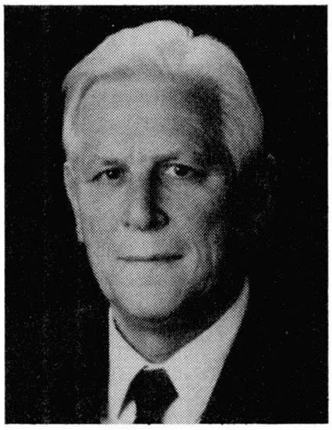
Combined Loading Effects in Concrete Box Girders

Effets des efforts combinés dans des poutres-caisson en béton

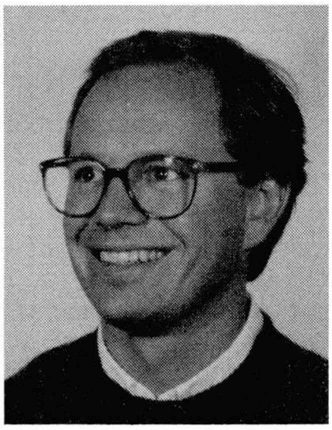
Kombinierte Beanspruchung von Kastenträgern aus Beton

Herbert KUPFER
Prof. of Struct. Eng.
Univ. of Munich
Munich, Germany

Hans BULICEK
Res. Assist.
Univ. of Munich
Munich, Germany



H. Kupfer, born in 1927, obtained his civil eng. degree at the Univ. of Munich in 1949. He was an assistant of Prof. Hubert Ruesch for 6 years. After that he worked at the construction company DYWIDAG, finally as chief engineer. Since 1967 he is full Professor for structural eng. at the Univ. of Munich.



H. Bulicek, born in 1961, obtained his civil engineering degree at the University of Munich in 1988. Since that time he is working as an assistant of Professor Herbert Kupfer.

SUMMARY

Concrete box girders are often subjected to substantial combined loading effects such as bending moments, normal forces, shear forces and torsional moments as, e.g. in the case of cable-stayed bridges suspended in the middle axis. Based on the «shear-wall-model» a consistent design method for the ultimate limit state is presented.

RÉSUMÉ

Les poutres-caisson en béton sont souvent substantiellement soumises aux actions combinées des moments de flexion, de l'efforts normal, des efforts tranchants et des moments de torsion, comme par exemple dans le cas de ponts haubanés soutenus par les câbles d'un support central. Une méthode cohérente de dimensionnement est présentée ici afin d'évaluer l'état de limite ultime.

ZUSAMMENFASSUNG

Kastenträger aus Beton unterliegen oft hohen kombinierten Beanspruchungen aus Biegung, Normalkraft, Querkraft und Torsion wie zum Beispiel bei Schrägkabelbrücken mit Mittelaufhängung. Auf der Grundlage des Schubwandmodells wird ein konsistentes Bemessungskonzept für den rechnerischen Bruchzustand vorgestellt.

1. INTRODUCTION

National codes as well as international codes dealing with concrete structures mostly cover the combined effects of actions by the use of empirical formulas or even neglect the interaction. A standardized consistent design model is missing. A more detailed consideration of the combined action-effects especially is recommended for slender box girders which are substantially subjected to combined effects of actions such as bending moments, normal forces, shear forces and torsional moments.
This paper presents a universal method for the design of concrete box girders in the ultimate limit state by the use of the "shear-wall-model" under consistent consideration of the load transfer by the webs and the chords. Combined action-effects such as slab moments and in-plane load are not treated in this paper.

2. DESIGN PROCEDURE

2.1 Design Principle

As long as bending moments acting in a horizontal plane are not considered, the action-effects such as bending and normal force as well as the longitudinal forces resulting from the diagonal compression field in the webs are allocated to the chords. The webs carry the shear forces. Torsional moments, however, affect webs and chords. Following this rule of distributing the action-effects, slender beams such as box girders can be divided into "shear-walls" being dimensioned for parts of the considered effects of actions. By this way inconsistences and overstresses are avoided. The distribution of the considered action-effects within the respective shear walls is given if a suitable inclination θ of the resulting compressive stress field in each web is derived according to the next paragraph. With regard to the following explanations it is required that the shear reinforcement is located rectangular to the axis of the beam. Furthermore all strengths, strains and action effects are supposed to be derived at "design level" according to reference [1] so that the subscript "d" is renounced within this paper. The action-effects thereby have to be derived taking account of prestressing forces.

2.2 Webs

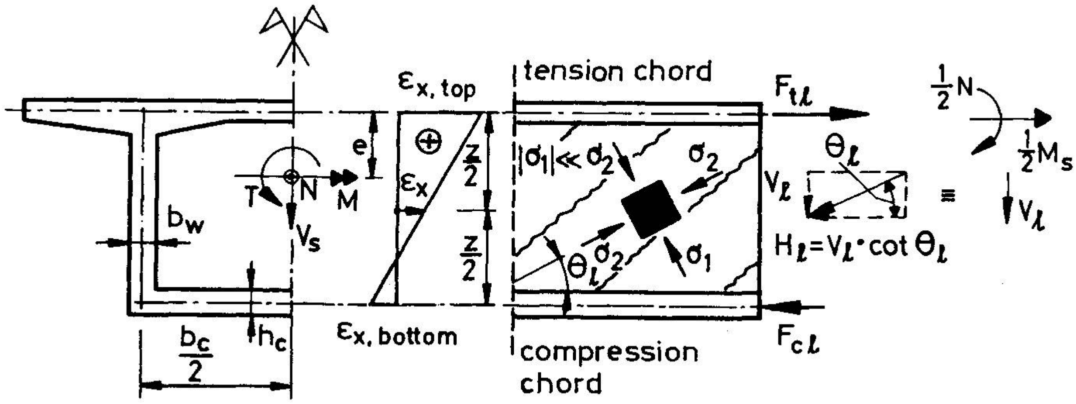


Fig. 1 Notations

Webs of continous beams mainly are subjected to shear forces V_s and the effects V_t of torsional moments T. For bearing this kind of action-effect the modified truss analogy turned out as a suitable model for calculating the magnitude of concrete stresses as well as the amount of the required shear reinforcement in the webs. In reference [2] a consistent model for calculating the resulting stress state in the webs has been developed. The model fulfills the compatibility of deformations in the web and considers the influence of the average axial strain ϵ_x of the chords upon the shear resistance of the webs. It turns out that a biaxial stress field prevails in the web concrete characterized by a predominating principal compressive stress σ_2 and a perpendicular acting subordinated principal compressive or tensile stress σ_1 (see figure 1). For practice design, however, it is confirmed that a uniaxial compressive field in the web concrete is a suitable approximation. Figure 1 illustrates the left part of a box girder (subscript "l") as well as the used notations.
Based on the above mentioned model the following applicable design formula can be derived for calculating the inclinations θ of the uniaxial compression field in the web on the left ($\rightarrow \theta_l$) and on the right hand side ($\rightarrow \theta_r$):

$$\tan\theta = 1 - [\Delta\tan\theta_{plast}] \cdot \frac{0.0015 - \epsilon_x}{0.003}$$

where $$\Delta\tan\theta_{plast} = 1 - \tan\theta_{plast} = 1 - \frac{1 - \sqrt{1 - \nu^2}}{\nu}$$

so that the complete formula is:

$$\tan\theta = 1 - \left(1 - \frac{1 - \sqrt{1 - \nu^2}}{\nu}\right) \cdot \frac{0.0015 - \epsilon_x}{0.003} \qquad \begin{cases} \tan\theta \geq \frac{1}{3} \\ \tan\theta \geq \frac{1 - \sqrt{1 - \nu^2}}{\nu} \end{cases} \qquad (1)$$

where $$\nu = \frac{2V}{b_w \cdot z \cdot f_{cd2}} \qquad (2)$$

The vertical force V in equ. (2) acting in the web has to be determined for the web on the left hand side (V_l) as well as on the right hand side (V_r) according to the following equations:

$$V_l = \frac{V_s}{2} + \frac{T}{2b_c}; \qquad V_r = \frac{V_s}{2} - \frac{T}{2b_c} \,. \qquad (3)$$

Thereby the average strain ϵ_x of the webs follows from the strains in the chords as:

$$\epsilon_x = \frac{\epsilon_{x,top} + \epsilon_{x,bottom}}{2} \qquad (4)$$

where the chord strains (considered as positive in case of tensile strain) have to be derived taking account of the chord forces given by equ. (7) and (9) respectively. The required iterative calculation of ϵ_x and θ shows a quick convergency since the strain in the chords is influenced only slightly by the value of θ.
Thus the resulting amount of vertical shear reinforcement can be derived from:

$$\omega = \frac{2 \cdot A_{sw} \cdot f_y}{s \cdot b_w \cdot f_{cd2}} = \nu \cdot \tan\theta = \frac{2 \cdot V}{f_{cd2} \cdot b_w \cdot z} \cdot \tan\theta \,. \qquad (5)$$

Figure 2 illustrates the resulting design curves according to the preceding equations.
The associated strut inclinations θ_l and θ_r for the web on the left as well as on the right hand side can be read from figure 2 taking account of the average axial strain in the chords according to equ. (4). Thus the resulting horizontal tensile force which has to be considered with regard to the chords in addition to the effects of M and N is:

$$\Sigma H = H_l + H_r = |V_l| \cdot \cot\theta_l + |V_r| \cdot \cot\theta_r \,. \qquad (6)$$

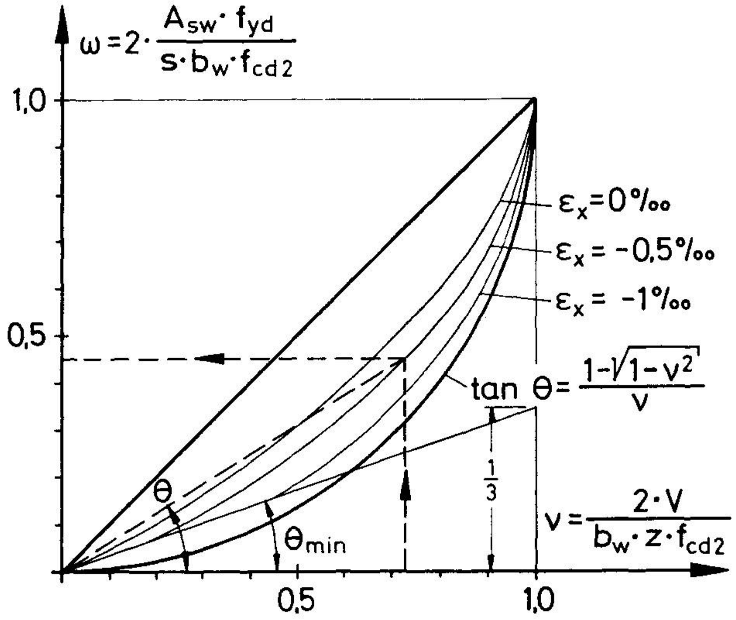


Fig. 2 Required vertical shear reinforcement in the web

2.3 Chords

2.3.1 Compression chords

The compression chords in concrete box girders are subjected to the longitudinal compressive force F_c:

$$F_c = \frac{M_s}{z} - \frac{\Sigma H}{2} \quad \text{whereby} \quad M_s = M + N \cdot e \tag{7}$$

Furthermore they are affected by a variable shear flow having a magnitude of V_l/z on the left and of V_r/z on the right hand side resulting from shear and torsion (see figure 3). With regard to the following evaluation the course of this shear flow is supposed to be approximately linear although strictly speaking a nonlinear course adjusts between the left and the right hand side due to the differential connection to the associated longitudinal stresses σ_x. In a considered element the compressive strength f_{cd1} (according to [1] applying to a uniaxial loaded concrete prism under sustained load) can not be taken as the admissible longitudinal stress σ_x if shear stresses are acting at the same time. Therefore the ultimate longitudinal stresses σ_x (see figure 3) are determined in this paper in terms of the acting shear stresses in the compression chord by the use of a suitable fracture criterion for a combined loaded concrete element as illustrated in figure 4.

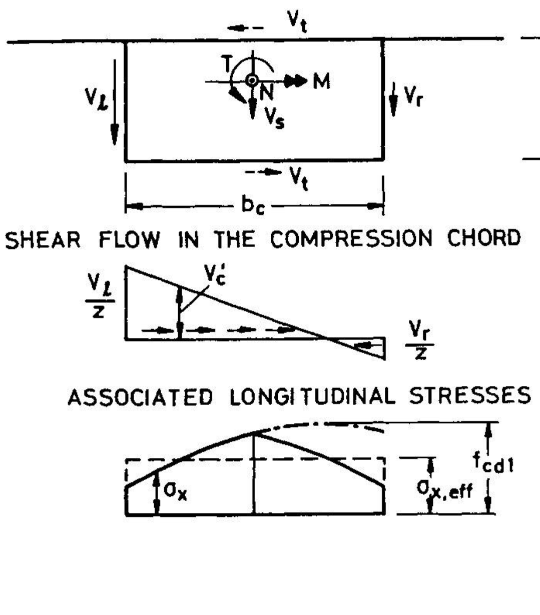


Fig. 3 Stress state in compression chords

In it the concrete compressive strength is supposed to be f_{cd1} in case of pure longitudinal compression of the uncracked concrete whereas it is reduced to 0.8 f_{cd1} in case of pure shear due to the diminishing influence of cracks. The almost elliptic course of the interaction diagram of figure 4 in the range of $0,4 \leq \sigma_x/f_{cd1} \leq 1,0$ (passed through line) is obtained by the use of reference [3] assuming a magnitude for $\sigma_y = \rho_y \cdot f_y$ (represented by the transverse reinforcement) which leads to concrete failure in the element.

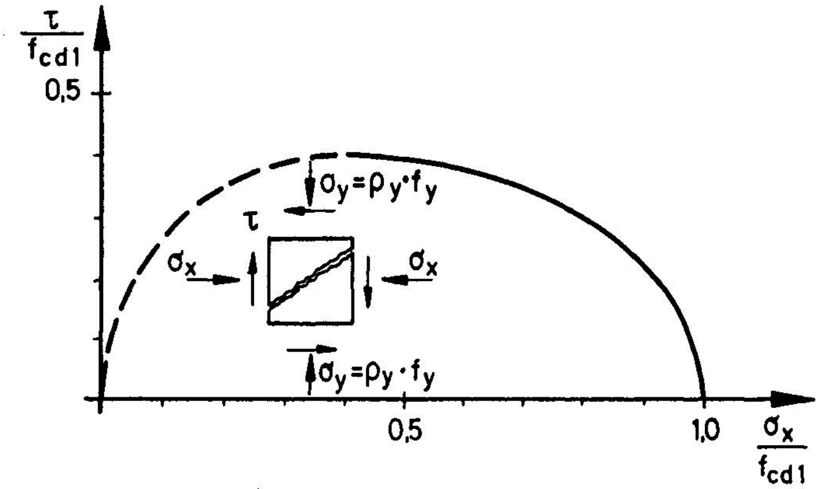


Fig. 4 Fracture criterion for a concrete element in concrete failure

As a simplification on the safe side the course of σ_x along the breadth of the compression chord is supposed to be symmetrically (More favourable values for σ_x could be obtained if the internal horizontal bending moment $(H_l - H_r)\cdot 0,5b_c$ is taken into account for both chords). Thus an average ultimate longitudinal stress $\sigma_{x,eff}$ (see figure 5) is derived applying for combined loaded compression chords by assuming an optimized distribution of load effects within the compression chord according to the theory of plasticity. As a consequence the compressive force F_c according to equ. (7) has to fulfill the following inequality:

$F_c \leq \sigma_{x,eff} \cdot b_c \cdot h_c$ (8).

In regions of the compression chord where $V_c' > F_c/b_c$ (for V_c' see figure 3) a longitudinal reinforcement acc. to $\rho_x \cdot f_y \cdot h_c = V_c' - F_c/b_c$ is required assuming a strut inclination of 45° and a uniform stress distribution of σ_x. The required amount of transverse reinforcement in compression chords can be derived by the use of reference [1].

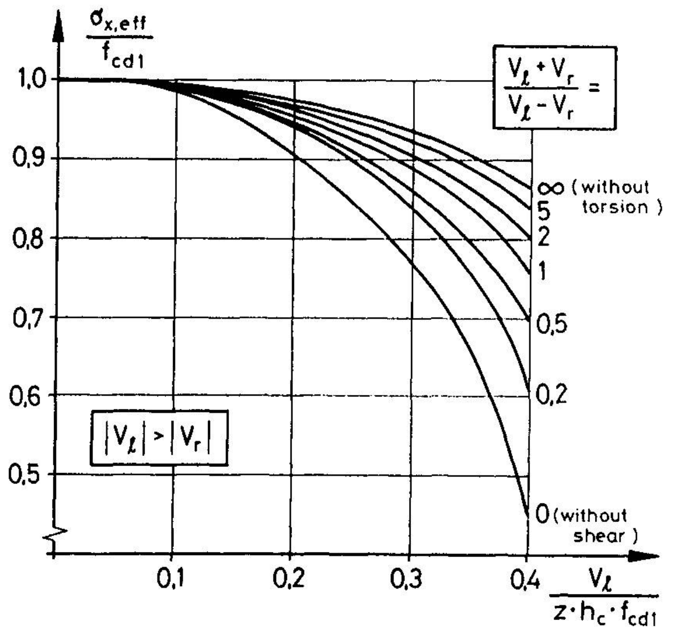


Fig. 5 Average ultimate compressive stress $\sigma_{x,eff}$ in terms of the acting shear forces in the webs

2.3.2 Tension chords

Tension chords in concrete box girders are subjected to the longitudinal tensile force F_t:

$$F_t = \frac{M_s}{z} + N + \frac{\Sigma H}{2} + \frac{T}{2z} \, . \qquad (9)$$

The term $\Sigma H/2$ in equation (9) only covers the horizontal part of the diagonal forces in the webs without including the effects of the diagonal stress field in the tension chord itself. Therefore only those prestressing tendons or reinforcing bars (crossing the decisive section) can be taken into account which are anchored more far from the decisive section than from the nearest web. This is not required for reinforcing bars or prestressing tendons which are curtailed due to a varying magnitude of the torsional moment supposing that this curtailed reinforcement is steady distributed within the tension chord inbetween the webs.

3. SUMMARY

This paper presented a consistent model for the design of concrete box girders which are subjected to combined action-effects. It is based on the shear-wall-model under consistent consideration of the load transfer by the webs and the chords. A simple formula for the determination of the resulting strut inclination in the webs under taking into account the chord strains was given to the designer. The resulting distribution of the inner forces within the cross section was observed and the resulting design forces allocated to the shear walls were obtained. Furthermore an average limit value for the ultimate longitudinal compressive stress in combined loaded compression chords was derived in terms of the acting shear forces in the webs.

REFERENCES

1. CEB-FIP Model Code for concrete structures 1990. Bulletin d'information N° 196, Comité Euro-International du Béton. Lausanne, March 1990.

2. KUPFER H., BULICEK H., A Consistent Model for the Design of Shear Reinforcement in Slender Beams with I- or Box-Shaped Cross Section. Proceedings to the International Workshop on Concrete Shear in Earthquake, University of Houston, Texas, December 1990.

3. FIALKOW M. N., Crushing Strength of Reinforced Concrete Membranes. ACI Structural Journal, pp. 485-91, September-October 1988.