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# New Trends in the Design of Steel Bridges in Czechoslovakia

Tendances nouvelles dans le projet de ponts en acier en Tchécoslovaquie

Neue Tendenzen in der Berechnung von Stahlbrücken in der Tschechoslowakei

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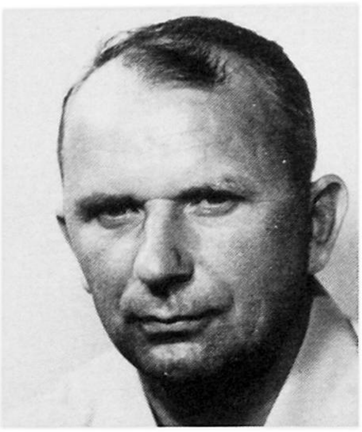
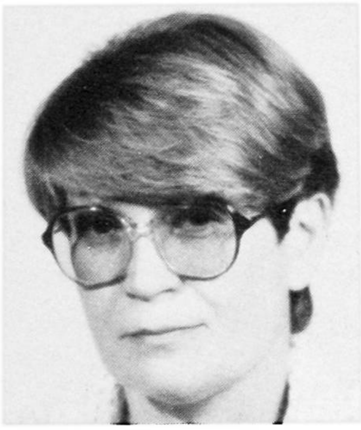




## SUMMARY
The contribution deals with several recent investigations, both theoretical and experimental, into the limit state of plate elements in steel bridges, special attention being paid to the ultimate limit state of longitudinally stiffened compression flanges. On the basis of an analysis of the experimentally determined deformation- and stress states, a definition of the ultimate limit state is presented, and then applied in a theoretical study of the ultimate loads of the longitudinally stiffened compression flanges of steel box girder bridges.

## RESUME
La contribution concerne plusieurs études théoriques et expérimentales, de l'état limite ultime des éléments plans des ponts en acier, faisant attention particulièrement à l'état limite ultime des semelles comprimées raidies. Sur la base d'une analyse des états de déformation et de tension déterminés expérimentalement, une définition de l'état limite ultime est présentée, puis appliquée dans une étude de la capacité portante des semelles comprimées raidies des ponts d'acier en caisson.

## ZUSAMMENFASSUNG
Der Beitrag behandelt einige neuere theoretische und experimentelle Untersuchungen des Grenzzustandes der Plattenelemente von Stahlbrücken, mit spezieller Aufmerksamkeit auf den Traglastzustand von längs ausgesteiften, gedrückten Gurtplatten. Auf der Grundlage einer Analyse der experimentell festgelegten Deformations- und Spannungszustände wird eine Definition des Traglastzustandes gegeben und dann in einer theoretischen Untersuchung auf die Tragfähigkeit von längs ausgesteiften, gedrückten Gurtplatten stählerner Kastenträgerbrücken angewandt.

## 1. INTRODUCTION

The necessity to save steel leads in Czechoslovakia to a fast development of thin-walled plated steel structures. In the domain of steel bridgework it is particularly box girder construction that has grown popular with designers. Thus one of the current tasks of the Czechoslovak research is to give enough information about the behaviour of such bridges. As one of the key problems in this line is that of the limit state of longitudinally stiffened compression flanges, the efforts of three departments /i.e. /i/ Department of Bodies Made of Homogeneous Materials at the Institute of Construction and Architecture , Slovak Academy of Sciences, Bratislava, /ii/ the Department of Metal Structures at the Building Research Institute, Czech Technical University, Prague, and /iii/ the Stability Department at the Institute of Theoretical and Applied Mechanics, Czechoslovak Academy of Sciences, Prague, have been combined to contribute to the solution to the above problem. The objective of this paper is to report briefly about the main results of the research.

## 2. THEORETICAL RESEARCH

One of the Czechoslovak theoretical studies concerning the ultimate limit state of longitudinally stiffened compression flanges was conducted in Bratislava by the first author and his associates.

In this study longitudinally stiffened compression flanges are treated as geometrically orthotropic compressed plates, the solution being corrected in the second stage of the analysis by taking account of the effect of local sheet buckling between longitudinal ribs. The investigation is based on non-linear large deflection theory, the influence of an initial "dishing" /both of the flange as a whole and of its partial sheet panels/ being taken into consideration, and the ultimate limit state is defined /on the basis of the experimental research described below in sec. 3/ by the onset of membrane yielding at the most highly stressed point of the flange sheet.

The ultimate load of the flange is then written as follows:

$$\sigma_{ult} = \sigma_{1N}\, \sigma_{2N}\, R_d \,, \tag{1}$$

where $\sigma_{1N}$ is the coefficient of global flange buckling, $\sigma_{2N}$ that of local flange sheet buckling and $R_d$ the s.c. design strength of the flange material /which in the Czechoslovak Limit State Design approach replaces the yield stress $R_y$; $R_d = 0.87\ R_y$ if $R_y \leq 300$ MPa and $R_d = 0.80\ R_y$ if $R_y > 300$ MPa/.

The large deflection theory analysis is summarized in the following formulae /derived by I. Baláž and the first author/ for the coefficients $\sigma_{1N}$ and $\sigma_{2N}$:

$$\sigma_{1N} = 1 - \frac{\alpha_2}{2}\left[\sqrt{\left(\frac{\psi_1 - \psi_2}{\psi_2}\right)^2 - \frac{2\alpha_3^2}{\sqrt{1+\alpha_2^2} - 1}} - \frac{\psi_1 - \psi_2}{\psi_2}\right], \text{ if } \sigma_{1N} \geq 1 - \frac{\alpha_2}{2}$$

or (2a)

$$\sigma_{1N} = 1 - \alpha_2 \frac{2\alpha_3^2 - \frac{\psi_1 - \psi_2}{\psi_2}\left(\sqrt{1+\alpha_2^2} - 1\right)}{2\alpha_3^2 + \sqrt{1+\alpha_2^2} - 1}, \text{ if } \sigma_{1N} \leq 1 - \frac{\alpha_2}{2} \quad (2b)$$

where

$$\alpha_2 = 0.835 - 0.04\alpha + 0.01\frac{\lambda}{100} \quad (3)$$

$\alpha$ being the side ratio of the flange panel ($\alpha = a/b$) and $\lambda$ its width-to-thickness ratio ($\lambda = b/t$),

$$\alpha_3 = 0.14\alpha + 0.127, \quad (4)$$

$$\psi_1 = \frac{B_x}{B} - \frac{12\nu^2}{1-\nu^2\frac{D}{D_x}}\left(\frac{e_{st}}{t}\right)^2 - 2\alpha^2\left(1 + \frac{GJ_{t,st}}{2Bb_{st}}\right) + \alpha^4,$$

B denoting the flexural rigidity of the flange sheet ($B = Et^3/12(1-\nu^2)$), $B_x$ that of the longitudinally stiffened flange ($B_x = B + Ete_{st}^2/(1-\nu^2) + EJ_{st}/b_{st}$), D the normal rigidity of the flange sheet ($D = Et/(1-\nu^2)$), $D_x$ that of the longitudinally stiffened flange ($D_x = D + EA_{st}/b_{st}$), $e_{st}$ the distance of the centroid of a cross-section having its area equal to $A_{st} + b_{st}t$ (where $A_{st}$ is the area of one longitudinal stiffener, t the thickness of the flange sheet and $b_{st}$ the spacing of the longitudinal ribs), $\nu$ Poisson's ratio of the flange material, G its elasticity modulus in shear. $I_{st}$ the moment of inertia of one longitudinal stiffener with respect to the centroidal axis of the cross-section $A_{st} + b_{st}t$ and $I_{t,st}$ the moment of inertia in tension of one longitudinal rib

$$\psi_2 = (\delta_x - \nu^2)\frac{\alpha^2\lambda^2}{720}\frac{R_d}{210}, \quad (5)$$

$\delta_x$ designating the ratio $D_x/D$.

The local sheet buckling coefficient is worked out as follows:

$$\rho_{2N} = \frac{\rho_N + A_{st}/(b_{st}.t)}{1 + A_{st}/(b_{st}.t)} \quad (6)$$

where for boundary flange sheet panels

$$\rho_N = \frac{40}{\frac{b_{st}}{t} + 10} \sqrt{\frac{210}{R_d}} \quad (7a)$$

and for inner sheet panels

$$\rho_N = \frac{40 \sqrt{\frac{210}{R_d}}}{\frac{b_{st}}{t} + 10} \left(1.3 - \frac{12 \sqrt{\frac{210}{R_d}}}{\frac{b_{st}}{t} + 10}\right), \quad (7b)$$

the design strength, $R_d$, of the flange material being inserted in MPa. The above two formulae were derived by Z. Sadovský and the first author.

The aforesaid orthotropic plate approach is currently being complemented in Bratislava by an analysis of the ultimate limit state of flanges fitted with discrete stiffeners, which case is of practical importance when the number of longitudinal ribs is so small that the orthotropic plate approach is not acceptable. The theoretical studies conducted in Prague at the moment are centred on /i/ a non-linear large deflection variant of folded plate theory and /ii/ the problem of the interaction that exists in wide flanges between shear lag and flange buckling, this latter investigation being performed in cooperation with University of Liège.

## 3. EXPERIMENTAL RESEARCH

One of the experimental studies that have recently been carried out by the second and third authors in Prague also deals with the limit state of longitudinally stiffened compression flanges.

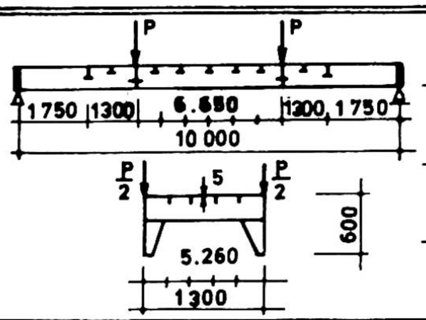
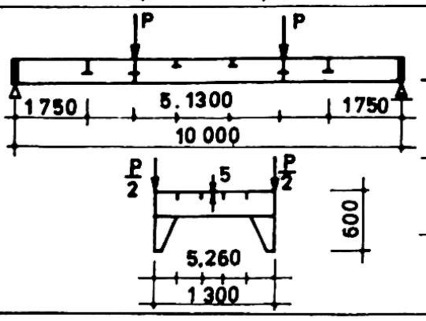
Two series of box girders were tested. The objective of the first series of experiments, comprising four girders, was to look into the difference in behaviour between /a/ compression flanges fitted with /$a_1$/ single-sided and /$a_2$/ double-sided longitudinal ribs and /b/ compression flanges stiffened by /i/ a small number of bulky ribs and /ii/ a large number of flexible ribs. In the other series of experiments, conducted on eight test girders /see Fig. 1/, the number of longitudinal stiffeners was kept constant, but their size and the aspect ratio of the flange panel varied.

The buckled pattern of the compression flange was carefully measured by means of the stereophotogrammetric method. Thanks to a great number of strain gauges being attached to both sides of the flange sheet and of the longitudinal stiffeners, the stress state, the progression of plasticization and the formation of a failure mechanism in the flange was studied.

It has been concluded that the ultimate limit state of longitudinally stiffened flanges of steel box girder bridges can be determined either by the onset of membrane yielding in the flange sheet or by the onset of plasticization in the stiffeners. In the context of the modified orthotropic plate approach /sec. 2 hereabove/, only the onset of membrane yield in the flange sheet can be reflected. Then two question arise:

1. Does the ultimate load calculated via the above definition of the ultimate limit state provide enough safety, or - on the other side - is it not too conservative, with respect to the actual experimental load carrying capacity?

2. Is not the safety of a compression flange, designed via the above approach, jeopardized in the case of steel bridges, subject to intensive variable repeated and dynamic loadings, by local plasticization which occurs in the flange, for example, due to the effects of the peaks of bending stresses that arise as a result of "breathing" of the flange sheet and are not checked by the above definition of the ultimate limit state?

| TEST GIRDER | | LONGITUDINAL STIFFENER | $P_{ult}$ / kN / | YIELD STRESS /MPa | |
|---|---|---|---|---|---|
| | | | | FLANGE | STIFFENER |
|  | TG 1 | - | 450 | 461 | - |
| | TG 2 | 35.8 | 680 | 429 | 374 |
| | TG 3 | 55.8 | 828 | 391 | 311 |
| | TG 4 | 65.8 | 920 | 391 | 414 |
|  | TG 5 | - | 450 | 490 | - |
| | TG 6 | 55.12 | 800 | 242 | ? |
| | TG 7 | 90.12 | 1060 | 431 | 287 |
| | TG 8 | 110.12 | 1100 | 439 | 432 |

As for the first question, the experimental results show that - in the case of the authors´ test girders - the plastic reserve of the onset-of-membrane yielding loads with respect to the failure loads was of about 25%; i.e. it can be regarded as fitting for the compression flanges of steel box girder bridges.

In order to give a reply to the other question, the second and third authors analysed in detail the membrane and bending stresses that occurred in the compression flanges of the test girders at different levels of the load and came to the conclusion that their intensity was such that at loadings lower than the above defined ultimate loads /and the more so at loadings which would correspond to the level of the working loads of the structure/no danger of incremental collapse or low-cycle fatigue developed.

As the large-scale girders /of length $l = 10$ m and fabricated following exactly the technique used in the production of ordinary steel bridges/ tested in Prague can be regarded as reasonably representative for steel box girder bridges, it can be anticipated that the aforesaid conclusions hold generally.

Thus, it is concluded that the onset of membrane yielding can serve as a reliable definition of the ultimate limit state of the longitudinally stiffened compression flanges of steel box girder bridges, and may safely be employed in theoretical analyses such as that presented hereabove in sec. 2.

Another extensive experimental investigation conducted currently by the second and third authors in Prague deals with the ultimate limit state of longitudinally stiffened webs subjected to partial edge loading. This problem is of importance , for example, when a bridge structure is "launched out" into its definitive position above the river. 94 girders have been tested to date. It has been concluded that the effect of the longitudinal stiffener on an increase in ultimate load is significant /in the authors' tests it amounted to 30-45%/ only when the stiffener is located close $(b_1 < b/4$, b being the web depth$)$ to the loaded flange and its size is sufficient for the stiffener to behave as a fully effective one. Formulae for the optimum rigidity of such a stiffener and for the ultimate loads of such webs were also derived.

## 4. COMPARISON BETWEEN THEORY AND EXPERIMENTS

It is of interest to check how the theoretical approach presented in sec. 2 correlates with the results of the experiments on longitudinally stiffened flanges described in sec. 3. An analysis of the experimental conclusions shows that the predicted ultimate loads correlate very well /the difference amounting merely to less than 10% on the safe side/ with the experimental onset-of-membrane yielding loads - as it should be. For this reason this approach has been incorporated /as one of the two normative approaches for the design of stiffened compression flanges, the other one being based on a bar simulation analogy/ into the new edition of the Czechoslovak Design Code for Steel Bridges.