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Buckling behavior of the web panel subjected to bending and transverse stresses, considering the torsional stiffness of the stiffeners

PROJECT OBJECTIVES AND GOALS

In view of aesthetic aims as well as economic efficiency slender bridges are composed of thin plates prone for buckling. Bridges with large spans are built using the incremental launching method (ILM). When steel and steel composite bridges are pushed forward using the incremental launching method, high reaction forces occur, particularly at the supports, which are introduced as transverse stresses into the web and bottom panel (Fig. i).

The stresses that occur in the construction state due to the incremental launching method are in most cases decisive for the design of the bridge.

Fig. ii shows the structure and the stresses of the box girder. As a result of the reaction force q_A, a multiaxial stress state occurs in both the web panel and the bottom panel. The web panel is subjected to a bending loading in the longitudinal direction and to one-sided transverse stresses. Due to inclined web panels a biaxial stress state may also act on the bottom panel.

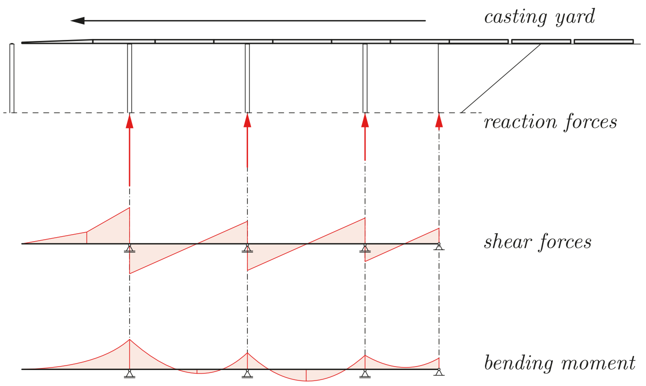

Fig. i: *Schematic representation of the incremental launching method with the reaction forces and the shear and bending moment distributions.*

However, EN 1993-1-5 [2] lacks rules for the analysis of panels subjected to multiaxial stresses, and the existing rules are not sufficiently verified. In practice, these cases are either calculated incorrectly or with conservative assumptions. Therefore, it was necessary to intensively investigate the panels under multiaxial loading, which has been done in research projects [4, 5, 6]. This work is a part of the result of project [5]. The aim of the projects was to review existing design rules and to develop safe and economic design rules.

This master thesis focused on the investigation of the web panel subjected to pure bending in longitudinal direction and one-sided transverse stresses (patch loading). It gives solutions for the verification of the subpanels of the web panel where the transverse stresses are distributed non-linearly in the plate due to patch loading. It also discusses the need to consider the nonlinear stress distribution in determining the critical buckling stress $\sigma_{cr,c,z}$ in the transverse direction.

Recent investigations have shown that considering the torsional stiffness of the longitudinal stiffener in the buckling design leads to an overestimation of the load bearing capacity [8]. The reliability of the global buckling check considering the torsional stiffness of the stiffener is also investigated in this thesis. A simplified approach to consider the torsional stiffness in the buckling analysis is recommended in this thesis.

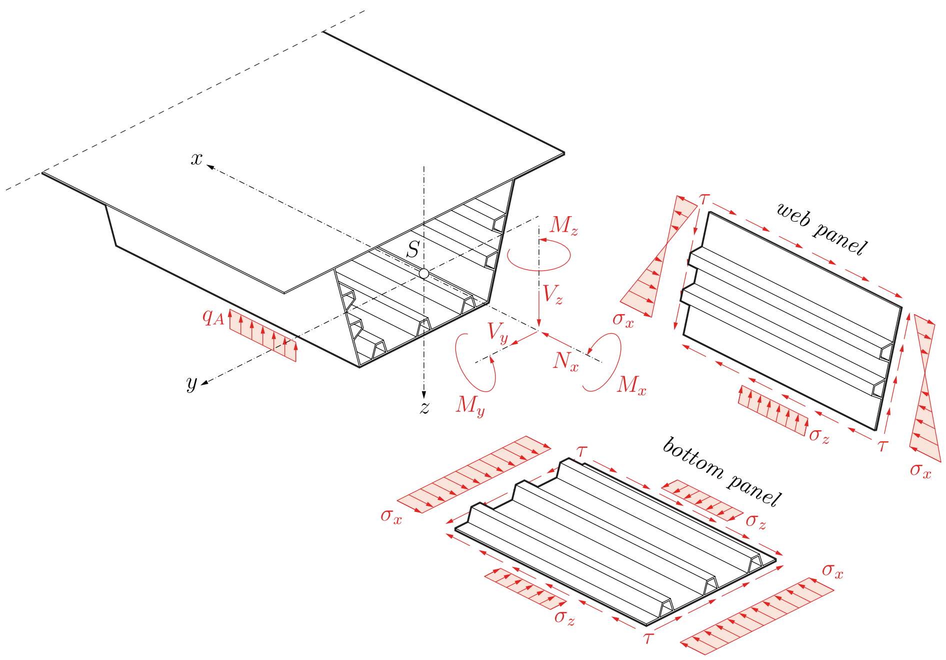

Fig. ii: *Box girder with the loads due to bending and the locally applied reaction force* q_A [3].

ANALYSIS OF THE NON-STIFFENED PLATE

One of the investigation points of the sub-panel is the determination of the transverse stress at the edge of each sub-panel due to transverse stresses. It leads to a non-linear stress distribution over the height of the web panel. The stress distribution in the middle of the panel is decisive. There is a number of methods that can precisely or approximately describe this process. Exact solutions include the use of FE software or analytically by solving the partial differential equation (biharmonic equation). Furthermore, solutions exist that serve as an approximation to the analytical solution in various publications.

Fig. iii shows the exact (analytical) transverse stress distribution $\sigma_z(z)$ along the panels height and the stress distribution $\sigma_z(z)$ along the panel width in horizontal sections. Verifying the sub-panel requires the resulting forces along the horizontal sections. The horizontal curves $\sigma_z(z)$ are replaced by an equivalent constant distributed load (see dashed rectangle in Fig. iii).

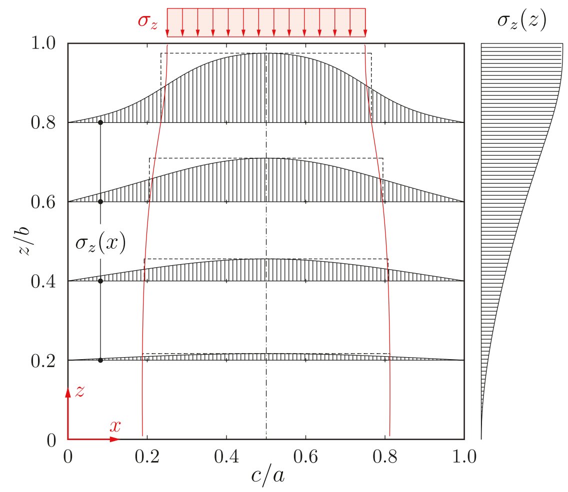

Fig. iii: Stress distribution $\sigma_z(z)$ and $\sigma_z(x)$ of the analytical solution as a function of the loading length ratio of $c/a = 1/2$. The aspect ratio of the plate is $\alpha = 1{,}0$.

Based on this, the sub-panel verification is to be carried out according to prEN 1993-1-5 [1]. As a first step, a LBA (Linear buckling analysis) of the model is performed. Fig. iv shows the results of this investigation. It shows that as the load lenght ratio c/a and/or the aspect ratio α increases, the curves flatten out. In other words, increasing c/a and/or the aspect ratio α is just above the column buckling behavior.

It can therefore be concluded that, in the case of patch loading, there is usually no column-like behavior expected. The buckling behavior shows either pure plate-like behavior or an interpolation of column-like and plate-like behavior. Only with a load introduction ratio of $c/a = 1{,}0$ and a „large" aspect ratio (here $\alpha = 10$) values are slightly below the lower limit, i.e. in transition to pure column-like behavior.

Following the LB-analysis, a GMNIA (geometrically and materially nonlinear analysis with imperfections included) is performed. Fig. v shows the verification with and without using Eq. (6.14) according to prEN 1993-1-5. Eq. (6.14) takes into account the various stress distributions between both ends of the panel due to patch loading by reducing the modified buckling length b_{cr} (height of panel). POUROSTAD [7, 9] proposes additionally the use of a new interpolation function (black dots).

$$f = (\ln(\xi + 1))^P \qquad (1)$$

ξ is the weighting factor of the respective plate-like and column-like behavior $\xi = \sigma_{cr,p} / \sigma_{cr,c} - 1$. Furthermore, a distinction is made between longitudinal stresses ($P = 0{,}5$) and transverse stresses ($P = 1{,}5$). The factor f is defined as an interaction function and used to determine the reduction factor ρ_c.

$$\rho_c = \chi_c + (\rho_p - \chi_c) \cdot f \qquad (2)$$

For comparison, the gray dots show the values using the interpolation function according to prEN 1993-1-5 section 6.6.1.

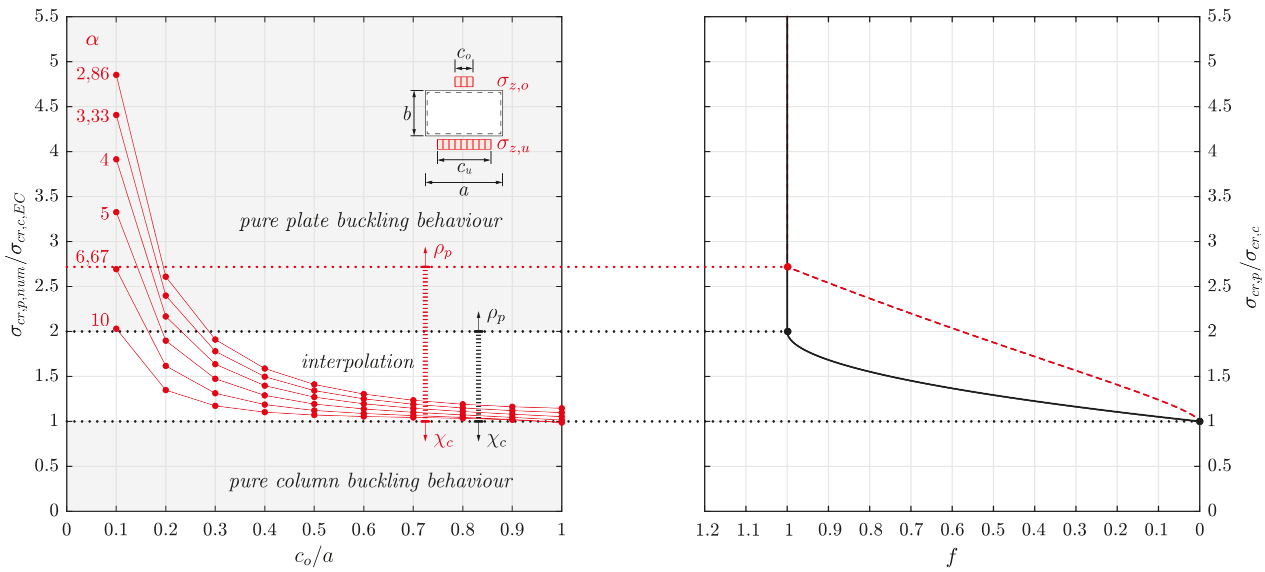

Fig. iv: The interpolation function (right) according to prEN 1993-1-5 (——) and the proposal of POUROSTAD (-----) for non-stiffened plates. On the left side, the results are showing the LB-analysis (ratio of numerically evaluated critical plate buckling stress $\sigma_{cr,p,num}$ and the critical column buckling stress $\sigma_{cr,c,EC}$ according to prEN 1993-1-5) depending on the aspect ratio α and the loading length ratio c/a. The areas of pure column buckling and pure plate buckling behavior are highlighted. In addition, the interpolation area according to prEN 1993-1-5 (┃┃┃┃┃) and the proposal of POUROSTAD (┃┃┃┃┃) are shown.

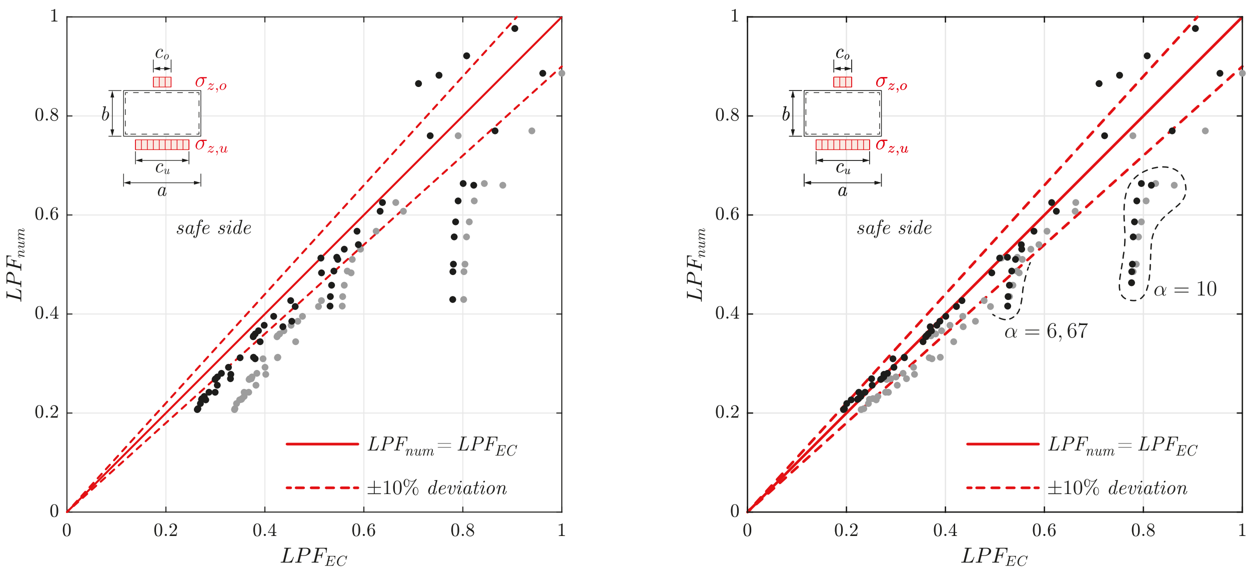

Fig. v: LPF (Load proportionality factor) of the GMNIA **without** *(left) and* **with** *(right) using Eq. (6.14) according to prEN 1993-1-5. Furthermore, the scattered points shows the use of the interpolation function proposed by Pourostad (•) and according to prEN 1993-1-5 section 6.6.1 (•).*

ANALYSIS OF THE STIFFENED PLATE

The verification of the stiffened panel (global buckling) according to prEN 1993-1-5 Eq. (12.1) for biaxial compression is not sufficiently validated by test data. Therefore, the standard alternatively proposes the verification of the longitudinal stiffener according to the second order analysis [1, 2]. For this purpose, the bending moment of the decisive stiffener caused by a precamber (imperfection) is to be examined. The decisive second order bending moment must not exceed the yield strength f_y of the material.

The goal of the thesis is to investigate an alternative and simpler verification method, because the verification of the longitudinal stiffener according to the second order analysis shows notably conservative results (see Fig. vi). Pourostad [7, 9] studied the application of the *Reduced Stress Method (RSM)* for the stiffened panel under biaxial constant stresses (bottom panel (see Fig. ii)). He proposed using the reduction curve according to section 12.4(5) of the prEN 1993-1-5 for the longitudinal stresses. In the transverse direction, he was able to show that column-like behavior is always decisive and therefore the reduction factor for the column-like behaviour χ_c (EN 1993-1-1, 6.3.1.2) has to be used. He further proposed the use of a new interpolation equation for interpolating between column-like and plate-like behavior. In the case of a stiffened panel the formula depends on the global slenderness λ_p and the weighting factor of the respective plate and column-like behavior $\xi = \sigma_{cr,p} / \sigma_{cr,c} - 1$.

$$f = \left(\bar{\lambda}_p + 1\right)^{-2/3} \cdot \left(\ln\left(\xi + 1\right)\right)^{1{,}5} \tag{3}$$

This thesis checked these proposals for the longitudinal bending and the one sided transverse stresses (web panel (see Fig. ii)). Fig. vii shows the results of the GMNI-analysis. It is observed that in some cases applying the stresses at the edge of panel and the interpolation according to proposal of Pourostad leads to unsafe results in comparison to numerical results. Several approaches are investigated to achieve safe results by using the design rules in comparison to the numerically determined data. Finally, it is recommended that in case of panel subjected to bending and transverse stresses, global slenderness λ_p should be increased with a factor of f_λ.

$$\bar{\lambda}_p = f_\lambda \cdot \sqrt{\frac{\alpha_{ut,k}}{\alpha_{cr}}} \tag{4}$$

A constant factor is determined that covers the entirety of all numerical values. The constant factor is determined using the least squares method. In this method, the squared residuals (differences between numerical and model data) are squared and summed up. With the model data, the verification is carried out with the magnification factor.

An interval between $f_\lambda = 0$ and $f_\lambda = 2{,}0$ is studied and the smallest error (residual) is determined. The investigation showed that a magnification factor of $f_\lambda = 1{,}3$ has the smallest error. Fig. viii shows the evaluation

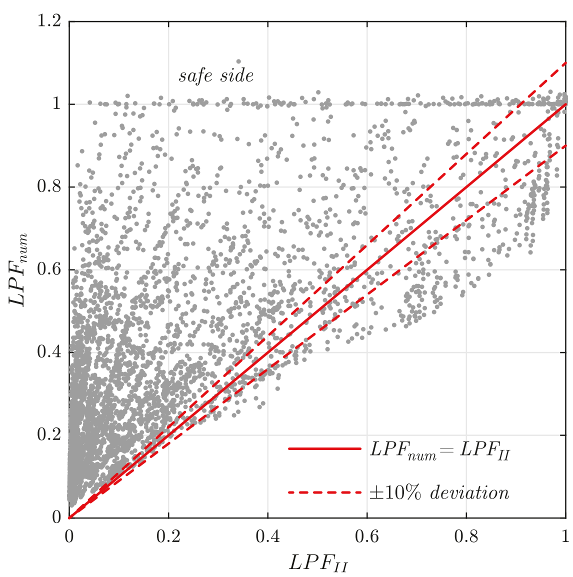

Fig. vi: Results (LPF: Load proportionality factor) of the longitudinal stiffener according to the second order analysis (prEN 1993-1-5).

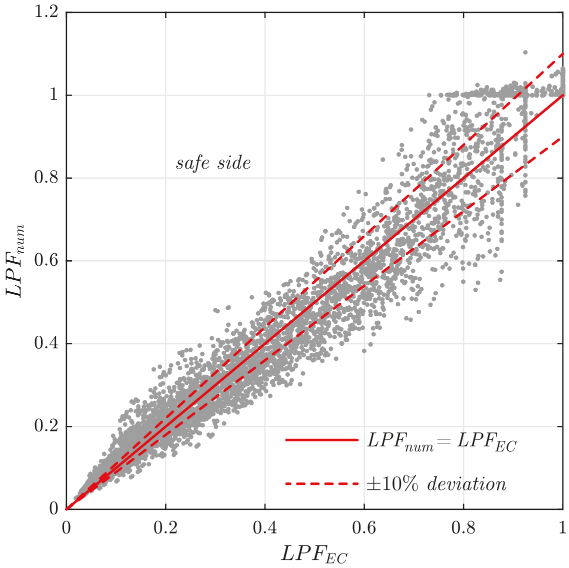

Fig. vii: Results (LPF: Load proportionality factor) of the GMNI-analysis showing the decisive results of the individual subpanel and stiffened panel, considering the suggestions of POUROSTAD.

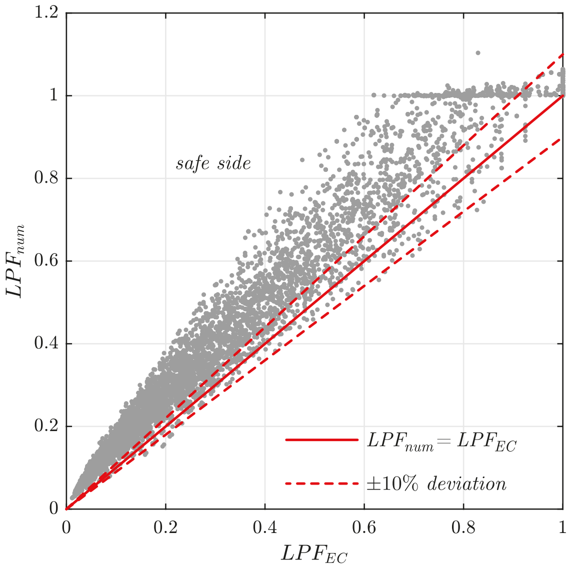

Fig. viii: Results (LPF: Load proportionality factor) of the GMNI-analysis showing the decisive results of the individual subpanel and stiffened panel, considering the proposals of POUROSTAD *and a magnification factor of $f_\lambda = 1{,}3$ for increasing the global slenderness λ_p.*

of the sub-panel and the stiffened panel using the investigated magnification factor f_λ. The application of $f_\lambda = 1{,}3$ leads to safe results in all cases and is recommended as a conclusion of this thesis. This approach allows to consider the torsional stiffness of the stiffeners and to obtain safe results.

POTENTIAL FOR APPLICATION OF RESULTS

The results of the thesis show that the load-bearing capacity of the individual panel with the applied transverse edge stresses and the interpolation function according to POUROSTAD lead to good agreement with the numerically determined values from GMNIA. In addition, the modification of the buckling length indicated in prEN 1993-1-5, Eq. (6.14) is needed for the calculation of critical stresses for column-like behaviour.

In case of the verification of the stiffened web panel, it was evident that the application of the Reduced Stress Method according to prEN 1993-1-5 in combination with the individual verifications of each stress component as proposed by POUROSTAD [7], the proposed interpolation equation and a factor of $f_\lambda = 1{,}3$ for Increasing the global slenderness λ_p, leads to reliable results and its use is therefore recommended. Furthermore, the use of the reduction curve according to prEN 1993-1-5 Section 12.4(5) for determination of $\rho_{c,x}$ and the column buckling stress curve according to DIN EN 1993-1-1 Section 6.3.1.2 for determining the reduction factor $\rho_{c,z}$ proved to be advisable.

The verification of the longitudinal stiffener according to the second order analysis (prEN 1993-1-5) showed a very conservative distribution of the values.

The study has confirmed the consideration of the torsional stiffness (of the longitudinal stiffeners) and their effect on increasing the load capacity. This alternative procedure showed promising results and the longitudinal stiffener verification (according to second order analysis) can therefore be ignored. The application guarantees a more effective planning and reduces the panel thickness and welding, resulting in a more economical design. The results of the investigation allow to reduce the amount of material without endanger safety.

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