Investigation on stiffened panels subjected to biaxial compression

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Abstract. This paper intends to provide an overview on large-scale buckling tests, which were carried out at the Technical University of Munich in January 2018. In the experiments, the load introduction was simulated as it usually occurs during incremental launching of a steel bridge when a biaxial stress state from direct stresses from the bending moment due to cantilever action and local transverse compression stresses due to load introduction at the bearings occurs. The topics and background of the research project will be presented, explaining the test program as well as the structure of the whole test setup and first numerical calculations. Initial results from the experiments are presented and compared with the numerically validated model, which is carried out at the University of Stuttgart. For this purpose, two of the specimens are compared and differences of their buckling behavior are analyzed.

1. General

Large bridge constructions are frequently erected by incremental launching. During launching, the cross-section is stressed by bending due to cantilever action and at the same time, local compression in the vertical direction from the load introduction at the bearings occurs. In this case a biaxial compressive stress state arises in the web panels in the area of the bearings. At least in German bridge construction the use of stiffeners for this type of large steel bridges is common. One of the existing verification methods is, among others, the reduced stress method according to EN 1993-1-5 (10.5) [1].

\[
\eta = \left( \frac{\sigma_{x,Ed}}{\rho_{cx} \cdot \frac{fy,k}{YM1}} \right)^2 + \left( \frac{\sigma_{z,Ed}}{\rho_{cz} \cdot \frac{fy,k}{YM1}} \right)^2 - V \cdot \left( \frac{\sigma_{x,Ed}}{\rho_{cx} \cdot \frac{fy,k}{YM1}} \right) \cdot \left( \frac{\sigma_{z,Ed}}{\rho_{cz} \cdot \frac{fy,k}{YM1}} \right)^2 + 3 \cdot \left( \frac{\tau_{Ed}}{\chi_w \cdot \frac{fy,k}{YM1}} \right) \leq 1
\]  

(1)

The reduced stress method allows the utilization of individual components only up to the yield limit, so that the weakest cross-sectional part may only be exploited up to yielding. As already shown in [2] and [3], the reduced stress method in EN 1993-1-5 [1] section 10 seems not always lead to safe results for panels under biaxial compression. Therefore, for panels under biaxial compression in [2], a modification factor \( V \) for the current verification format equation (10.5) according to EN 1993-1-5 [1] was proposed and also introduced as an amendment to EN 1993-1-5 by TC250/SC3.

In contrast to unstiffened plates, longitudinally stiffened buckling plates have a pronounced anisotropy and thus a pronounced column-like buckling behavior. For the biaxial stress state they are not systematically investigated so far and the application of the reduced stress method has been verified by some numerical calculations but not by real testing. For this reason, EN 1993-1-5 does not contain...
any specific rules for the verification of the global buckling when taking into account the effects of column-like behavior in a longitudinal stiffened plate under biaxial compressive stresses. Due to the lack of rules, in [4] and [5] additional design checks of the flexural buckling of the longitudinal stiffeners according to Second Order Theory by taking into account deviation forces from transverse compression, are suggested. Since the existing verification method [1] does not explicitly take account of these deviation forces of transverse compression in longitudinally stiffened plates, the here presented tests were carried out in order to get a better knowledge about the behavior of biaxially loaded panels with longitudinal stiffeners.

2. Experimental Setup

As part of the planning of the replacement of the Thulba viaduct, a composite bridge with a box cross-section in northern Bavaria, which will be erected by incremental launching in 2019, six large-scale buckling tests were carried out at the Technical University of Munich.

The test setup was designed as a modular U-frame with external dimensions of 7.64 meters x 11.08 meters. Test specimens with a size of 3.0 meters x 4.0 meters were used. The test setup is laid horizontally and supported by in total six HEB 600 profiles. The bending moment and the normal force $F_1$ are applied through the legs of the U-frame by a hydraulic jack and two tension rods. Furthermore two pressure-rated hydraulic jacks initiate the lateral loads $F_2$ in the middle of the specimen. This force is short-circuited by means of a traverse, which is clamped to the U-frame with the help of four tension rods. This allows a maximum bending moment of 24 MNm combined with an external normal force of 4.3 MN ($F_1$) and a maximum lateral load of 8.6 MN (2*$F_2$) on the test specimen. Figure 1 shows the test setup and the loading schematically. The specimen is highlighted by the grey area.

![Figure 1. Test setup, load transmission](image)

The forces $F_1$ and $F_2$ can be controlled independently. As a first step, the $F_1$ is brought to a certain level, which results from numerical pre-calculations realized at the University of Stuttgart. Subsequently the transverse loads $F_2$ are applied and increased until failure of the specimen. During the test, the loading, the strains and the deformations are continuously measured. In addition, the deformation is measured by a 3D scanner before the beginning of tests as initial imperfections, when reaching the transverse loads obtained from numerical pre-calculations and after the ultimate load. The measurement results could be used to investigate the behavior of panel and for the comparison with numerical models.
In the six tests, the stiffness and the position of the stiffeners and the stress ratio $\sigma_z/\sigma_x$ are varied. In the following the tests V3 and V4 are presented, in which only the stress ratio $\sigma_z/\sigma_x$ varies.

3. Results from tests V3 and V4

3.1. General
The geometry of the specimen is the same for test V3 and V4. It can be taken from Table 1. Table 1 also shows two different planned stress ratios $\sigma_z/\sigma_x$. In this case, the stress ratio $\sigma_z/\sigma_x$ is 1.0 at V3 and 0.5 at V4. So the influence of the stress ratios could be studied since V3 has the same geometry and boundary condition like V4 but with significantly higher transverse stresses than V4. Figure 2 shows the geometry of the specimens in general and the acting stresses.

|       | $h_w$ | $t_w$ | $a$ | $b_1$ | $B_w$ | $t_1$ | $b_2$ | $b_3$ | $b_4$ | $\gamma_{st}$ | Stress ratio $\sigma_z/\sigma_x$ |
|-------|-------|-------|-----|-------|-------|-------|-------|-------|-------|---------------|------------------|
| V3    | 3000  | 8     | 4000| 500   | 30    | 300   | 6     | 300   | 400   | 700           | 700              | 27                | 1.0               |
| V4    | 3000  | 8     | 4000| 500   | 30    | 300   | 6     | 300   | 400   | 700           | 700              | 27                | 0.5               |

Figure 2. Cross-section of specimen V3 and V4 and acting stresses

3.2. Imperfections
Figure 3 and Figure 4 show the initial imperfections of specimen V3 and V4. Red areas indicate positive, blue indicates negative pre-deformation. The positive direction is defined in the direction of the stiffeners. It can be seen from both figures that the position of the maximum deflection is in the 3rd sub-panel. However, the imperfection of specimen V3 is significantly higher than that of specimen V4. It can be seen from the position of the first stiffener that the specimen of test V3 has a larger negative imperfection than the one of V4.

Figure 3. Imperfections of specimen V3
Figure 4. Imperfections of specimen V4
3.3. Deformations

For the measurement of the deformations transducers were mounted under the specimen directed vertically on the specimen and thus measuring the deformations out of the plane. In Figure 5 and Figure 6 the deformations of panel subjected to longitudinal stresses $\sigma_x$ due to $F_1$ are shown.

![Figure 5. Deformations out-of-plane under longitudinal stresses (V3)](image1)

![Figure 6. Deformations out-of-plane under longitudinal stresses (V4)](image2)

At this state of the tests, no transverse loads $F_2$ were applied. The deformations were all in the positive range. This resulted from the fact that the load was applied in the center of the web panel. Due to the longitudinal stiffeners, the overall center of gravity of the panel was slightly above the web. The resulting eccentricity between load introduction and the center of gravity of the longitudinal stiffened panel led to hogging bending and caused the deformation in positive direction (see Figure 7). The deformations observed during test V4 were higher because the longitudinal loading and therefore also the hogging bending moment were 1.6 times bigger than in test V3. In addition, Due to the different initial imperfections of the position of the flanges of the first stiffener, a rotation of the first stiffener in the counterclockwise direction was observed.

![Figure 7. Internal forces due to direct compressive stresses](image3)

In Figure 8 and Figure 9 the deformations under biaxial compression for test V3 and V4 are shown. They show the deformation at maximum transverse compression at failure. The ratio of the longitudinal stresses between V3 and V4 remained 1.6 as before. The ratio of the transverse loads was 1.0. Therefore, in case of V3 a different ratio $\sigma_z/\sigma_x$ between longitudinal and transverse stresses was realized compared to V4. The influence of the transverse load is higher in test V3 than in V4, since the applied longitudinal
load is smaller in case of V3. In the shape of the deformations at failure, a clear difference between the two tests can be seen. While in test V3, the deformations in the region of the first stiffener switched to the negative direction, the deformations in test V4 showed a deformation until failure in the positive direction. On the one hand, this behavior may also be due to initial imperfections, which are more pronounced in test V3 than in test V4. On the other hand, this effect can also result from the influence of the transverse load and the resulting internal forces. Similarly, in test V3, a change in the direction of rotation of the first stiffness can be observed. This effect does not occur in test V4 and may be attributed to the influence of transverse load because the imperfections occurred exactly opposite.

![Figure 8. Deformations out-of-plane under biaxial stresses (V3)](image)

![Figure 9. Deformations out-of-plane under biaxial stresses (V4)](image)

The mechanical background of how a change in the direction of rotation of the stiffener can result is explained in Figure 10.

![Figure 10. Influence on the rotation of the stiffener](image)

4. Numerical investigations

4.1. Imperfections

In slender structures, imperfections are unavoidable. The imperfections can influence the ultimate load, the buckling behavior as well as the shape of failure of structures. Generally, in buckling structural and geometrical imperfections are distinguished. They can be triggered by production or processing.
Residual stresses are mainly caused by the welding process. Sinur stated based on his investigations [7] that the influence of residual stresses in slender plate girders is rather small and may be neglected. Therefore, the measurements and simulations presented here mainly concentrated on the effects of geometrical imperfections.

Out-of-plane deflections were measured with laser scanner as well as Linear Variable Displacement Transducer (LVDT). For the recalculation of the tests, the imperfection shape has been determined and simplified taking only the maximum measured geometrical imperfections of each sub-panels and stiffener (13 different points) into account. Figure 11 shows the applied imperfection shape in the numerical model of V3 and V4.

4.2. Material
The steel was modeled as an elastic-plastic material. Swedish Steel Standard BSK07 [8] provides a parameterized material curve, see Figure 12. It can represent very simple the material behavior and consider the strain hardening. For the numerical simulation of the tests, the material parameters of each panel were obtained from the tensile tests. The recalculation of the tests e.g. in [7] with this assumption showed good results. Therefore, it is used in the numerical investigation. However, the elastic modulus $E$, $f_y$ and $f_u$ were obtained from the tensile material tests and the Poisson’s ratio assumed to $\nu = 0.3$. These engineering material curves were, for finite element simulation, modified in the form of the true Cauchy stresses on logarithmic strains acc. to Annex C of EN 1993-1-5.

5. Numerical Model
5.1. General
A nonlinear numerical model based on the Finite Element Method was developed with ABAQUS [9] applying the same boundary conditions as in the tests, see Figure 13. The specimens and test setup were modeled to simulate exactly the boundary condition of the test panel. However, the traverse girder that formed a support for loading jacks in the transverse direction, was not modeled. The transverse loads were applied to the specimens by means of two jacks. The load contact areas on the pressure flanges

Figure 11. Out-of-plane of tests

Figure 12. Material curve acc. to BSK07 [7]
were coupled with a reference point in the center of the surface so that the load introduction in ABAQUS was modelled relatively close to reality.

Since the ratio of width to thickness of the steel panel is small, the shell element called “S4R” [9] was used which is a suitable element for the geometrical and materially non-linear calculation of thin-walled structures. The application of loads has been simulated in two steps like in the tests. At the first step, only $F_1$ is applied then GMNIA analysis is conducted, in the second step $F_2$ is applied and the ultimate load is obtained using arc length method.

**Figure 13.** Numerical model

### 5.2. Load-carrying capacity

In Table 2, the maximum force obtained from the numerical simulations is compared with the test results. It can be seen that with increasing the transverse load the difference between the numerical results and test results slightly increases. The out-of-plane deformations of the tested panel in Figure 14 and Figure 15 are compared to results from the numerical simulations.

**Table 2.** Comparison of the ultimate load of tests and FE.

| Test | $F_{1,FE}/F_{1,Test}$ | $F_{2,FE}/F_{2,Test}$ |
|------|------------------------|------------------------|
| V3   | 1                      | 1.15                   |
| V4   | 1                      | 1.02                   |

**Figure 14.** Out-of-plane deformations of test V3 (left) and numerical model (right)

It can be seen that the numerical results have a similar out-of-plane deformed shape as the test results. Global buckling had been already pre-calculated as decisive buckling shape and was observed for both tests. The direction of buckling is the only difference which was found for the test V4. This difference may occur due to the simplification of the imperfection shape or small eccentricity in load introduction in the transverse direction. This will be investigated as the next step based on more refined
measurements. Generally, a good agreement between numerical models and tests can be concluded, especially in view of the complexity of the system and acting forces.

![Figure 15. Out-of-plane deformations of test V4 (left) and numerical model (right)](image)

6. Summary
Experimental investigations were conducted on six welded girders. Here, the results of two tests are presented. The tests focused explicitly on the influence of the interaction of biaxial stresses induced from a bending moment and transverse loading. In the tests the stress ratio $\sigma_z / \sigma_x$ was varied. In both cases a global buckling failure was observed including the longitudinal stiffeners. In the case of a higher transverse compression, a failure in the negative deformation direction (on the other side of the longitudinal stiffener) in the area of the first stiffener was observed. It may be as a result of the rotation of the lowest stiffener and should be investigated. The tests are numerically re-calculated. The numerical models were developed using the material parameters from the tensile tests and measured geometrical imperfection shapes. The results show a good agreement in view of loading and shape of failure.

It can be seen, that an increasing $\sigma_z / \sigma_x$ ratio increases the deviation of the ultimate load. A sensitivity under higher transverse loads and the concomitant torsional stress of the lowest stiffener seem decisive. Since effects of imperfections, as well as influences on the torsional resistance of the stiffener, such as local plasticization and/or distortion of the cross-section, may play a significant role, these influences have to be considered in further investigations on the numerically validated model, in order to analyse the behavior of longitudinally stiffened plates under biaxial buckling and improve the verification.

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