Effect of transverse bending on the shear capacity of concrete bridges accounting for the load-distribution between web and deck / bottom flange

Within the framework of this Master’s Thesis, the influence of a transverse bending moment on the shear capacity of a box girder bridge is studied on a system level. The magnitude of the transverse bending moment in the web depends on the relative stiffness of the web and the deck [1]. The relation of the deck and web stiffness is not constant but varies depending on the applied loads.
The main goal is to assess, if system behaviour in the box girder section has a beneficial effect of the shear capacity of the section. The hybrid test provides insight into the system behaviour of the bridge. Capacity reserves due to a decrease of the transverse bending moment in the web will be shown. The results also suggest the possibility of rehabilitation by increasing the deck stiffness instead of performing expensive measures for web strengthening.

Introduction

In 2016, the swiss national road system had a total length of 1840 kilometres. Most of this infrastructure was built in the 1970s and 1980s, which means that today it is over 30 years old. During that time, the infrastructure has aged due to external factors and traffic intensity has risen. Especially the intensity of heavy traffic has known a large increase over the last decades [2]. The issue of ageing infrastructure subjected to increasing requirements is common, not only in Switzerland, but in many western European countries.
In future, even higher traffic intensities are expected and will lead to infrastructure with insufficient capacity. An increase in capacity can be achieved by planning additional lanes for the existing road system. To provide the necessary space, the decks of bridges along the concerned road sections might need to be widened, further increasing the structural demand on existing bridges.

The shear capacity of the webs combined with transverse bending is of crucial importance for the capacity assessment of the existing bridges. The increase in traffic intensity has the effect of a larger overall load on the web. In addition, possible deck widening measures increase the eccentricity of the applied loads, which leads to larger transverse bending moments in the web.
The bridges built between 1950 and 1980 typically have low stirrup reinforcement ratios. Existing design models ([3], [4]) appear overly conservative on the one hand, as they are meant to ensure ductile failure modes. On the other hand, effects like tension stiffening are not taken into account, which may lead to unconservative results [1]. To determine the bearing capacity of bridge web safely while avoiding unnecessary strengthening, a new model for shear and transverse bending is needed.

State of the art

In their previous work on the subject of shell elements in shear and transverse bending, Karagiannis and Kaufmann [5] envisage a new layered model. The model subdivides the shell element in a number of layers with a small thickness and assumes a linear strain distribution at its edges. The cracked membrane model [6] can then be applied and the generalised stresses at the edges of the element can be found.
The analyses performed with the model show, that an increase in the transverse bending moment reduces the shear capacity of the elements. Furthermore, the effect of an imposed tensile axial strain is analysed [1]. The additional axial strain can be shown to have a negative effect on the maximum shear.
In addition, a large scale test series was performed in the Large Universal Shell Element Tester (LUSET) [7]. The test series studies the effect of the reinforcement ratio, the boundary conditions and the sequence of load application in shear and transverse bending tests.

Numerical model

The numerical model used in this thesis analyses a section of a concrete box girder bridge with dimensions and reinforcement ratios similar to typical bridges built 30 years ago. The section is chosen close to a support so that large shear forces are to be expected in the web. The longitudinal bending moment is taken into account as an imposed axial strain. Vertical loads are applied to the cantilever and the transverse bending moment distribution is determined (figure 1).

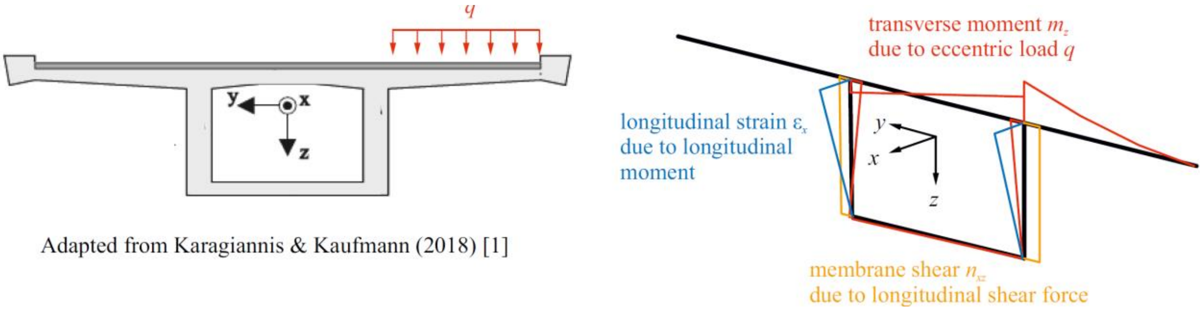

Figure 1: Load case considered for the hybrid experiment. Left: Eccentric load applied on the box girder section close to the support (Adapted from [1]). Right: Frame model and internal forces.

First, the model is used to simulate the redistribution of the transverse bending moment from the web to the deck. The model was developed by Karagiannis [8] before the start of this thesis. In the thesis, the numerical stability of the model and its running time were evaluated and improved, as they are important parameters for its applicability in the hybrid test.

The model operates as illustrated in figure 2. The load on the deck is applied in small increments. In each load step, the transverse bending moment distribution is calculated by a discrete frame model, representing a section of the box girder bridge. A longitudinal strain distribution, resulting from bending moments in the longitudinal direction and a shear force are additionally applied to each element of the web (figure 1 right). The stiffness of the web elements (five elements per web, see figure 2) is calculated using the layered model [5], taking into account effects such as cracking and tension stiffening. With increasing load, the stiffness of the web elements decreases and the frame model redistributes the transverse bending moments from the web elements to the deck elements.

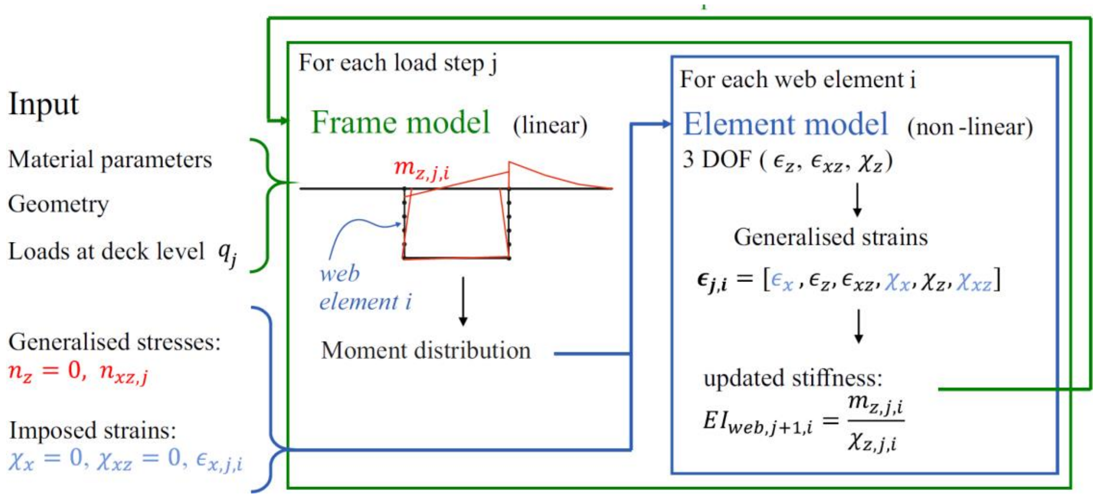

Figure 2: Flow diagram of the numerical model.

Hybrid Experiment

After the preliminary numerical simulations, the hybrid test is performed in the LUSET. An element at the top of the right web of the box girder bridge is built as a physical specimen and tested. The specimen has a height and a width of 2 m and a thickness of 350 mm. It is reinforced with reinforcing bars diameter 8 mm every 200 mm in the vertical direction and diameter 18 mm every 200 mm in the horizontal direction. The concrete used for the specimen is a conventional concrete C20/25 with a maximum aggregate diameter of 16 mm. The specimen geometry, reinforcement ratio and material are chosen similarly to the test series performed by Karagiannis [8], and it should be representative for webs of bridges built 30 years ago.

During the hybrid test, the transverse bending moment applied to the specimen is calculated by the hybrid model and the measured stiffness of the specimen is used as an input for the hybrid model. This is equivalent to replacing one numerical web element of the simulation by the physical specimen. The test is run by increasing the fictive load on the cantilever, and proportionally, the shear and the imposed longitudinal strain until several reinforcing bars fail. Figure 3 shows the specimen after failure.

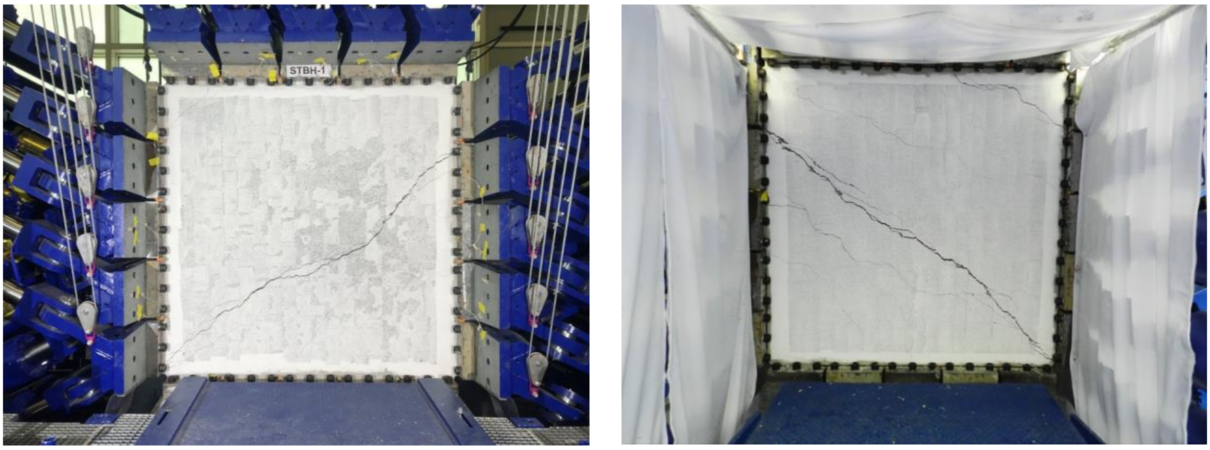

Figure 3: Specimen after failure in the hybrid test. Left: front side. Right: back side.

The strains on the back and front surfaces of the specimen are monitored with digital image correlation (DIC). This also allows tracking cracks in the surfaces using an automated crack detection and measurement (ACDM) [9]. Additionally fiber optic (FO) sensors are installed on ten reinforcing bars and the strains in the reinforcing steel can be measured quasi-continuously along the length of the reinforcing bars. In figure 4 the strains measured by FO in the instrumented reinforcing bars are shown in blue. The cracks, measured by ACDM are shown as black lines, with a thickness according to the crack width. The figure shows that the strains in the reinforcing bars increase at the same location, where cracks are detected, so the DIC and FO data are in good agreement.

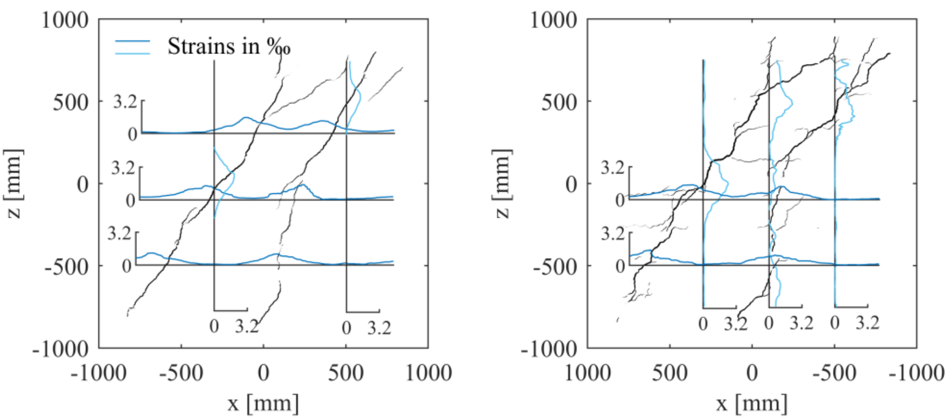

Figure 4: Comparison of the fiber optic and the DIC data at a shear force of 50 kN. Left: front side. Right: back side.

Results and discussion

Three large-scale tests with the same geometry, reinforcement and material can directly be compared. The data of a pure shear test was provided by Karagiannis [8]. During the thesis, a shear transverse bending test and a hybrid test were performed. Figure 5 shows the transverse moment – shear interaction diagram.

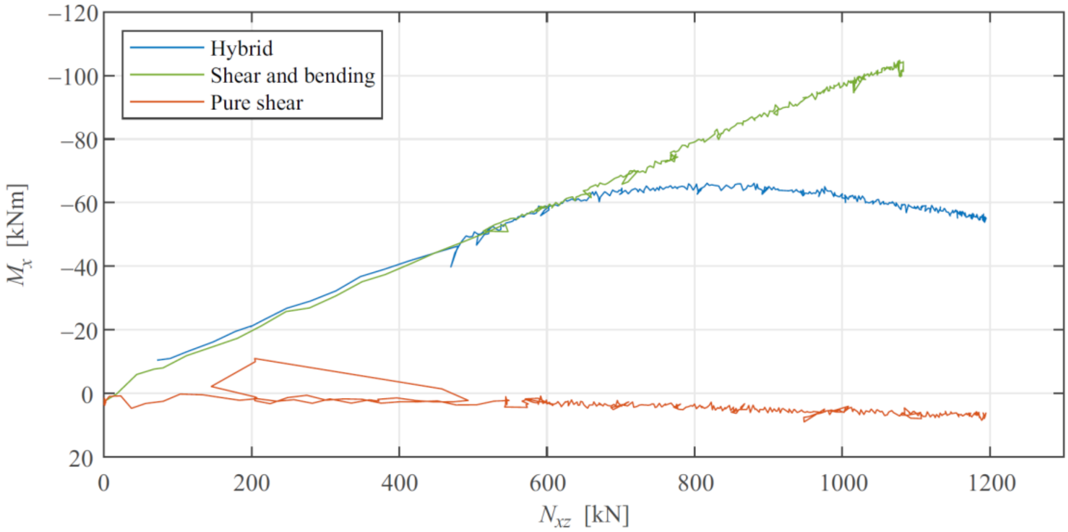

Figure 5: Transverse moment – shear interaction diagram for a pure shear, a shear and transverse bending and a hybrid test on similar large-scale specimens.

The proportions of shear, longitudinal strain and load applied on the cantilever in the hybrid test were chosen in a way that it would have reached the same point in the interaction diagram as the shear and bending test if no bending moment redistribution had taken place. This is apparent in figure 5 because the slopes of both experiments are similar in the beginning of the experiment. At a shear force of around 600 kN, the specimen's stiffness has decreased enough for a moment redistribution to take place. The hybrid model reduces the bending moment that is applied to the specimen and the curves deviate. The specimen tested in the hybrid experiment reaches nearly the same shear capacity as the specimen tested in the pure shear test, even though a considerable bending moment is applied. This shows, that if a moment redistribution is possible, the web of a concrete box girder bridge can sustain larger loads than experiments with proportional bending moment and shear ramps suggest.

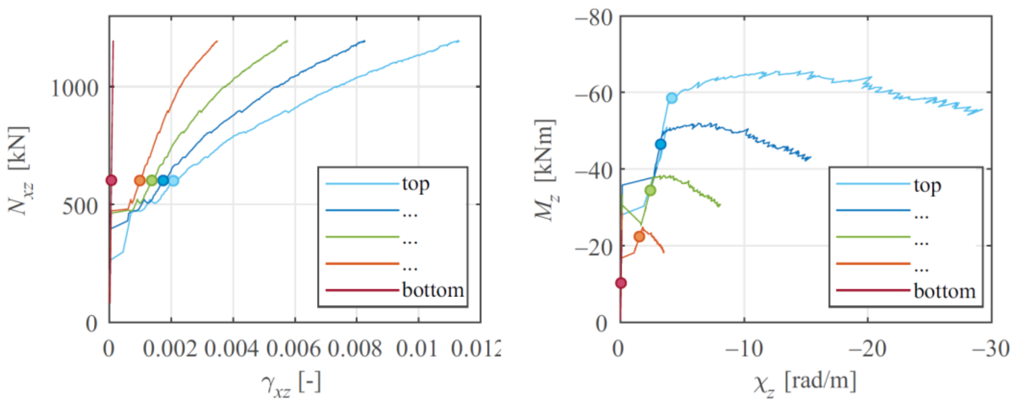

Figure 6: Back-calculation of the shear and bending response of the numerical elements in the right web during the hybrid experiment.

A back-calculation allows conclusions on the shear and bending behaviour of the numerical elements during the test. As imposed, the shear force is the same in all of the elements (figure 6 left). The shear strain is larger in the top element of the web (light blue). This is due to the combined action of a larger imposed axial strain and a larger transverse bending moment in those elements. Cracking of the elements can be seen by the jump in the shear strain and yielding is marked by a coloured dot. In the moment-curvature diagrams in figure 6 on the right, one can see that the largest bending moment is reached in the top element of the right web. The moment distribution is calculated using the frame model and varies depending on the relative stiffness of the elements. The curvature of the top element (light blue) is nearly twice as large as the curvature of the second element from the top (dark blue). The secant stiffness of element decreases as the load is increased. This leads to a redistribution of moments from the web to the deck and eventually a decrease of the transverse bending moment in the web. The bending moment applied to the right cantilever can continue increasing, as long as the deck has reserve capacity.

Conclusion

With this information one can conclude, that the redistribution of bending moments in a box girder section due to system behaviour has a beneficial effect on the bearing capacity of the bridge in question. A redistribution is possible, as long as the remaining structural elements have reserve capacity. The bending moments are mainly redistributed to the deck of the box girder bridge, so a strong deck can help increasing the bearing capacity when considering system behaviour. It should be noted that in the hybrid test, the deck is assumed to have an infinite bending capacity, leading to a large redistribution. In practice, the deck will reach its bearing capacity at a certain load level, so that it might become governing. The results do however suggest that an increase of a bridge deck’s stiffness leads to beneficial system behaviour and a higher bearing capacity. Thus, a stiffening of the deck could replace the strengthening of the webs in some cases.

References

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