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Full-scale testing of concrete deck slabs under fatigue-causing axle loads

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ABSTRACT: The conservation of existing structures including maintenance, assessment and, if necessary, strengthening is a current challenge for engineers. For the evaluation of the load carrying capacity and the remaining service life, detailed knowledge of the load bearing behavior especially due to proceeding fatigue damage is required. In this paper, concrete deck slabs of hollow box girder bridges subjected to vehicle axle loads are examined.

The paper presents first test results from a large-scale experiment on a concrete deck slab specimen under cyclic loading. The test specimen has a span of 12m and a width of almost 6m. The axle loads (Swiss Code loads) are simulated using three hydraulic cylinders, which act one after another. First, the experimental procedure is presented. Second, the experimentally determined bending moments, strains and curvatures in the deck slab are shown. These results are calculated with an in-house software tool and they are compared with results from a 3D FE-Model based on nonlinear material behavior.

Finally, it is discussed how the load bearing behavior of the deck slab changes due to proceeding fatigue damage in the structure. This research project aims at contributing towards a better judgment of whether the service life of a bridge can be reached or strengthening is necessary.

1 INTRODUCTION

1.1 *Initial Situation*

The construction of prestressed concrete bridges started in the 1940s and reached its peak in the 1960s. By that time, the need for new bridges was increasing and the prestressing technology was extensively being taken advantage of. Today, increasing traffic loads and serious durability problems require regular inspections of the bridges. Since the planned service life of most of these bridges has not been reached, it is often more economical to maintain and strengthen, rather than replace them.

In 2009 a study on segmental bridges built between 1958 and 1976 was published (Buschmayer, W. et al. 2009). The study shows that almost 90% of the reviewed bridges exhibited cracks or damaged coupling joints and strengthening would be necessary. The question arises whether global or local strengthening of such bridges is really necessary or whether corrosion protection might be sufficient.

If strengthening is necessary, first it needs to be determined what stresses are acting on the bridge and what type of failure is decisive: Failure by reaching the bearing load or fatigue.

1.2 *Research Objectives*

In general, existing bridges are assessed using presently valid design loads. Due to constantly increasing traffic loads, the design loads in the present design standards are considerably higher than the design loads, which were used at the time of construction of the bridges. This means that often the requirements for the ultimate limit state and the service limit state cannot be met. Even when using detailed numerical calculations with sophisticated models, the resistances of the structures are frequently found to be much smaller than the design actions (Borkowski, G., Sigrist, V., 2012).

For the assessment of existing bridges, fatigue requirements often govern. In many cases these requirements cannot be met because the methods in the design standards are based on strongly conservative assumptions. The research project presented in this paper seeks to address these issues.

Large-scale bending tests on slabs are used to analyze their load-bearing behaviour. In these tests, segments of bridge slabs are cyclically loaded until their bending reinforcement fails due to fatigue.

Three hydraulic jacks are used to simulate recurring vehicle crossings. The applied vehicle loads meet the size and geometrical specifications given in the relevant Swiss standard (SIA 261, 2003).

The aim of the research project is to provide monitoring methods for determining and assessing the damage process cause by fatigue. Further, it is planned to incorporate the gained knowledge in the relevant design standards.

2 EXPERIMENTAL INVESTIGATIONS

2.1 *Specimen*

The investigations focus on determining the load transfer within deck slabs. The test setup is based on the cross-sectional geometry and reinforcement detailing of older bridges. Further, the bending reinforcement is designed so that fatigue damage occurs after three to four million test load cycles (s. Tab. 1). The specimen dimensions can be seen in Figure 1.

The specimen represents the top slab of a box girder. As the bottom slab is missing in the test setup, the transverse stiffness of a box girder is reproduced with six prestressed (50 kN each) threaded rods (Figure 1–4). The test specimen is mounted on four 0.5 MN hydraulic jacks, so that its position can be adjusted during the test if necessary.

2.2 *Experiment set-up*

The load is applied with three hydraulic jacks, which successively load the specimen. Therefore, during one load cycle the three jacks are applied one after another. Following the provisions given in the relevant Swiss standard (SIA 261, 2003), a transverse beam distributes each jack load to two load distribution plates. The transverse spacing between the plates is 2 m (Figure 1) and corresponds to the distance between the two point loads of an axle load as stipulated by the code. The 270 kN load applied by each jack corresponds to the characteristic value of this axle load. In the longitudinal direction the distance between the jacks is 2.4 m (Figure 3). The load history of one cycle is shown in Figure 5. As can be seen, the loads are applied successively, but a minimal load of 30 kN is always maintained at each jack so as to ensure that the testing equipment is never completely unloaded during the test.

Table 1. Reinforcement in the specimen slab.

	Reinforcement	
Layer	Ø [mm]	Spacing [cm]
Top transversal	14	20
Bottom transversal	10	20
Top longitudinal	10	20
Bottom longitudinal	14	20

Besides the continuous load and deformation measurements at the locations of the jacks, the vertical deformations of the test specimen at 16 locations and the force in the prestressed transverse rods are measured every five hours for 20 seconds. This means that the specimen deformations due to at least five full load cycles (fictitious vehicle crossings) can be measured (Figure 5).

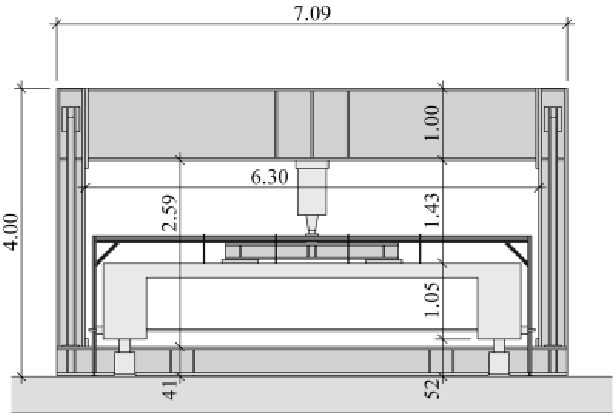

Figure 2. Cross section of the experiment set-up.

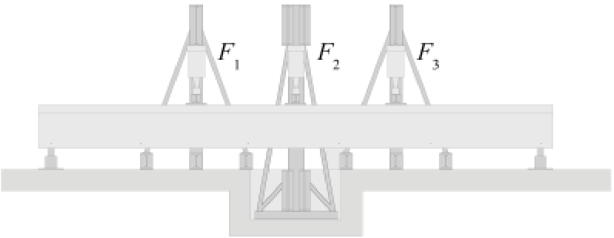

Figure 3. Longitudinal section of the experiment set-up.

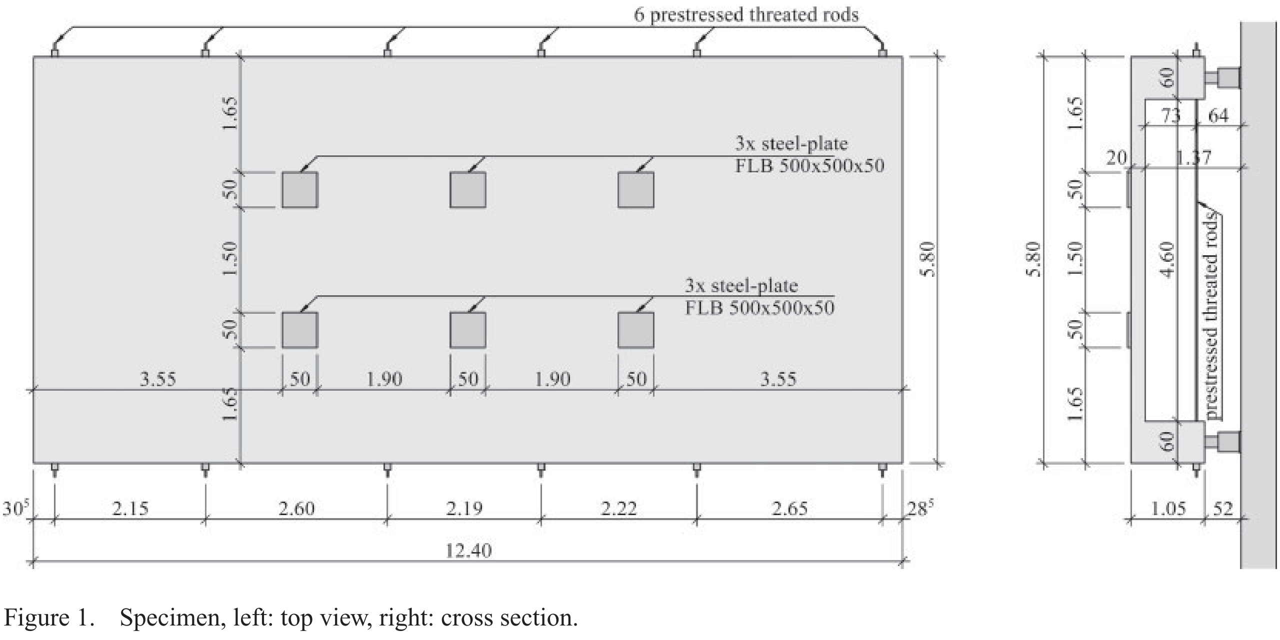

Figure 1. Specimen, left: top view, right: cross section.

Figure 4. Photo of the experiment set-up.

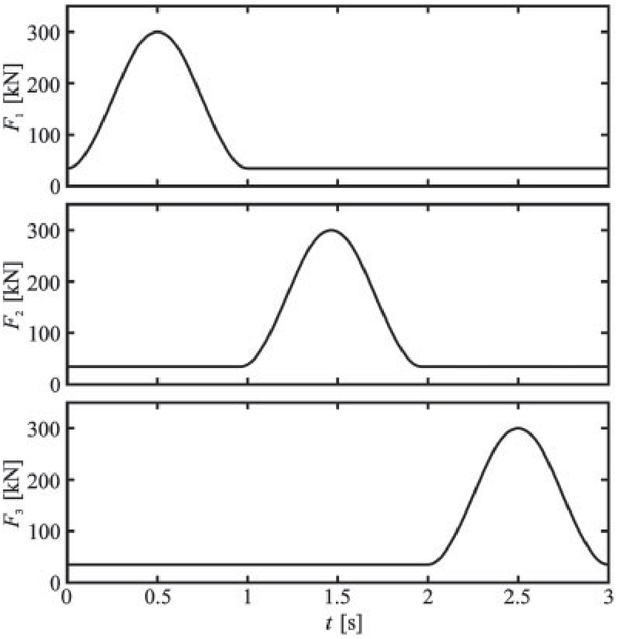

Figure 5. Load history for one cycle.

After every 500 thousand (500 k) cycles the loading process is interrupted. During these breaks the surface deformations on the upper and lower slab face are measured with a hand-held mechanical strain gauge (measurement accuracy 1/1000 mm). The measurements are carried out three times on one half of the slab. Thereto each jack is loaded separately up to 300 kN and put into deformation control mode, while the other two jacks are maintained at 30 kN. The crack pattern is recorded at each load application so that the cracking progress is documented after every 500k cycles (Figure 6).

With a program especially designed for this purpose, which is based on the layer model for slabs according to (Kollegger, J., 1991, CEB, 2008, Seelhofer, H. 2009, Urweider, T., 2012,), the cross-sectional strains, curvatures, steel stresses and bending moments in the slab can be determined from the deformation measurements taken with the hand-held mechanical strain gauge.

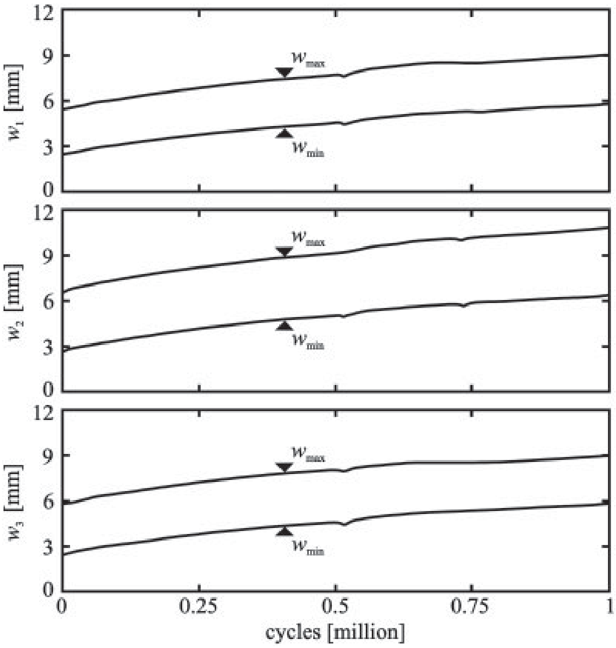

Figure 6. Vertical slab displacement vs. load cycles up to 1 million cycles.

Thereto, each layer is assumed to have a plane stress state, which is determined with the Cracked Membrane Model according to (Kaufmann, W., 1998).

3 RESULTS

3.1 *Measurements*

At the time of submission of this paper, a total of one million load cycles have been applied to the specimen. At present, only results from the load level of 500 k cycles can be presented as the mechanical strain gauge measurements are taken and evaluated every 500 k cycles.

Figure 6 shows the recorded vertical slab deformations below each of the three jacks. The envelopes of the maximal and minimal deformation values are shown. The figure shows to which extent the test specimen exhibits residual deformations due to cyclic loading. It can also be seen that the specimen stiffness relative to the load is almost constant.

Figure 7 shows the initial cracks and the crack pattern established after 500 k cycles. The top and bottom face of one half of the slab is shown. It is clearly visible that the cyclic loading caused a progression of the cracks. The cracks progressed in both the longitudinal and transverse direction of the slab, which indicates an enhancement of the global load-bearing action in the slab.

3.2 *Nonlinear FE-Calculations*

The deck slab was designed and verified with a nonlinear three-dimensional Finite Element (FE) Model. The results of the model allowed the determination of the right amount of reinforcement necessary to achieve

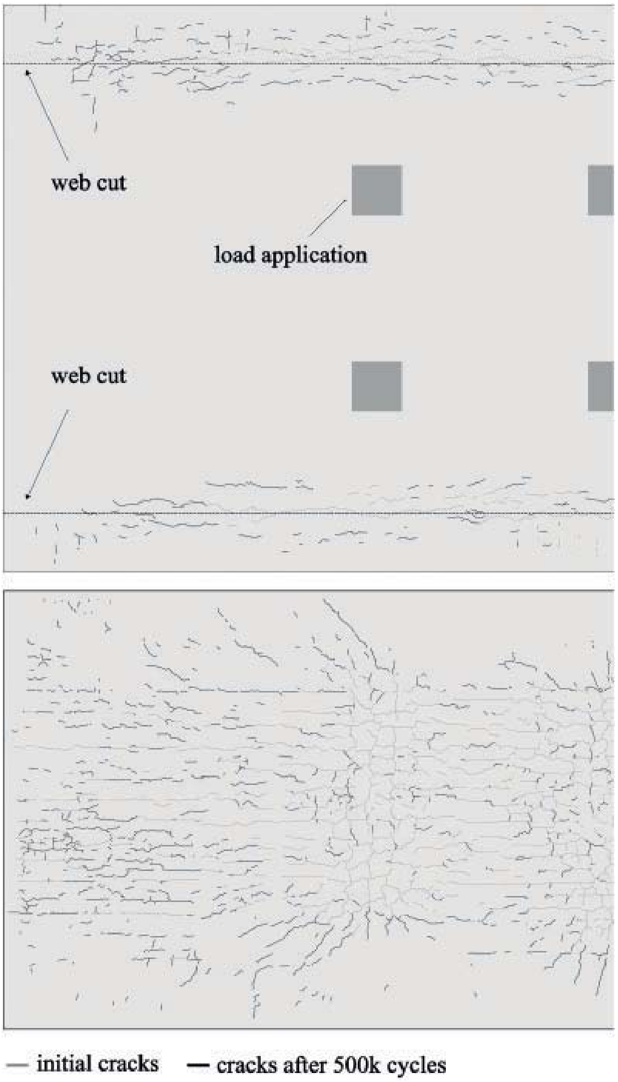

Figure 7. Cracks in one half of the deck slab; top: top view of the slab, bottom: bottom view of the slab between the webs.

the desired stress level in the reinforcement of the specimen. Through computational reassessment of the specimen during testing it is possible to check the model assumptions regarding the stress levels in the reinforcement to ensure that fatigue relevant stresses are developing.

Further, during the course of the test it is possible to determine to which extent the FE model needs to be adapted so that it can account for the progressive damage of the test specimen. Hence, from this model the necessary stiffness adjustments due to fatigue damage can be deduced for general recalculations of existing bridges.

The FE Model uses shell elements (Figure 8, Sofistik 2010). Bilinear material behaviour is assumed for the reinforcing steel. For the concrete in the compression zone non-linear material behaviour is adopted, while the tensile concrete is modelled according to Hillerborg et al. (Hillerborg et al. 1976). The material constants are determined during the course of the test and can be directly entered into the FE Model. The following figures show the calculated bending moments about the transverse and longitudinal axes (Figure 9 and 10). On both figures only one half of the slab is shown.

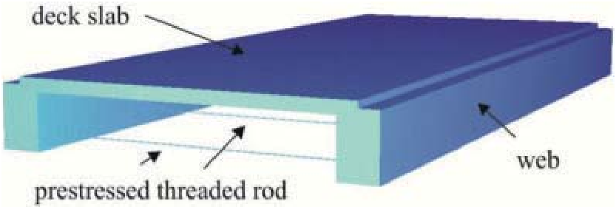

Figure 8. FE-Model.

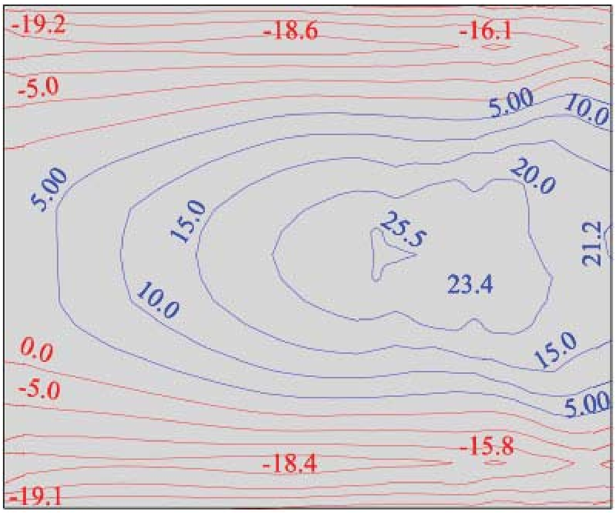

Figure 9. Calculated bending moments about the longitudinal axis.

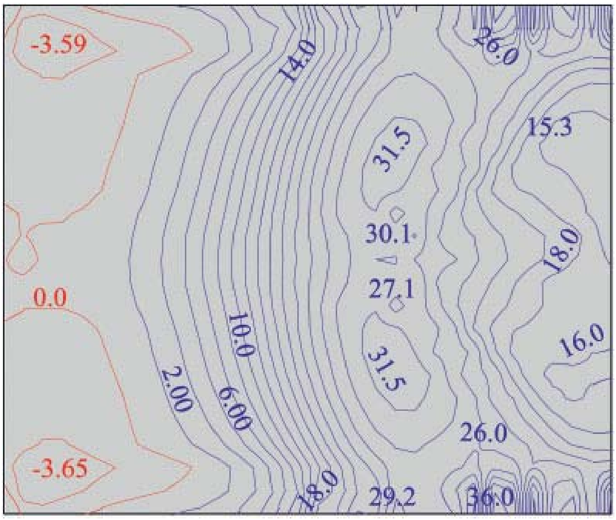

Figure 10. Calculated bending moments about the transversal axis.

It can be seen that the calculated stress resultants correspond well with the stress resultants determined from the measurements (Figure 11 and 12). This means that the values obtained from the initial design describe the effective behaviour well and that the desired stress levels are being reached in the bending reinforcement of the test specimen. Further, the FE calculations can provide information for locations of the test specimen,

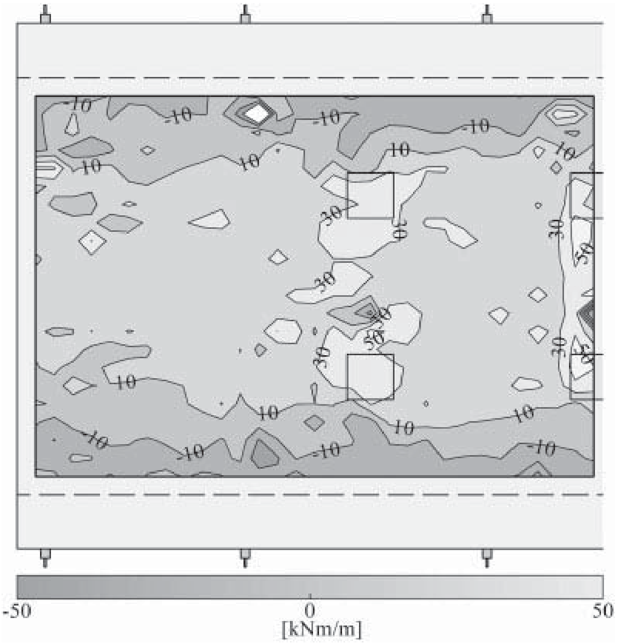

Figure 11. Bending moments about the longitudinal axis.

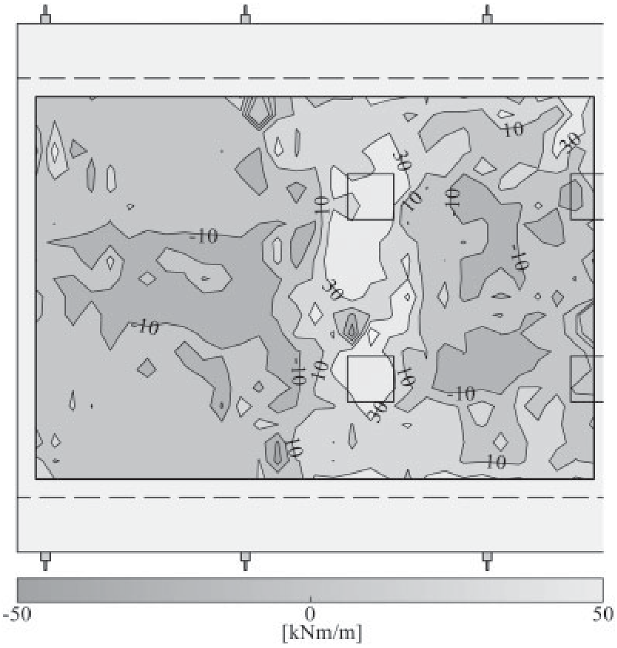

Figure 12. Bending moments about the transversal axis.

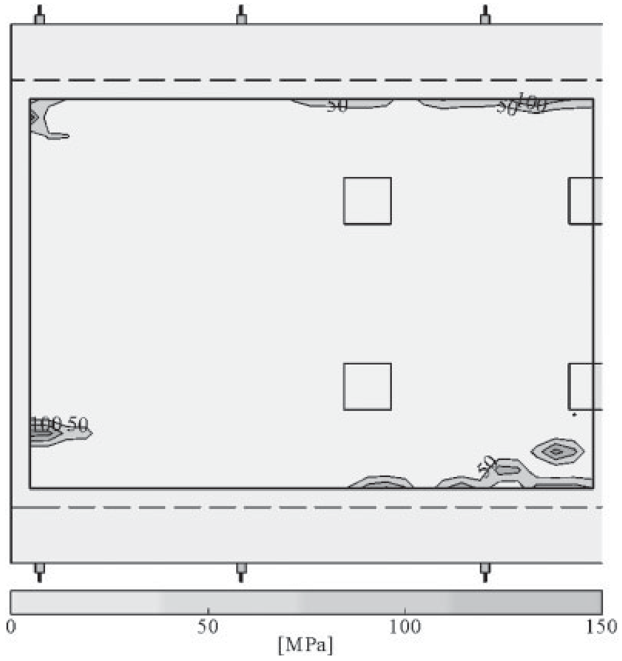

Figure 13. Stresses in the top reinforcement in transversal direction after 500 k cycles.

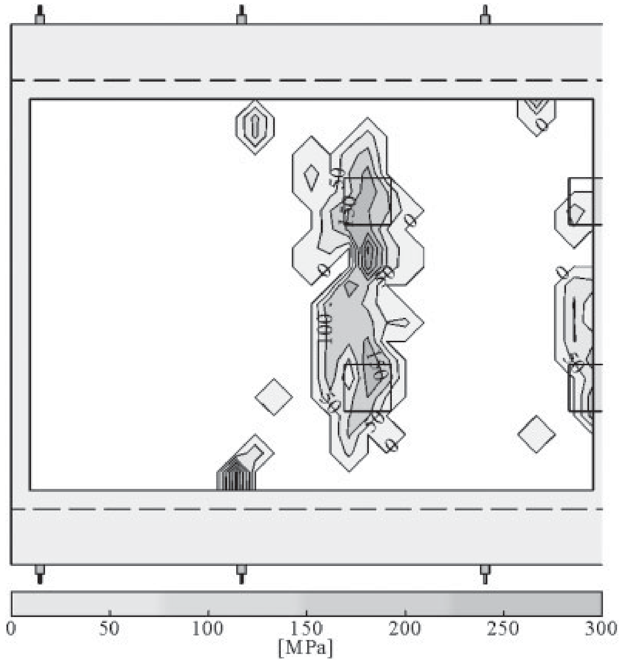

Figure 14. Stresses in the bottom reinforcement in transversal direction after 500 k cycles

where no measurements are being carried out, e.g. the stress levels in the bending reinforcement in the web.

3.3 *Stress state of the Reinforcement*

Based on the measurements carried out on the test specimen and on the in-house software tool, the bending steel stresses can be determined for each reinforcement layer of the specimen. The following three figures show the stresses after 500 k load cycles in the top transverse reinforcement (Figure 13), the bottom transverse reinforcement (Figure 14) and the bottom longitudinal reinforcement (Figure 15).

These stresses can only be determined experimentally in regions with target studs on the top and bottom face of the slab. This means that the steel stresses due to negative bending moments at the flange-web intersection cannot be determined. These values have to be provided by the FE model.

As can be seen in the figures, the bottom reinforcement in the transverse and longitudinal direction is subjected to stresses equal to 200 MPa. As the transverse negative moment at the flange-web intersection dies down rapidly, relatively low stress levels are measured experimentally. However, if the FE Model is used to determine the steel stresses, steel stresses of

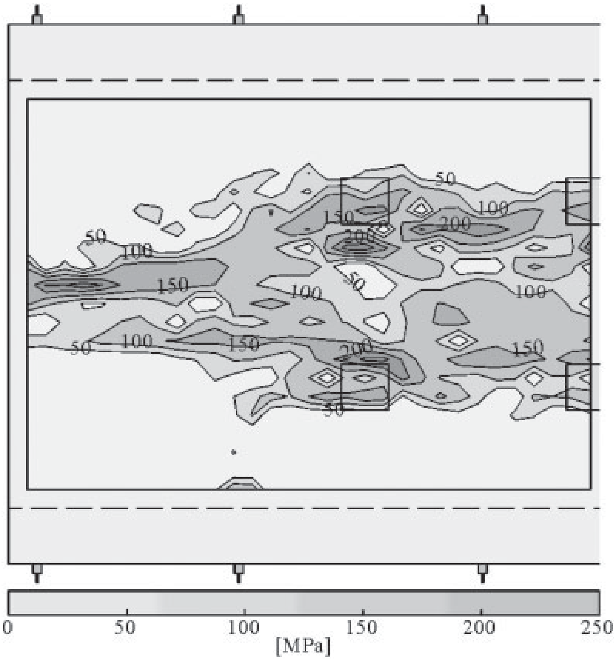

Figure 15. Stresses in the bottom reinforcement in longitudinal direction after 500 k cycles

170 MPa are found in the transverse reinforcement above the web.

As there is hardly any stress present in the reinforcement in the unloaded state, fatigue relevant stress amplitudes equal to 200 MPa and 170 MPa can be assumed.

4 CONCLUSIONS AND FURTHER RESEARCH

The present research work comprises the execution and evaluation of large-scale tests on bridge deck slab members, which are subjected to fatigue relevant stress levels caused by vehicle axle loads. First, the general testing program is presented. The test specimen is described and the loading sequence is explained.

Further, the components of the measuring program are presented and it is shown which data can be gained from the measurements. Then the experimentally determined stress resultants are compared with the results from non-linear FE calculations and a good agreement is found. Finally, the stress levels in the slab bending reinforcement are illustrated.

By means of the experiment and the evaluation program it is possible to illustrate the load bearing behaviour in the slab due to fatigue damage. It is planned to carry out at least three further tests on identical test specimens. These test specimens will be preloaded with tensile and compressive forces in the longitudinal and transverse direction, in order to be able to represent effects such as longitudinal and transverse bending in the span and support regions of the bridge.

FE calculations will be carried out to simulate the load bearing behaviour in the case of fatigue damage.

The knowledge gained from this research project is intended to be incorporated in the Swiss Standard for the assessment of existing structures. On this basis, the load bearing reserves of existing bridges can be more accurately determined and evaluated, in order to prevent unnecessary strengthening measures.

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REFERENCES

Buschmayer, W., Roder, C., Gusia. 2009. Erfahrungen bei der Beurteilung der Dauerhaftigkeit vorgespannter Bewehrung von älteren Spannbetonbrücken. *Bautechnik Vol. 86*

Borkowski, G., Sigrist, V. 2012. Computational Assessment of Prestressed Concrete Bridges. *18th IABSE Conference Seoul*

CEB Comité Euro-International du Béton. 2008. Practitioners' Guide to Finite Element Modeling of Reinforced Concrete Structures. *bulletin state of the art report No. 45*

Hillerborg, J., Modeer, M., Peterson, P. E. 1976. Analysis of Crack Formation and Growth in Concrete by Means of Fracture. Mechanics and Finite Elements. *Cement and Concrete No. 6*

Kaufmann, W., 1998. Strength and Deformations of Structural Concrete Subjected to In-Plane Shear and Normal Forces. *Institut für Baustatik und Konstruktion ETH Zürich Nr. 12'711*

Kollegger, J. 1991. Algorithmus zur Bemessung von Flächentragwerkelementen unter Normalkraft- und Momentenbeanspruchung. *Beton- und Stahlbetonbau 86 p. 114ff*

Seelhofer, H. 2009. Ebener Spannungszustand im Betonbau: Grundlagen und Anwendungen. *Institut für Baustatik und Konstruktion ETH Zürich Nr. 18'486*

Sofistik, 2010.,*Finite-Elemets-Software. Vers. 2010*

Swiss Code SIA 261, 2003. Actions on Structures. *Swiss Society of engineers and architects*

Urweider, T., 2012. Plattenschnittkräfte auf Basis von Setztdeformetermessungen. *Master-Thesis, Lucerne University of Applied Sciences and Arts*