Strengthening the Orthotropic Steel Deck Structure of the Movable Bridge across the Hartelkanaal, The Netherlands

Jurgen Voermans, MSc, Struct. Eng., Royal HaskoningDHV, Rotterdam, The Netherlands; **Willem Souren,** MSc, Civil Eng., Lightweight Structures BV, Delft, The Netherlands and **Marius Bosselaar,** MSc, Civil Eng., Royal Haskoning DHV, Rotterdam, The Netherlands. Contact: jurgen.voermans@rhdhv.com

DOI: 10.2749/101686614X13844300210434

Abstract

This paper focuses on the fatigue assessment and the strengthening of the orthotropic steel deck structure of the movable bridge across the Hartelkanaal. The chosen strengthening method involves adhesively bonding an additional steel plate to the existing deck plate. Prior to carrying out this bonding, the existing fatigue cracks are repaired. The bonding procedure is carried out *in situ* using a vacuum infusion process.

Keywords: movable bridge; existing structure; orthotropic steel deck structure; fatigue cracks; adhesively bonded deck plate.

Introduction

The Hartel Bridge is located in the Netherlands close to the port of Rotterdam and is part of the N218 highway. The bridge was constructed towards the end of the 1960s and spans (besides a sluice) a primary and a secondary canal. The total length of the bridge is ~600 m and consists of several parts, among them two movable bridges and a concrete cantilever bridge with a main span of 114 m. *Fig. 1* shows a longitudinal cross section of the bridge.

Until the beginning of 2012, the bridge was divided into three traffic lanes and a bicycle path. The service life of the bridge was to be extended by 40 years, for which a project "Extensive Maintenance of the Hartel Bridge" was initiated. Moreover the capacity for road traffic was to be increased by converting the bridge into 2 × 2 lanes, by replacing the bicycle path with a traffic lane. An assessment of the structural safety of the entire bridge structure was therefore carried out.

This paper focuses on the fatigue assessment and the strengthening of the movable bridge across the Hartelkanaal.

Description of the Bridge Structure

The movable bridge across the Hartelkanaal is a bascule bridge with a span of 30,95 m. The bascule leaf consists of an orthotropic steel deck structure with closed trapezoidal longitudinal stiffeners (troughs). It has two T-shaped main girders and T-shaped crossbeams every 3 m. Closed stiffeners of 5 mm thickness are fitted between the crossbeams. The thickness of the deck plate is 12 mm, and that of the wearing course is 12–15 mm which is relatively thicker compared with similar structures. The back end of the leaf, including the counterweight that balances it, is enclosed totally in the pier. The bridge is operated electromechanically. The principal dimensions of the bascule leaf and the main girder are shown in *Figs. 2* and *3*.

Fatigue Cracks

During a periodical inspection, fatigue cracks in the heavy vehicle lane of the bridge were observed in the year 2009. With the Saturated Low Frequency Eddy Current (SLOFEC) method it was found that most of these cracks are located in the deck plate in the field between the crossbeams at the joint between the deck plate and the stiffener. The stiffener is connected to the deck plate by butt welds made from one side. The location of the fatigue cracks is shown in *Fig. 4*.

Ultimate Limit State Assessment (Static Strength)

The assessment of the static strength was carried out based on the Eurocodes in combination with the NEN 8700-series that cover the assessment of existing structures in case of reconstruction and disapproval. NEN 8700 (basic rules)[1] and NEN 8701 (actions)[2] are Dutch national codes that provide additional rules to NEN-EN 1990 and NEN-EN 1991, respectively. These codes take into account the difference between new and existing structures.

The action effects caused by the reduced LM1 were analysed by a FE model using plate elements, as shown in *Fig. 5*. It was found that in all cross sections the yield criterion according to NEN-EN 1993-1-1 art. 6.2.1 (5) was met (maximum Unity Check = 0,85).

Fatigue Limit State Assessment

Refined Fatigue Load Model According to NEN 8701

For the fatigue assessment, the refined fatigue load model (FLM) according to NEN 8701[2] was used. For existing structures, this refined FLM is more

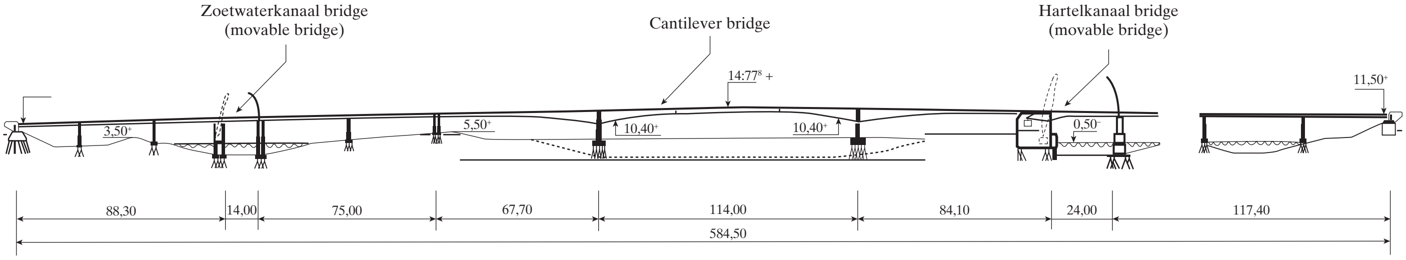

Fig. 1: Longitudinal cross section of the Hartel Bridge (units in m)

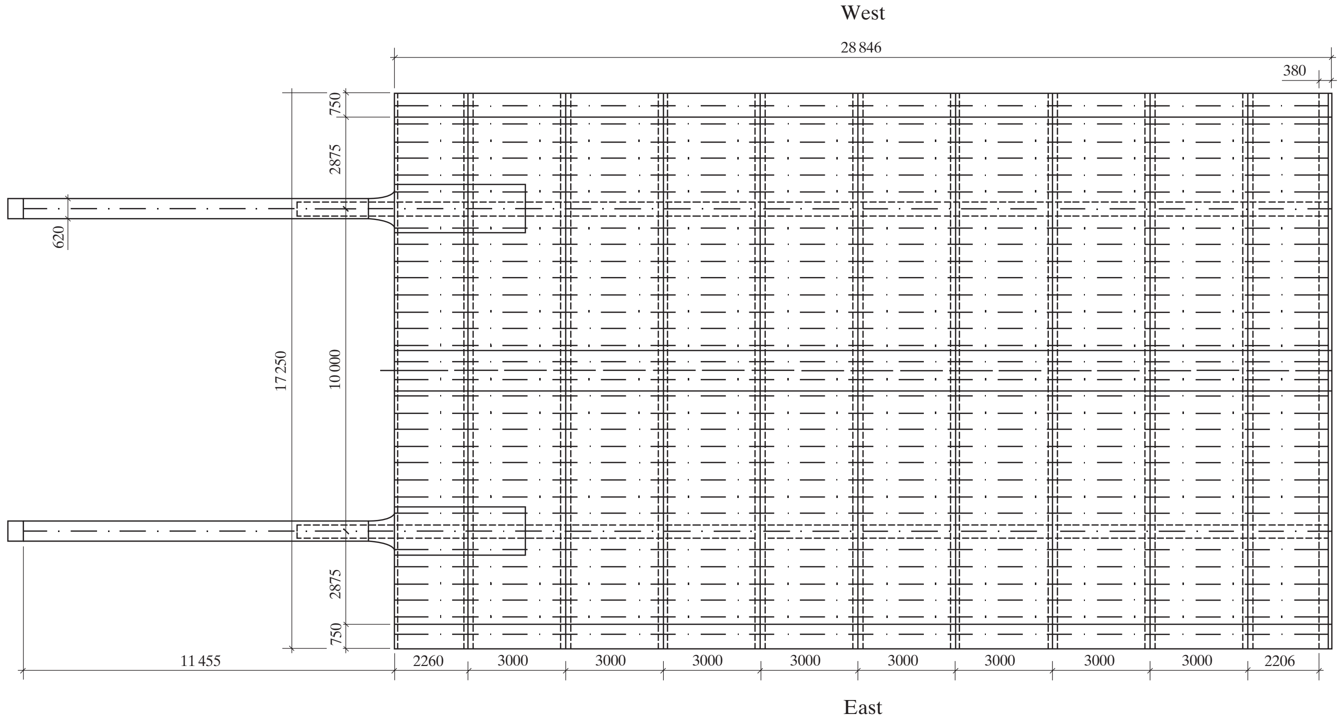

Fig. 2: Plan view of the bascule leaf (units in mm)

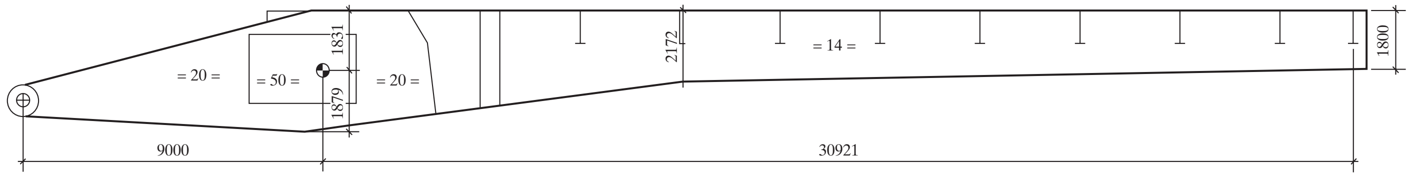

Fig. 3: Side view of the main girder (units in mm)

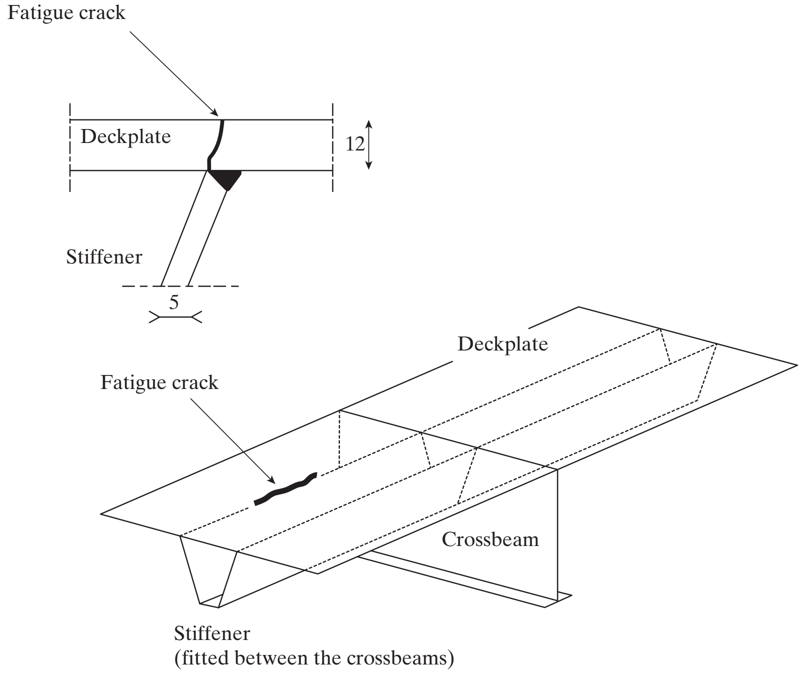

Fig. 4: Location of the fatigue cracks (units in mm)

realistic than the FLM4 according to NEN-EN 1991-2. The FLM takes into account traffic actions in three different periods in order to evaluate past, present and future:

- opening bridge – 1990 (5 × 3 different lorries)
- 1991–2010 (5 × 3 different lorries)
- 2011 – end reference period (6 × 3 different lorries).

The history of the lane layout on the bridge was also considered. In *Fig. 6* the lane layout for the periods 1968–1980, 1980–2012 and 2012–2052 are shown.

Three types of traffic, namely long distance, medium distance and local traffic, giving the percentage of each lorry are defined. For the movable bridge across the Hartelkanaal, medium distance is applicable. In this model, every lorry is defined by the number of axles, the axle spacing, the axle type (wheel contact area and transverse distance between wheels) and the load of each axle. The number of heavy vehicles per year and per slow lane (N_{obs}) was computed based on the measured traffic volume. This results in N_{obs} = 255,000 for the year 2009 (reference year).

Strengthening

Preliminary analysis showed that in order to extend the fatigue service life by 40 years, the deck plate needed to be strengthened. In consultation with the owner, it was decided to strengthen the deck plate by adhesively bonding an additional steel plate to it, after repair of the existing fatigue cracks.

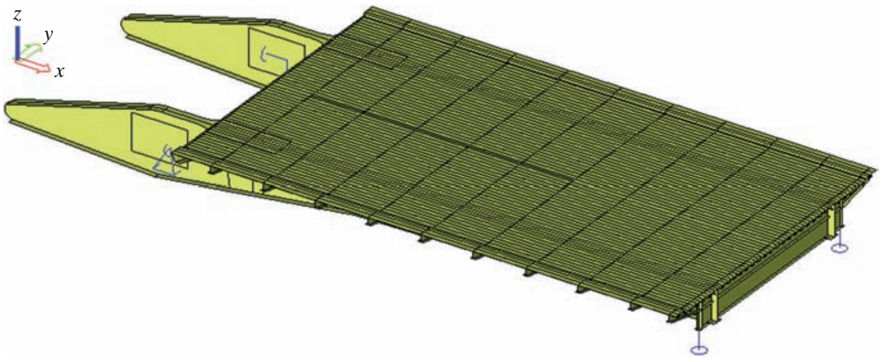

Fig. 5: Three-dimensional plate FE-model

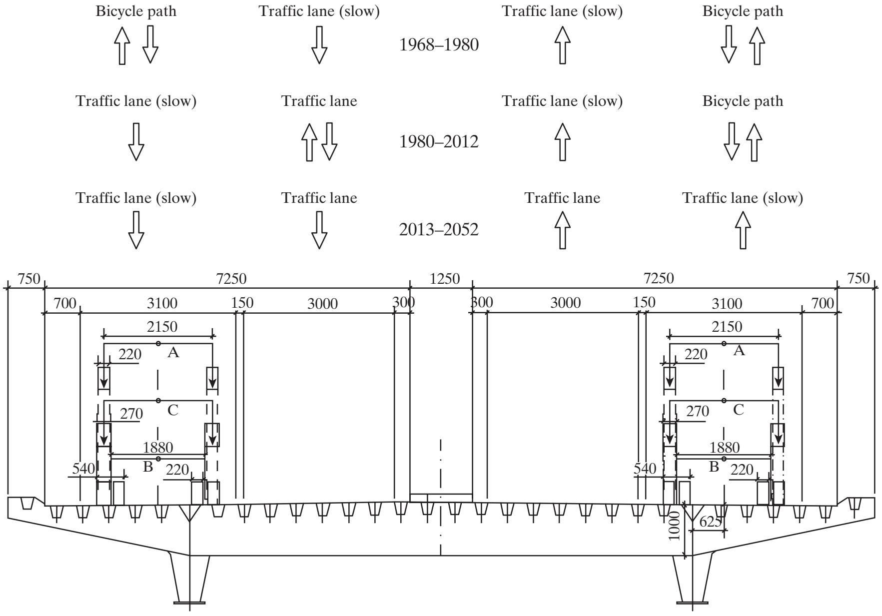

Fig. 6: Lane layout for the period 1968–1980, 1980–2012 and 2013–2052 (units in mm)

No other strengthening methods were considered because there is no other alternative in terms of minimal weight increase and technical performance within the height restrictions. The only alternative considered was full replacement, which was rejected because of its costs compared with that of strengthening.

Bonding Procedure

Small fatigue cracks were repaired by gouging out the cracks and applying new high-quality welds. In the case of large fatigue cracks, the deck was first reinforced by applying a brace which prevents the deck from distortion during the repair operation. Then the cracked part of the deck plate was cut out and a new thicker plate was inserted and welded.

The adhesive bonding technique was already successfully applied to two other movable bridges in the Netherlands (Scharsterrijn bridge and Gideon bridges, see Refs [3] and [4]). The adhesive bonding procedure comprises five consecutive steps:

1. Removal of corrosion by grit blasting and subsequent application of a primer.
2. Application of the primed additional steel plate using dedicated hoisting equipment (see *Fig. 7*).
3. Application of epoxy adhesive carried out using vacuum infusion (see *Fig. 8*).
4. Curing of the adhesive at elevated temperature of 50°C.
5. Scanning for possible defects in the adhesive layer and repair if needed.

Finally a wearing course, that is an epoxy slurry with grit, is applied to the deck plate. The wearing course flattens out the unevenness due to the bonding of the strengthening plate, provides a small slope for water drainage and protects the epoxy adhesive joint. The main threat to the epoxy adhesive joint is corrosion of the steel at the steel-epoxy interface that may arise from exposure to de-icing salt.

The epoxy adhesive has good resistance to thermal deformation and weathering. The most important mechanical properties are listed below:

E-modulus = 4,9 GPa
Poisson's ratio = 0,34
Tensile strength = 74 MPa
Glass temperature T_g (TMA) = 82 °C

The glass-liquid transition temperature (or glass temperature T_g for short) is the reversible transition in amorphous materials from a hard and relatively

Fig. 7: Application of primed additional steel plate

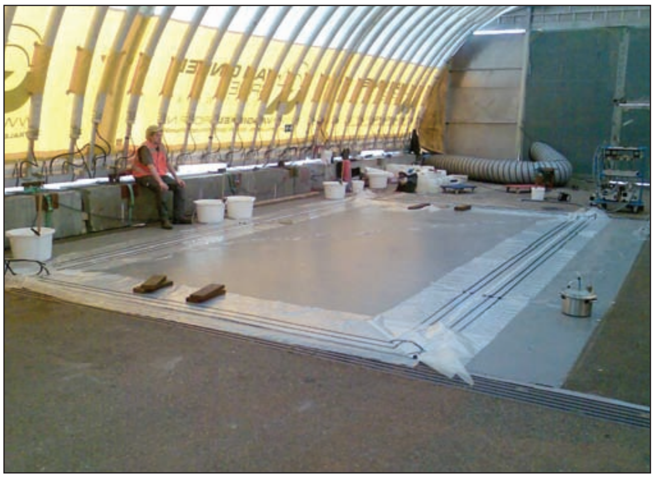

Fig. 8: Application of adhesive using vacuum infusion

brittle state into a molten or rubber-like state.

Thermomechanical analysis (TMA) is a technique used in thermal analysis, a branch of materials science which studies the properties of materials as they change with temperature.

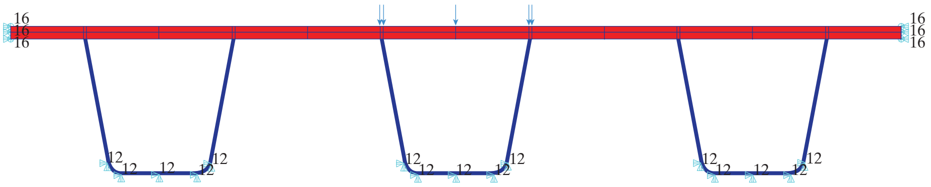

Fig. 9: FE-model of cross-section of bridge deck

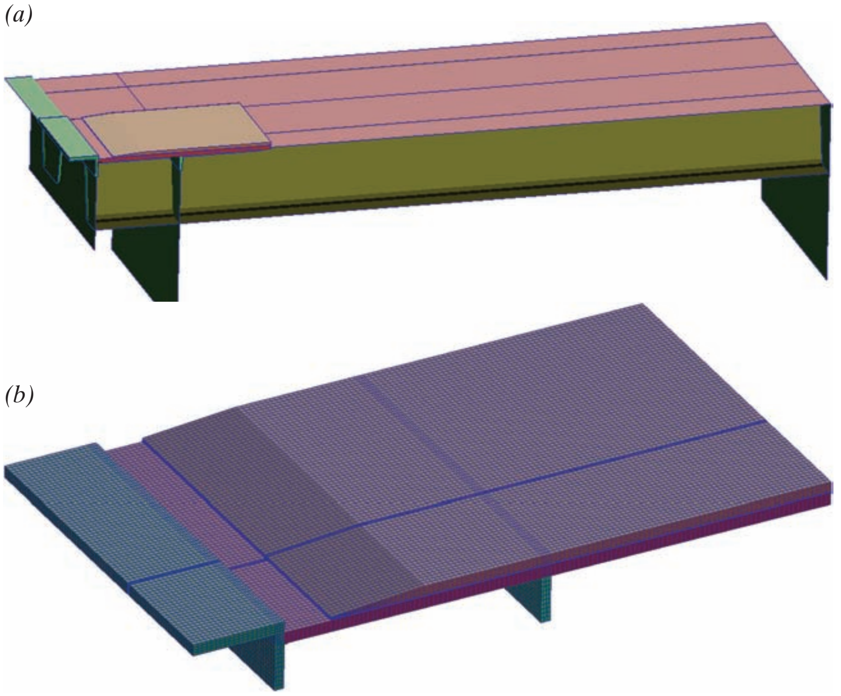

Fig. 10: Front end FE-model (a) Front end FE-model; (b) Solid elements part front end FE-model

Fatigue Calculations

As the orthotropic deck structure is subjected both to the highest stresses and the highest number of stress cycles, the fatigue calculations were focused mainly on the orthotropic deck structure. The main girders and crossbeams were assessed less extensively.

The fatigue analysis is performed by using the same FE model as used for the ultimate load calculations. The stress spectra that result from the passage of the different lorries are determined using the reservoir counting method. The fatigue damage D (starting from 1968) is calculated from the assessed details using the linear Palmgren-Miner damage rule. For the observed cracks the mean value of the detail category was computed based on the conditions in the year 2009, where: $D_d \geq 1{,}0$. The partial factors were kept at 1,0 ($\gamma_{Mf} = 1{,}0$; $\gamma_{Ff} = 1{,}0$). Subsequently, the characteristic value was derived based on an assumption for the standard deviation. This detail category corresponds to 71 according to NEN-EN 1993-1-9 (Table 8.8; detail 7). The S-N curves for the remaining details were adopted from the Eurocode and relevant literature.

Both an increase and a decrease in traffic loads of 20% in the next and past 100 years were taken into account. Also an increase and a decrease in the number of load cycles with a factor of 2 in 100 years were accounted for.

Further, the following factors were used:

Factor for dynamic effects: $\varphi_{s,1} = 1{,}1$
Factor at the transition of the expansion joint: $\Delta\varphi_{fat} = 1{,}15$
Partial factor for load effect: $\gamma_{Ff} = 1{,}0$
Partial factor for fatigue strength (based on a damage-tolerant design with high consequence.): $\gamma_{Mf} = 1{,}15$

The partial factor for fatigue strength is based on a damage-tolerant design with high consequence of failures. The detail at the location where the fatigue cracks were observed was assessed based on additional steel plates of 6, 8 and 10 mm thickness. This gives the following results for the fatigue damage: $D_{2052;\,6mm} = 2{,}13$; $D_{2052;\,8mm} = 1{,}11$; $D_{2052;\,10mm} = 0{,}52$. Thus, in order to extend the fatigue service life by 40 years, an additional steel plate of thickness 10 mm had to be applied.

Hereby full composite action between the adhesively bonded additional steel plate and the existing deck plate was assumed. To verify this assumption, a FE model of a cross section of the bridge deck was created using 2D solid elements (see *Fig. 9*). Both a solid 22 mm deck plate and the actual bonded steel plate of 10 mm on top of the existing deck plate of 12 mm using an epoxy bond line of 2 mm were modelled. The analysis of both cases subjected to a wheel load showed nearly similar response. Hence the assumption of full composite action was justified.

Bridge End Details

The most sensitive place for the fatigue service life of the adhesive bond line is at the ends of the bridge, where the bonded plate ends. The stresses in the adhesive bond line at the ends of a bonded plate are predominant. Moreover, at this location the fatigue traffic loads are heaviest due to dynamic effects at the transition of the expansion joints. In order to reduce the stresses, the ends of the plates are tapered.

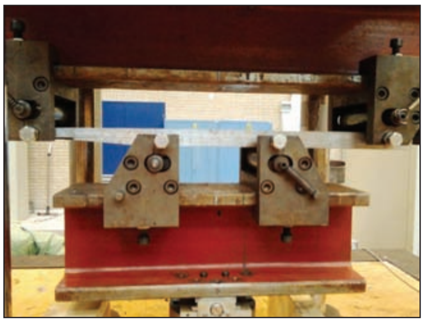

Fig. 11: Test set-up to determine S-N curve

To verify the fatigue service life of the adhesively bonded end details, dedicated FE models were built. The bonded deck plate and the adjacent parts of the crossbeams and stiffeners are built of solid elements and the remaining part of the structure are built of shell elements. The model for the front end of the bridge is shown in *Fig. 10*.

The fatigue strength of this adhesively bonded end detail is determined by fatigue testing, using a test set-up as shown in *Fig. 11* which yields a S-N curve i.e. shear force versus number of cycles until failure. The fatigue tests were performed using adequate test equipment at Delft University of Technology,

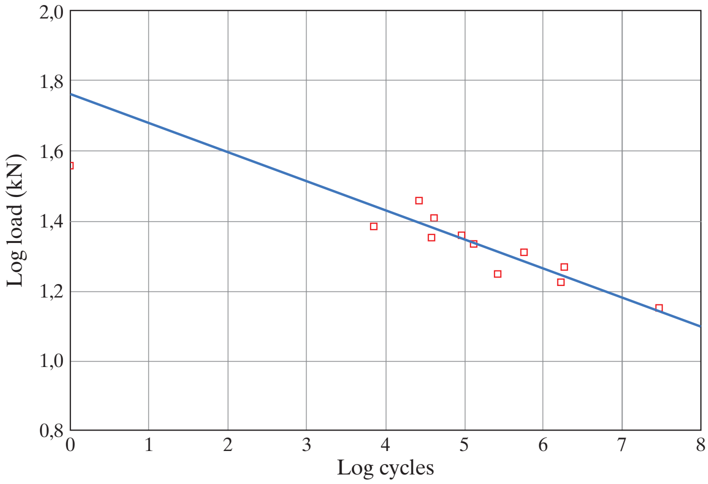

Fig. 12: S-N curve for adhesively bonded end detail (shear force versus number of cycles until failure)

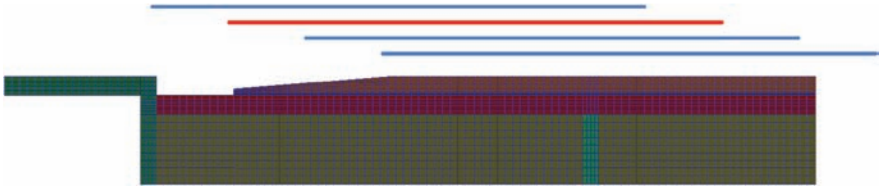

Fig. 13: Wheel loads for the front end FE model

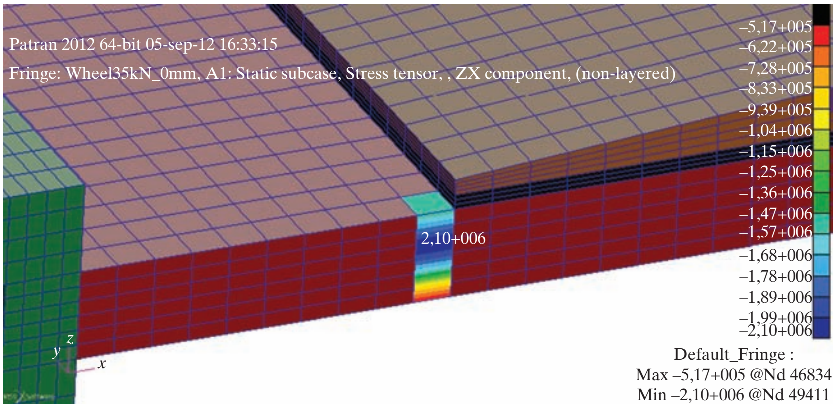

Fig. 14: Shear stresses T_{zx} due to wheel load at front end

faculty of Civil Engineering (Steven laboratory II).

In total 11 fatigue test were carried out for this particular case at a stress range of 40% to 80% of the ultimate load strength level (R = 0,1). The fatigue test data and the S-N curve are shown in *Fig. 12*.

The characteristic S-N curve (for $R = S_{\min}/S_{\max} = 0{,}1$) reads as follows:

$$^{10}\log N = 20{,}193 - 12{,}044\ ^{10}\log S \qquad (1)$$

In this equation, N is the number of cycles until failure and S the load. The characteristic S-N curve was obtained by subtracting twice the standard deviation from the mean S-N curve. To conform to Consequence Class 2 and reliability index $\beta = 3{,}8$, an additional material factor $\gamma_m = 1{,}17$ was applied.

In order to find the maximum shear force, the wheel loads are shifted over the models as shown in *Fig. 13* for the front end. The red line indicates the position of the wheels that gives the governing shear stresses.

The shear stresses in the deck plate at the plate end as a result of the wheel load are shown in *Fig. 14* for the front end.

The fatigue damage of the adhesively bonded plate for 40 years starting from 2011 was calculated using the linear Palmgren-Miner damage rule. A damage of $D_{2052;\,10} = 0{,}011$ was found. This result shows that there is ample reserve in the required fatigue service life of the adhesively bonded plate.

Besides the deck plate, the orthotropic deck structure has a few other potentially fatigue sensitive areas. One of them is the connection of the stiffeners at the bottom to the crossbeams. If fatigue cracks should arise at this place, they can be repaired from the bottom side with relative ease. Another potentially fatigue sensitive area is the connection of the legs of the trapezoidal stiffeners to the deck plate. As a measure of precaution, as welding after repair will damage the bonding layer, these areas were investigated and repaired prior to bonding the deck plate. The bonded deck plate reduces the stresses in these areas.[4]

Conclusion

From the assessment of the orthotropic deck structure of the movable bridge across the Hartelkanaal the following conclusions can be drawn:

- By adhesively bonding an additional 10 mm steel plate to the existing 12 mm deck plate, the bridge deck was strengthened, thus obtaining an additional fatigue service life of 40 years for the deck plate.
- It is justified in this case to assume full composite action between the adhesively bonded additional steel plate and the existing deck plate.
- The bridge end details having boundary stresses in the bonding layer are sufficiently strong for the required service life.

References

[1] NEN 8700 (nl) *Assessment of Existing Structures in Case of Reconstruction and Disapproval - Basic Rules*, Nederlands Normalisatie-instituut, Delft, The Netherlands, 2011.

[2] NEN 8701 (nl) *Assessment of Existing Structures in Case of Reconstruction and Disapproval - Actions*, Nederlands Normalisatie-instituut, 2011.

[3] Labordus M. *Vacuum Infused Bonded Steel Reinforcing Plates for Bridge Rehabilitation*. International Bridge Technology Conference and Trade Show, Rotterdam, The Netherlands. Bridge Engineering, 2006.

[4] Teixeira de Freitas S. *Renovation of Movable Orthotropic Steel Bridge Decks*. Doctoral Thesis, University of Technology, Delft, The Netherlands, 2010.

SEI Data Block

Owner:
Province of South Holland

Consulting Engineer:
Royal HaskoningDHV

FEM Specialist:
Lightweight Structures BV

Reinforcing steel plates: approximately 16,000 kg

Estimated cost (EUR): 500 000

Estimated date: November 2013