TECHNIQUES AND SOLUTIONS FOR REHABILITATION OF ORTHOTROPIC STEEL BRIDGE DECKS IN THE NETHERLANDS.

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ABSTRACT
In the Netherlands a substantial part of our main road infrastructure are steel bridges. These structures often have orthotropic deck constructions. In 1997 we discovered fatigue cracks in the deck construction of the Van Brienenoord bascule bridge in Rotterdam. This resulted in the complete reconstruction of the bascule bridge. This unfortunate event in October 1998 gave reason for the Ministry of Transport, public Works and Water Management to start a project “Fatigue Problems on Steel Bridge Decks“ (Problematiek Stalen Rijvloeren”). The aim was to investigate the cause, to understand and control the fatigue mechanism for the 80 steel fixed and movable bridges in the Netherlands and to develop practical solutions for cost effective rehabilitation and renovation.

INTRODUCTION
The orthotropic steel deck construction consists of a deck plate supported by trough stiffeners, cross-beams and main girders. The deck plate acts as a top flange for the supporting elements. Investigation on traffic loads in the Netherlands showed that these loads have substantially increased over the last ten years. Also, the fatigue load was hardly considered in the design phase, due to the omission in the design bridge codes which were established in 1963. In 1994, the first new draw of the Eurocode 1 part 3, traffic load on bridges had been drawn up. In 1990 the second Van Brienenoord bascule bridge was built. After seven years of service we already noticed fatigue cracks in the most heavily loaded lanes. Since we used only 5mm thick epoxy asphalt on the movable bridges these fatigue cracks in the deck were found by visual inspection in most crossings of cross-beam web plate and the trough wall in the heavily loaded lanes. Further investigation showed that these cracks started at the root of the trough to the deck-plate weld and propagated through the full thickness of the deck plate. Shortly after an evaluation on the lifetime traffic load regarding the original design calculations with and without fatigue models the Ministry decided to replace the existing deck with a newly built strengthened deck construction. It was clear that this was not a stand-alone case and that it only would be a matter of time that we would be confronted with new fatigue problems in our orthotropic bridges. We also noticed that various initiatives were taken regarding the fatigue problem and that is was very important to work together to solve this problem. So the Ministry decided to start an overall project “Fatigue Problems on Steel Bridge Decks“ (Problematiek Stalen Rijvloeren”) in 1998. The aim was to investigate the cause, to understand and control the fatigue mechanism for the 80 steel fixed and movable bridges in the Netherlands and to develop practical solutions for cost effective rehabilitation and renovation.

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OUTLINE OF THE PROJECT

Definition of the project results

To tackle the fatigue problem and find solutions for existing and future bridges we wanted full control over the fatigue problems through:
- Having the knowledge of the specific cracking mechanisms to stop the fatigue problem on the existing bridges and the use of a design philosophy which would prevent these problems on new bridge deck designs;
- Knowing the condition on fatigue of our main steel orthotropic highway bridges by inspection and by fatigue lifetime calculations, based on a new developed probabilistic design philosophy;
- Having the knowledge of repairing discovered cracks and the knowledge of crack propagation.

Priority

High priority was given to the fatigue crack DPS01. This crack was discovered in the Van Brienenoord bridge by visual inspection. The crack initiation is at the root of the longitudinal fillet weld between the trough wall and the deckplate at the intersection of the crossbeam and the continuous closed trapezoidal stiffeners (see figure). After the initiation phase the crack growth is in vertical direction from the bottom side to the top side of the deckplate. After the crack is grown through the deckplate the crack growth is in horizontal/longitudinal direction.

These research tasks were carried out by six task forces that worked together closely to give full attention to all project aspects and to build one integral overall solution: A system in which we founded the knowledge to deal with the existing fatigue problems and which would prevent future problems for new designs.
Task forces

A short description of these task forces follows:

**Inspection techniques**, this task force had to research and develop existing or new inspection techniques which would be suitable for inspecting fatigue cracks in a early stage of growth. Also there was a task to enhance the techniques for inspecting from beneath the bridge deck or even through a thin (5 mm) or thick (5cm) wearing coarse on top of the deck.

**Lifetime (remaining) calculations and prediction and asphalt**, this task force had to make fatigue calculations for the 80 bridges.

**Reparation techniques**, this task force had to research and develop reparation techniques for the different fatigue cracks and to record the knowledge in procedures. It was a challenge to develop a reparation technique which would be superior to the original construction for fatigue load and which would minimize the heat input during welding activities.

**Solutions for enhancing lifetime**, this task force had to research and develop smart ideas which would enhance the lifetime of existing bridge deck constructions. These solutions may have consequences for all the other task forces.

**Design rules and Philosophy**, this task force worked closely together with the TNO Building Research Institute which we requested to assist us with the development of a design philosophy for fatigue based on a probabilistic approach.

**New designs** This task force is looking at the designs of the existing orthotropic bridge deck constructions in perspective of the new design philosophy and they will ensure that any new ordered bridge design complies with the appropriate design rules on a probabilistic approach. Also, the historical approach and various constructions over the years are described.

It was of importance to collect all relevant information, to record and to make it accessible for different users. In this way future enhancements would be possible and a central coordination on all the information would be a fact. We decided to work on different “books”.

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The optimal cost-effective decision for the preservation of a bridge-deck is a critical process and needs a close cooperation between the disciplines Design and Maintenance from which the practical information
like inspection results is collected. Future use, loads an distributions in respect to the extra required lifetime and the technical state of the construction details in respect to fatigue and other degradation processes would have an influence on the possibilities for lifetime enhancement. Also, the costs of the intermediate (safety) inspection method in respect to required liability has to be considered.

SOME PROMISING RESULTS

Lifetime calculation and prediction of fatigue cracking

First of all we started to focus on the project scope. Which bridges would be part of the project and what specific fatigue cracks would be considered. About 80 bridges, steel fixed and movable with orthotropic steel decks, built from 1925 to 1998 were adopted. We decided to focus on about 10 main fatigue cracks. High priority was given tot the deck plate crack to prevent any future events as experienced on the Van Brienenoord bridge.

At this moment we not only understand the mechanisms for the various bridge deck details but we can also calculate the fatigue lifetime in respect to traffic load and distribution. Depending on location (the type of traffic and the specific numbers) and the construction details of a bridge deck a special computer program was written for specific fatigue cracks and traffic was measured in load and numbers at various locations. In the present program various traffic models can be calculated for making lifetime predictions which would include inspection moments. The results of lifetime predictions are in accordance with detected fatigue cracks. We developed a philosophy and system for keeping our 80 bridges safe from deck-plate cracking. This system is based mainly on inspection, monitoring of existing cracks in relation to cost effective lifetime enhancement based on repairing and special tension reducing solutions underneath the deck construction.

Results on reparation techniques

Our task force reparation techniques developed several solutions; from emergency to qualitative reparations which suit our design philosophy. It is important that the procedure is very well described in every detail based on which future enhancements can be implemented. In the emergency cases a plate is simply welded upon the cracked section on the steel deck. This is only for a short period of time < 1 year so a definite reparation can be planned and organised. The deck-plate solution is an example of a definite solution and it is also used to replace a temporary solution. Development and enhancement on this repair method resulted in the replacement of the existing steel plate with a thicker one which would fit exactly in position after shortening the trough legs. To lower the stress on critical welding positions, it would be better to cut not just above the trough legs but in between the next trough and the cracked trough where the bending moments are low.

Results on inspection techniques

Because the start of the deck plate fatigue crack is at the top of the trough weld to deck connection, which is at the inner side of the trough stiffener it was necessary to develop alternative inspection methods. One of the results can make it possible to inspect the deck plate on a fully trough the deck plate grown crack through the 5 cm thick wearing coarse. We also developed an ultrasonic based inspection technique from beneath the bridge deck. Without interrupting traffic we can still inspect or monitor on specific locations. However, the accessibility of the structure is important and can be expensive, especially for monitoring
purposes. Two other promising techniques, based on Pulse Eddy Current, for inspecting from the bridge deck, through the 5 cm thick asphalt layer have been developed in cooperation with private enterprise. Critical in the performance so far is that only cracks can be found that have fully propagated through the deck plate. This may be useful for safety inspections but it is not adequate for all applications of lifetime enhancing techniques. The very reliable, but only on blank steel decks usable TOFD (Time of flight Diffraction) based inspection technique has been optimised and recorded in a specific inspection procedure.

Results on inspection strategy

Another development is the inspection strategy itself. On behalf of the probabilistic safety approach we are implementing an inspection strategy in which the safety inspection interval is user (traffic load) based in stead of a fixed time interval. First of all the most important bridgedecks are inspected at this moment. To share knowledge on techniques and approach of the overall inspection strategy a special task force (RISK) is founded. Conventional maintenance A is formed by time based inspections of the bridge structure and the replacement of parts of the structure when these parts are at the end of its lifetime. Probabilistic-based inspection is necessary and needs an individual approach for every specific bridge. This is were the lifetime-calculation has a direct relation with reliability analysis of critical construction details gathered from a safety inspection. Also when you have various options for renovation techniques it can be very cost effective to determine your optimal inspection interval. So eventually we try to reach situation B with minimal inspection efforts.

Results on lifetime enhancement

To enhance the lifetime of the existing bridges we have developed and reasonably well tested rehabilitation techniques for the fixed bridges. Starting with FEM-analysis and laboratory research we tested most of the promising solutions Full-scale on the remaining parts of the second Van Brienenoord Bridge.

- A very simple and useful technique for fixed and movable bridges is shifting the road lanes about 60 cm. It is by far the most cost effective method but at the same time you only gain a factor two at a
time. If there’s enough space on the bridge deck you can pursue this method without taking any traffic measurements.

- A very effective technique for fixed and movable bridges is filling two troughs under the heavily loaded lane with a special developed epoxy/cork mixture which is also capable of glueing to the deck plate. When keeping the structure mass low (critical on movable bridges) the stresses are decreased by factor two or three and the failure mechanism will be blocked.

- A very effective technique for fixed and movable bridges is based on glueing a 5mm thin steel plate onto the existing deck-plate. Field tests have just been carried out and this concept is ready for fatigue testing.

- A very effective solution for fixed bridges was based on one of our ideas focused on the replacement of the asphalt wearing coarse by a reinforced high performance concrete (RHPC) B110 overlay which is bonded to the bridge deck. This specially engineered interface was found to be a very promising solution. It turns the deck plate in a much more rigid construction with a higher “plate factor” due to the composite interaction between the RHPC overlay and the steel deck plate. Based on earlier FEM analysis and laboratory tests on various samples this overlay showed that stress reduction on critical places could be reduced by four to five times (from 124 MPa to 28MPa).

Research continued with a field test on the old Van Brienenoord sections that we saved for research. A fatigue loading test followed in which the Moerdijk traffic load spectrum was simulated for 75 years.

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The summary of the Final Element Calculations of the stresses and the deformations on the four most promising solutions, which have been validated on laboratory and field tests, are shown below.
A real Pilot project

A full scale Pilot is planned at the moment this paper is written. For the first time this solution is now carried out in a special Pilot section which measures two traffic lanes (6.7m wide) over 80 m on the Caland bridge. Because of specific future demands (when the Caland Tunnel is open for traffic) from 2004 the existing four lanes will be reduced to two lanes. This is giving the opportunity two combine the shifting lanes method with the concrete overlay method in a very effective way. The bridge deck will be fully inspected by TOFD inspection and cracks that have reached 5mm in the 10mm thick deck plate will be repaired before the RHPC concrete layer is applied. Lifetime calculations showed a 40 year increased lifetime.

For the Pilot Caland Bridge the following tasks were carried out:
Removing the 5 cm thick asphalt wearing course, the surface is shot blasted, TOFD inspection is carried out on the most heavy loaded through legs (six in total), if necessary, in judgement with the engineer, fatigue cracks will be repaired with sub-arc welding, afterwards the steel deck was cleaned and shot blasted on its total area to get a course layer for the epoxy adhesive. In the 2 mm thick epoxy layer we sprinkled 3 -6 mm bauxite grains to finish the bonding zone. This specially by the Ministry designed and tested bonding zone turned out to be a very good bonding design under all circumstances (stresses) for connecting the steel bridge deck with the concrete overlay. Also this method was developed to avoid local peak stresses in the deck surface when welds are used.

The welded mesh reinforcement (diameter 8mm, consisting of two pre-fabricated mats with bar spacing #50 x 100 mm placed on top of each other) was put in place. So the total thickness of the new layer would become 50 mm. The minimal concrete cover at the top of the new layer should be 10 mm. The concrete B105, is consisting of pre-blended materials and steel fibers (70 kg/m3), delivered by Contec ApS was transported by truck mixers and finally dumped by dumpers, which could travel on top of the welded mesh reinforcement.

To get a good bonding with the epoxy bauxite layer it is very important to compact with enough energy. Tests turned out that a 60 Hz vibration screed was satisfying. The layer must have a compressive strength of 50 Mpa (which was reached in about 10 to 12 hours from the last dump) before any traffic was allowed to pass. In the hardening process the top layer was kept wet by totally covering the surface with jute. After the compressive strength of the layer had become about 30 MPa a mobile shot-blasting machine blasted the surface layer to the right skid resistance. In one pass the prescribed skid resistance of 52 SRT was easily reached. Afterwards the traffic marks were painted on top of the brand new deck. The whole area has been kept wet for the next seven days by a perforated water hose.
Pictures are taken from the Pilot Caland bridge (29 April till 4 May 2003) in which the original wearing course has been replaced with a 50 mm reinforced high performance concrete layer bonded with the steel bridge deck. The last meter, showing the concrete surface, a fresh shot blasted concrete surface, which is ready for traffic.

CONCLUSIONS

Time is not on our side in respect of fatigue. Since this is an international problem there has to be more cooperation and communication in a scientific and practical approach. The fatigue problem of orthotropic steel decks can only be solved cost-effective with an integral approach, based on probabilistic inspection, lifetime calculations and suitable lifetime enhancement solutions. The RHPC concrete overlay which is bonded to the steel deck is a very promising solution for fixed steel orthotropic bridge decks for lowering stresses in fatigue critical construction details at the root of the longitudinal fillet weld between the trough wall and the deck plate.

ACKNOWLEDGMENT

The authors would like to acknowledge the work of the different taskforces behind the scenes and in particular the engineering input en support which has enabled the project to progress rapidly with a new developed lifetime enhancing method over the last month and for making the Pilot Caland Bridge a success.

REFERENCES


