Full-scale fatigue testing with initial damage as validation of FRP road bridge design

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Abstract

Bridges built in fibre reinforced polymers (FRP) bring the important advantage of low-maintenance costs, thus reducing the total cost of ownership. Various kinds of FRP-constructions have been built hundreds of times in the last decade, the technology is now beyond the stage of infancy. The Province of Groningen has positive experiences with bridges and lock gates built in FRP. For a 8m span lifting bridge for road usage, the province prescribed FRP as the structural material for the deck, and in parallel required additional validation of the material's fatigue resistance through full-scale testing.

Keywords: Movable bridge; FRP; full-scale testing; impact damage; fatigue.

1 Introduction

In civil engineering FRP is a relatively new material. During the last decade, it is increasingly used in bridges and other civil engineering structures. As a result, frameworks for acceptance and quality assurance are in place or being established in various countries. Due to the relatively small number of FRP structures compared to those built in conventional structural materials and their large geographical spread, these frameworks still have a status of guidance and have not yet reached the status of standards, such as Eurocodes.

In order to progress rather than wait, the road authority of the Province of Groningen (the Netherlands) procured the FRP 'Pijlebrug' in a competitive market, giving room to the material and the FRP supply chain to prove itself. The client has been following the emergence of FRP as a structural material for multiple years, and already commissioned FRP lock gates in 2011. The key reasons for opting for FRP were to:

- obtain a relatively lightweight bridge deck. The architectural design of the bridge left a relatively small space for the counterweights in de towers of the bridge;

- proceed in making FRP a more commonly accepted material in civil engineering, creating greater confidence in the use of FRP;
- actively develop the acceptance of engineering rules or testing of the structure;
- lower maintenance costs.

As each FRP fabricator has its own construction principle, the client decided to leave the responsibility for the design and detail engineering to the (sub)contractor. The client merely made an overall design (Figure 1 and Figure 2) and in addition to the required calculations of the structure, it prescribed a few testing methods in order to prove the proposed construction to meet the requirements

The client as well as the FRP fabricator had a common target in building a product that satisfied the functional requirements and would act as a benchmark for future projects, reducing the need for further testing and validation. Working together mainly on technical solutions fulfilled both needs.

The combination of testing and construction ensured that the tested configuration would be exactly that of what was to be built, with no interpretations required from other types of FRP construction.

Figure 1. The design of the Pijlebrug.

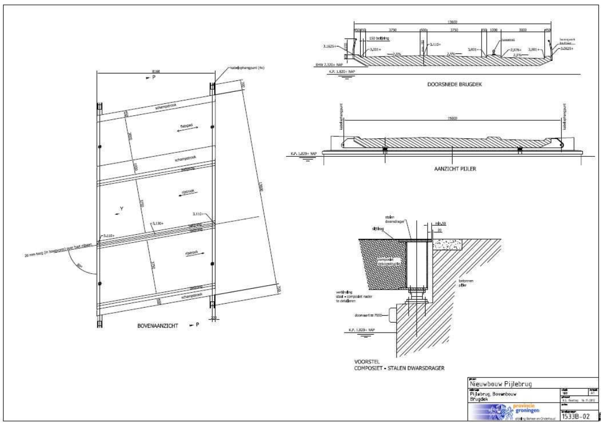

Figure 2. Contract drawing, showing only the overall principles.

2 Tender procedure

For the Pijlebrug, the client had clear ideas about the bridge's functional requirements, and the testing it required to validate the design. Only the overall design was specified at the tender stage, detailing was left to the successful contractor.

Rather than commissioning a test program that would provide the proof of suitability, the client decided to include the desired testing in the tender specifications, and tendered the full bridge (which involved concrete, steel and FRP) together with the FRP test program. Together with a conventional structural engineering design report, the results of the test program would be seen as a double, redundant, justification of the structure.

The winning bid for the project came from a main contractor that subcontracted all steelwork and the operating mechanism of the movable part to a steel fabricator with in-house engineering capacity. The steel contractor in turn subcontracted the design and supply of the FRP deck and its testing to an FRP Design & Build firm.

Considering the bridge as a landmark project, the successful FRP fabricator invested additionally and expanded the test program with the introduction of intentionally applied damage prior to the fatigue testing. In addition to fatigue-resistance, the tests would thus also demonstrate the absence of damage propagation that other types of FRP construction are known to be prone to.

3 Bridge design

The bridge consists of a bridge deck made of FRP with 2 steel lifting beams and 4 steel towers which contain and guide the counterweights. On the bottom of each tower an electromechanical drive unit is located. Steel cables are used to drive the movement of the bridge as well as to connect the counterweights to the bridge deck.

The steel lifting beams are shaped as a horizontal 'U', fitting around the deck and adhesively bonded (Figure 3), backed-up with vertical stainless steel pins through the steel flanges and the deck. These beams run transverse to the main span of the bridge, and include lifting points at their four ends. The connection between the deck and the steel beam was included in the test program.

The tests were executed successfully and did not result in changes to the deck design. The deck was built and inaugurated to the users in spring 2015 (Figure 4).

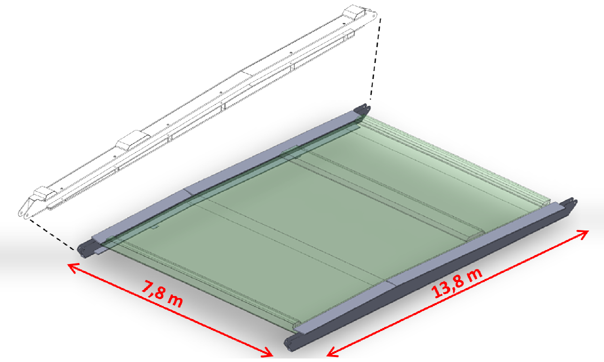

Figure 3. The design of the Pijlebrug consisting of an FRP deck spanning in between two steel lifting beams in crosswise direction.

Figure 4. The completed Pijlebrug.

4 The material FRP and its fabrication method

Fibre-reinforced polymers (FRPs) or composite materials, are combinations of load-bearing fibres and a polymer matrix. FiberCore Europe, the contracted designer and fabricator for the Pijlebrug, designs and manufactures load-bearing FRP structures using its patented InfraCore® technology. The most cost-optimal solution is to employ glass fibres in a thermoset polyester matrix. These FRPs typically combine high strength with low stiffness, compared to traditional construction materials such as steel. As such, FRP designs for bridge construction are usually stiffness-driven, resulting in low utilization ratios (unity checks typically between 0,10 and 0,20) in the ultimate limit state and a high fatigue resistance.

InfraCore® structures are sandwich-like structures where fibres in both skins also run vertically through the core, thereby eliminating the risk of skin-debonding and ensuring structural integrity at high loads and/or a high number of load cycles, even after local damage. InfraCore® panels are always built in this same manner. Depending on the application, laminate layup and panel dimensions can be varied.

5 Full-scale tests

FiberCore Europe had already conducted a constant-amplitude full-scale fatigue testing of a bridge deck. For the Pijlebrug project, additional fatigue testing at both the material level (according to methodology described in [3]) and at the full-scale level were required. The full-scale test comprised the harmonic response [4], the static deflection [5], creep during loading [6], creep during unloading [7], impact [8], fatigue [9] and ULS-loading [10].

5.1 Test setup

The inherent damage-tolerance and low utilization ratios promise high fatigue resistance for InfraCore® panels for bridge structures. To assess the fatigue resistance for bridge applications, in addition to fatigue calculations, a full-scale test specimen was produced for testing.

The test specimen measured 7,3m x 3m x 0,43m (length x width x height), which equates one lane of the bridge. Steel lifting beams were added to match the design of the full bridge. The specimen was not finished with coating or wear surface to maximize visibility of any damage or damage propagating in the test specimen. All typical construction details are included in the test coupons, so test results are generically applicable for InfraCore® structures.

The specimen was loaded at three points along the span (Figure 5), equivalent to the Eurocode fatigue load model LM4a [2], 20 million load cycles, with loads up to 200kN.

The tests were conducted at WMC (Knowledge Centre for Windturbine Materials and Construction, a cooperation between Delft University of Technology and ECN (Energy Research Centre of The Netherlands, specialized in fatigue testing of large-scale composite structures), see Figure 6. Both research facilities have broad expertise and experience in damage inspection and assessment. The fatigue test was running 24/7, and were stopped at regular intervals to inspect the specimen and assess the structure for the appearance of any new damage or propagation of the intentionally applied damage.

The full-scale tests at WMC have been witnessed by DNV-GL. While not formally required, it is common practice in the rotor blade testing procedure to ensure compliance to the agreed testing protocol and that the tests are performed independently.

In both tests, local damage in the skin laminates of the test specimens was introduced before fatigue loading (Figure 7). In real life, such damage can occur due to collisions, accidents happening on the bridge, loose cargo falling on the bridge surface, or other causes if no crack-arrestors are in place. These local damages can potentially become a hazard to the structure if they were to grow (due to heavy loading or fatigue) and lead to progressive collapse. This is prohibited in the Eurocodes [1]. In the InfraCore® construction method, the oblique lay-up of the skins and the shear webs together prevent progression of any crack and no collapse can occur.

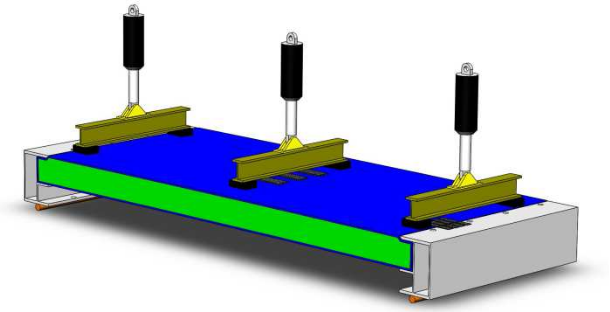

Figure 5. The design of the test setup.

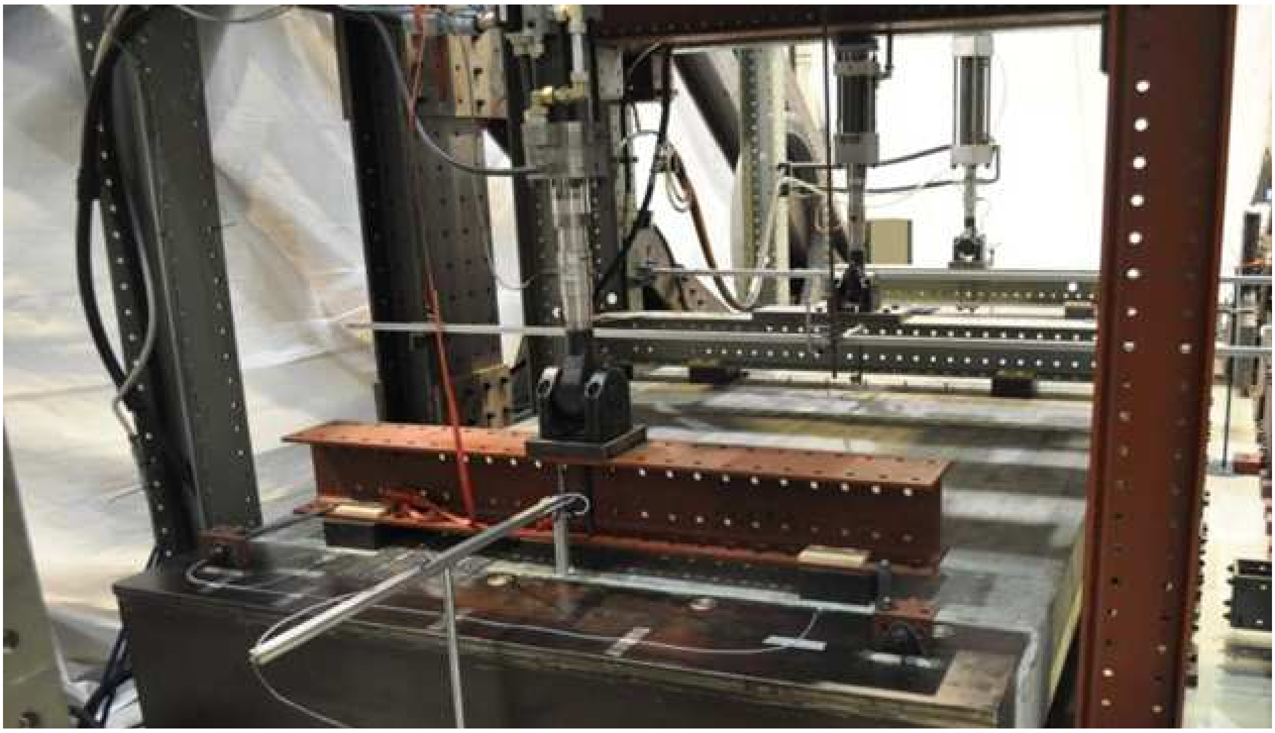

Figure 6. Full test setup at WMC. The fatigue loading is generated by three hydraulic cylinders. The load is introduced in the deck through HDPE 'wheel prints'.

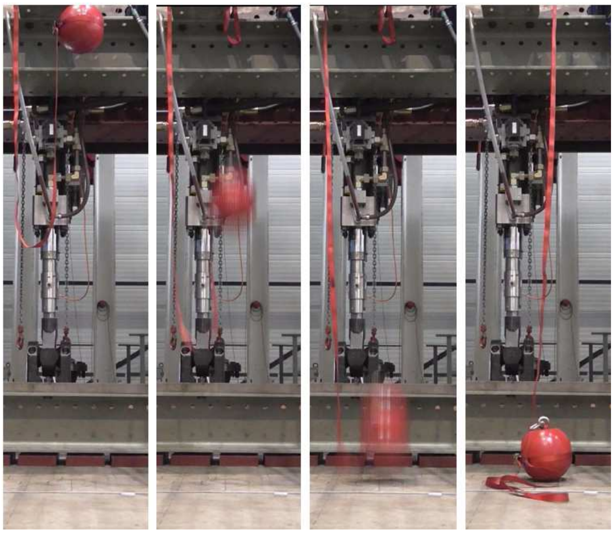

Figure 7. Impact of a steel sphere weighing 50kg, dropped from a height of 2m.

5.2 Test results

During the test and upon completion no damage initiation or damage-growth due to the fatigue loading was observed either by visual inspection (Figure 8) or infrared photography. In addition, no decrease in stiffness was measured, showing no decrease in functionality of the structure.

After fatigue testing, the test specimen was loaded by the full Eurocode design load with partial factors included [2]. The test specimen showed no decrease in load bearing capacity.

The fatigue loading had no adverse effect on structural safety.

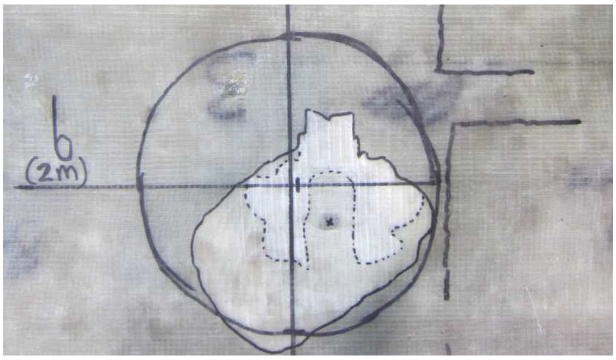

Figure 8. Local damage (delamination) in the upper skin as a result of the impact. No damage propagation was visible after the fatigue loading.

6 Material fatigue test

While full-scale tests are valuable for specific designs, results are difficult to generalise and hence do not provide evidence for all designs and load cases. The Pijlebrug deck being built using a standardised technology that is not redesigned for other applications, but only scaled, nonetheless allows for generic conclusions.

Generic use of test results requires more detailed information on material properties. For that purpose, and outside the scope of the Pijlebrug project, extensive fatigue testing on material samples have been performed to determine S-N curves in both longitudinal and transverse direction of the laminate used in InfraCore®. The test comprises a repeated cyclic load up to a certain level being applied repeatedly until failure. Higher stress levels result in a lower number of load cycles until failure.

Scientific research shows that – in contrast to e.g. steel – FRP materials have no fatigue limit and S-N curves are linear on a log-log scale [11]. Therefore, the test results can be extrapolated to higher loadings or cycle counts than such curves for metals.

The measured data in Figure 9 allows for more accurate fatigue calculations on InfraCore® structures for up to 1 billion load cycles, allowing the design of bridges intended for use in heavy-traffic areas.

Fatigue can threaten the structure at two locations in the deck; (1) at the supports in the shear webs connecting top and bottom skins and (2) at mid-span in the top and bottom skins. Using the material test results, the allowable number of load cycles can be calculated for both, taking into account the number of load bearing fibers in the principal direction.

FEM analyses and analytical approximations have shown the stress levels for the tested fatigue loading to be between 0 and 25 N/mm^2 at (1) (normal stress, tensile-tensile at the bottom skin, compressive-compressive at the top skin) and between 0 and 55 N/mm^2 at (2) (shear stress, tensile-tensile in fibre direction). As the tested fatigue loading has a variable amplitude, these maximum stresses only occur in less than 10% of the load cycles. The shear stresses in the webs are normative for the design. At the highest stress levels, the allowable number of load cycles is more than 15 million, at a confidence level of 95%.

Taking the variability of the fatigue loading into account, the allowable number of load cycles can be calculated using rain flow counting, and exceeds 100 million. The test specimen is at less than 10% of its technical life span. For excessive situations, the allowable stress can be even further increased by altering the composition or thickness of the shear webs or skins.

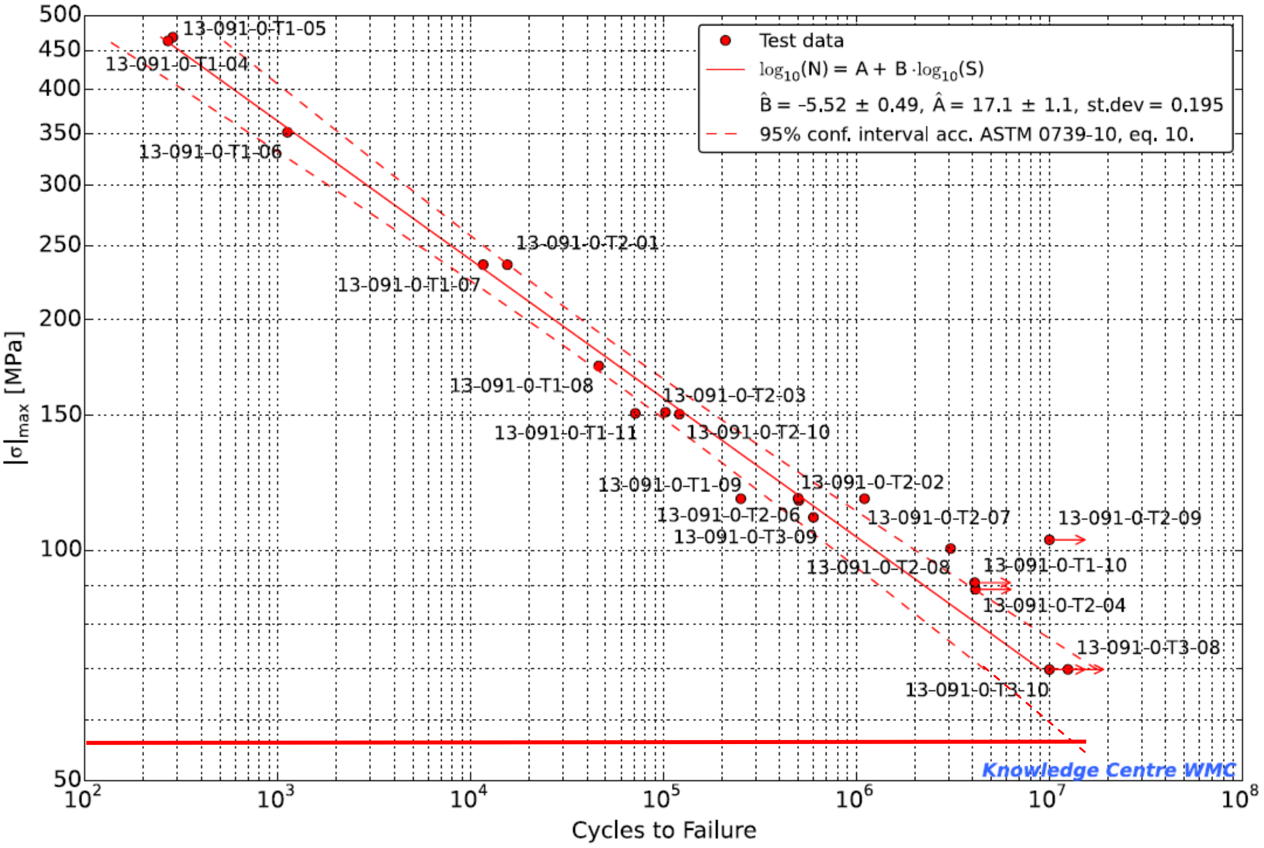

Figure 9. The S-N curve for a glass fibre reinforced polyester polymer plotted is a straight line when plotted on a log-log scale. The highest stress level occurring in the shear webs (tensile-tensile in fibre direction) is shown through the thick red line.

7 Conclusion

The client experienced the tendering of the Pijlebrug as satisfying. The successful tests increased the client's confidence in the use of FRP in civil engineering structures like bridges and lock gates.

Specifically, the client gained confidence in the engineering rules outlined in the CUR96. The testing proved the rules to meet the expectations.

In the near future the client expects FRP to be accepted as a regular construction material, like concrete or steel.

InfraCore® structural panels allow for the design of fatigue-resistant structures, such as heavily loaded bridges. The high fatigue resistance, even after initial local damage, is a result of excellent material properties in combination with the structural cohesion of the deck's construction method. None of the full-scale test specimens have failed, the number of load cycles up to failure have yet to be determined.

The full-scale test specimen that was used suffered no damage aggravation and despite being at the end of its technical life, is expected to last much longer. Together with the fabricator owning the specimen, the client is currently looking into a new life for this structure, with the aim of monitoring it and gaining further data.

8 Acknowledgements

The authors would like to acknowledge the efforts made by all parties that were involved in this project. The required testing created an additional procedure of approval that required everyone's

co-operation over the project's duration. The project's main contractor was Macadam BV. Machinefabriek Rusthoven BV was the subcontractor for all steelwork, the operating mechanism and the movable deck.

9 References

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