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Bio-Based Composite Bridge – Lessons Learned

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Abstract

The concept and design process of the world’s first bio-based composite pedestrian bridge at the campus of Eindhoven University of Technology was described and presented at the previous IASS conference in Tokyo [1], [2]. The bridge has a span of 14 m and uses a bio-composite as the main structural material, which is based on hemp, flax and Greenpoxy. In the meantime the project has been successfully realized and finished in November 2016.

The focus of this paper will be on a couple of major aspects, that can be helpful for future projects using bio-based composite materials: evaluation of the material tests, comparison of the FEM analysis with the 1:1 scale load test, production process as well as the monitoring of the bridge after installation. In order to understand the material properties in a better way a series of tests have been and still are being conducted in the laboratory at TU/e. Apart from the prior essential tests, such as strength and stiffness, further ongoing tests look at the creep behaviour of the composite material. The installation of the bridge was carried out in public space, so full approval of the authorities had to be obtained. Due to the fact that no building codes exist for bio-based composite materials the authors had to prove the correctness of their calculations with a full scale load test. At the moment the long-term behaviour of the bridge is monitored with in total 27 fibre-optical sensors to further study and evaluate the strain properties over a period of 1 year with varying environmental conditions. It can be concluded that bio-based composite materials show a great potential for applications in the built environment, while also a long list of questions remains for researcher to be answered.

Keywords: Footbridge, innovative structural design; new materials; bio-composites, fibre brag optical sensors; bio-based structures.

1. Introduction

In November 2016 the world’s first fully bio-based bridge was installed at the TU/e University Campus in Eindhoven, Netherlands over the river Dommel. Figure 1 shows the bridge in production (see [2] for more specific details on the production process) and Figure 2 shows the bridge after installation and in use, last December. The bridge has a length of 14 m and uses natural fibres: hemp and flax. The used resin is a bio-based epoxy resin around a core of PLA (polyactic acid) bio foam in combination with several cork interlayers. The bridge has been designed and built under a so-called 4TU Lighthouse research project in which also other parties have collaborated.

For the unit Structural Design at TU/e, and especially the chair ISD, Innovative Structural Design, the main research and design question was whether and how these bio-based composite materials could be used in a structural loadbearing (bridge and building) application.
2. Design and elaboration

For more detailed information on the bridge design process as well as fabrication process is referred to [1] and [2]. In the preliminary as well as final design, material properties from material tests were used to model the structural behaviour. With regard to the material properties including the short term behaviour a lot of information was obtained. For the long term material behaviour however there are still many unknowns. For this reason creep test have been performed and also it was decided to monitor the bridge on site and while in use. For the short term behaviour figure 3 gives a good indication of stress strain behaviour.
Based on these kinds of material test-results a FEM model has been developed to model the final design of the bridge. Figure 3a shows the expected elastic deflection of 43 mm under a combination of self-weight (about 1.0 kN/m²) and an imposed load of 5.0 kN/m².

During a load test at the production facility of the bridge the calculated deflections were compared to the measured deflections as well as the measured material strains (Figure 4b). These strains are measured using optical Fibre Bragg Grating sensor technology (FBG). This sensor technology is very suitable for composites because of its non-intrusive nature and small dimensions (~100 – 200µm diameter) as well as its high sensitivity [3]. In total 27 sensors have been successfully installed in the bridge: 13 sensors in the compressive zone, 14 sensors in the tension zone. Figure 5 shows the location of the 27 sensors.

3. Comparing material test and design models with observed bridge behaviour

Figure 4(a) Typical result of a repeated loading-unloading and reloading tension test in the laboratory on a test specimen of Woven (90 degrees) flax fibre composite showing hysteresis behaviour.

Figure 4: a) Deflections FE model bridge beam; b) Test set up full scale bridge beam, loaded with filled water tanks (5kN/m²) and comparing measured deflections and strains with calculated values in model.

3. Comparing material test and design models with observed bridge behaviour

During a load test at the production facility of the bridge the calculated deflections were compared to the measured deflections as well as the measured material strains (Figure 4b). These strains are measured using optical Fibre Bragg Grating sensor technology (FBG). This sensor technology is very suitable for composites because of its non-intrusive nature and small dimensions (~100 – 200µm diameter) as well as its high sensitivity [3]. In total 27 sensors have been successfully installed in the bridge: 13 sensors in the compressive zone, 14 sensors in the tension zone. Figure 5 shows the location of the 27 sensors.
The measured resulting strains during the imposed load test are shown in figure 6. They match the calculated maximum deflection of about 35 mm due to the imposed load. (This calculation is here not given)

Also, the measured deflections during the load tests (maximum of 33mm in the centre) in figure 7 almost exactly match the calculated model value of 35 mm.
Figure 7: Measured deflections during load test (maximum measured 33 mm, calculated 35 mm)

With the implemented optical glass fibre sensors it becomes possible to monitor the bridge during its service life. Figure 8 shows results of a first load test performed after installation of the bridge in December of last year. The load test involved carrying 20 loads of 30.6 kg, equivalent to 0.3 kN, on the bridge, and placing them in the middle of the bridge.

Figure 8: In situ measurements of strains after installation of the bridge during load test of 6.0 kN

Peaks in the beginning with increasing strains indicate the effect of persons walking on the bridge while carrying and placing the loads of 0.3 kN each in the middle of the bridge. The gradual increase in strains can be seen to the point at which there are 20 loads representing a total of 6.0 kN added in
the middle of the bridge. Comparing the measured results (Figure 8) to the elastic calculation (Figure 9), it can be observed that the strains on the tension side are comparable to the elastic calculations (145 μm/m measured versus 150 μm/m calculated). On the compression side the measured strains are -55 μm/m, so somewhat smaller than the -90 μm/m calculated. The reason for this is currently not clear, but is looked into. Part of the explanation could be the location of the sensors at the compression side, because these sensors are not placed in the 2 directional woven material, but located in the less stiff, non-woven material. Another thing that can be observed is that there are still remaining strains, after the loads have been decreased: the strains did not return to zero. The maximum remaining strain in tension is almost 30 μm/m. This corresponds with the hysteresis behaviour that was observed in earlier material tests, see Figure 3. The 30 μm/m corresponds to 0.003 %.

![Figure 9: Calculated elastic stresses and strains for a 6.0 kN load in the middle of the bridge](image)

4. Creep behaviour

Because it can be expected that the bridge will also show time dependent non linear behaviour, 3-point bending material creep tests on three different stress levels (5-15 and 25 Mpa) are performed at TU/e (still ongoing). Figure 9 shows the results (until date 1-5-2017). The creep slope of the samples under lower stress levels (indicated with 5 Mpa) when analysing the numerical data seems to decrease in time, however it is too early to draw conclusions. The higher stress level (25 MPa) shows only a very small reduction in creep slope. Based on preliminary calculations the long term deflection of the bridge can be estimated by using a simple reduction in E-modulus approach: with a reduction factor $k_{def}$:

$$E_{mean,fin} = E_{mean} / (1 + k_{def}).$$

(1)

Based on the creep curves for stress-levels of 5MPa (see graph in figure 10) and preliminary calculations, a $k_{def} = 0.8$ was found. Further analyses and combining these creep test results with in situ measurements of strains and measurements of deflections is currently ongoing.
Using the Logarithmic time scale for the creep curves (figure 11) it becomes more explicit that for higher stress levels larger increases in the deformations in time can be expected, and in time even failure of the material could occur.

From this perspective the design of the bridge was good structural design. In order to avoid large creep deformations the stress levels due to the permanent load (bridge beam and balustrade) were kept low. The characteristic values of the stresses are only 3.3 MPa in tension and 2.1 MPa in compression (of course also due to the low self-weight of the materials).
5. Conclusion and discussion

Good correlation was found between material tests, structural models of the bio-based bridge, the load test before installation as well as the first in situ strain measurements. The initial behaviour as measured in the tests match the modelled behaviour quite closely. The long term behaviour however is much more uncertain. Still ongoing material creep tests show significant increases in deformations in time and can even be expected to show failure at higher stress levels (> 25 MPa). Further in situ tests are needed to analyse the bridge time dependent behaviour in more detail and see to what extent they match the (ongoing) material tests. For this reason also the moisture and temperature dependent behaviour, influences on stiffness and strength need to be considered.

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