Fully bio-based-composite footbridge: strain monitoring during use phase

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FULLY BIO-BASED-COMPOSITE FOOTBRIDGE: STRAIN MONITORING DURING USE PHASE

Rijk Blok
Assistant Professor
TU/e Eindhoven University of Technology, Netherlands
R.Blok@tue.nl

Patrick M. Teuffel
Professor
TU/e Eindhoven University of Technology, Netherlands
P.M.Teuffel@tue.nl

Summary

Last year a bio based pedestrian bridge, first in its kind, has been installed at the TU/e University campus in Eindhoven. Material test formed the basis for the innovative design and the research project resulted in the production and installation of the bridge. Because there are still a lot of unknowns in the material behaviour of the used bio-composites, it was decided to monitor and test the bridge further after production. For this purpose optical FBG sensors have been installed. The FBG sensors show the material strains in good detail and the results of the thus measured strains in load tests are shown. The test results are compared with results from earlier material tests. The short term structural behaviour follows closely the used elastic models based on calculated as well as measured stiffnesses. The long term time dependent behaviour however shows a number of different influences from creep, temperature and moisture content that can not yet be fully explained by earlier measurements and tests.

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 (left) shows the bridge at its opening event in October 2016. The bridge has a 13 m free span and uses hemp and flax fibres in a bio-based epoxy resin around a core of PLA bio foam. The bridge is the result of a so-called 4TU Lighthouse project. In the material research, the preliminary bridge design, the structural optimization as well as in the final design and production and installation involved many students from different educational levels.

The main and ongoing goals of the research project on the bio-based materials were: investigating options for further reduction in the use of fossil fuels, preventing further depletion of raw materials and increasing options for a transition towards a more circular economy. For the unit Structural Design at TU/e, Eindhoven University of Technology the main research question was whether and how these bio-based composite materials could be used in structural loadbearing (bridge and building) applications. Until recently bio-based composites have already been sparsely used in façade applications and also some structures with limited bio-based materials are known, but a bridge fully made out of bio-based composite materials had not yet been realised.
2. **Design and elaboration**

The bridge, first in its kind, has been made fully out of bio-based materials: Flax and hemp fibres in a bio-based resin and round an internal shape of PLA bio-foam.

The project team-members together with students started off in joint design sessions, with generating design ideas in sketches and models. In further sessions the most promising designs were further elaborate. The designs were optimised using Rhino/Grasshopper programs. Materials were tested on strength and stiffness in the TU/e's structural laboratory in order to model the material behaviour as close as possible and to arrive at safe design values of strengths. Figure 2 shows a typical result of a (repeated) tension test on a woven Flax fibre composite. To optimise the structure, the woven fibres were positioned in tension and compression zones. Using values from the material tests as well as other sources the preliminary structural design calculations were made. In a later stage when more information became available simple beam-models were replaced by more complicated Final Element Models (FEM) (see also [1]).

![Graph showing stress-strain behavior](image)

**Figure 2:** 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.
For more info on the design and production process is referred to [1] and [2]. The resulting bridge beam is light-weight in comparison to other, for example concrete, bridges. The whole bridge including its rather heavy railing weighs 2.6 tons.

Figure 3 a: Bio-based Footbridge at production facility ready for vacuum infusion; b: Gluing optical glass sensors (FBG) between 2 fibre layers

3. Monitoring strains using optical sensors

With regard to the long term bio-composite material behaviour as well as its degradation behaviour there still are a lot of unknowns. For this reason further creep tests and material degradation have been performed and the influence of moisture uptake on strength and stiffness are being researched. Because of these unknowns regarding the material behaviour, it was decided to monitored the bridge during its service life. To obtain data on the material behaviour sensor technology has been integrated in the bridge design. Optical Fibre Bragg Grating sensor technology (FBG) is used because of its non-intrusive nature and small dimensions (~100 – 200 µm diameter) as well as its high sensitivity [3]. Until now TU/e does not have the equipment to constantly monitor the bridge behaviour although this the goal for the near future.

Because the thin glass fibre sensors are extremely vulnerable during production, the glass fibre is glued between two layers of Uni-Directional (UD) fibres for protection. Figure 3 (b) shows the preparation of the glass fibre sensors, before integrating the protected sensors in the production process. In total 28 sensors have been installed in initially 3 lines. Figure 4 shows the location of the 28 sensors:

![Figure 4: Location of Sensors. Line SG-01 and SG-04 are mainly compression (in bridge deck). Line SG-02 and SG-03 are mainly tension (under-side bridge).](image)
The compression line was broken during production. Due to this in the test of October only the sensors 1-1 to 1-7 were registered. In the test of December the sensors 4-1 to 4-6 could be recovered by accessing them from the other side (line 4). Sensor 1-8 was lost.

4. Results of Strain measurements

4.1 Load test before Installation

On 16 October 2016, at the production facility Rosmalen (before installation of the bridge), the bridge was tested as part of the construction permit process. The temperature of the bridge (after curing) is estimated at about 20 °C.

![Figure 5. a: Impression of the load test using water tanks. b: Elastic calculated stresses and strains under maximum load (7x 9.5 kN) based on E= 10.000 MPa]

The result of the measured strains in the optical sensors is shown in figure 6. They show a good correlation with calculated results (and also with the deflection measurements (here not shown) that involved Youngs modulus estimations based on fibre content calculations [2] as well as results from material tests. The maximum measured strain on the tension side was about 800 μm/m compared to 780 μm/m calculated. On the compression side the measured strain was about 550 μm/m compared to 520 μm/m calculated, this is with a 2.5% to 6% difference.

![Figure 6: Measured strains during the load test.]
4.2 Load test 1-12-2016

After installation of the bridge a static load test was performed at 1-12-2016 from about 13.25 hrs. to 13.50 hrs. The load test involved carrying 20 loads of 30.6 kg equivalent to 0.3 kN on to the bridge and placing them in the middle of the bridge (see figure 7).

Figure 7. a Top view and b: Weights loaded onto bridge deck

The resulting strain measurements of the load test on 1-12-2016 are shown in figure 8. The positive strains tension are located at the underside of the bridge. The negative strains in the deck of the bridge. It can be seen that they show a gradual increase with increasing loads. Peaks indicate the effect of persons walking on the bridge while carrying and placing the load in the middle of the bridge. The small horizontal platforms are more or less static situations in which the load is constant. 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 (Figure 7). The more or less horizontal plateau at about 13.37 hrs. shows the strains in this situation.

Figure 8. Resulting strains of load test 1-12-2016.
For comparison the elastic load model and the calculated resulting stresses and strains are shown in figure 9.

![Figure 9. Calculated stresses and strains under maximum load (F=6.0 kN) based on E= 10.000 MPa](image)

Figure 9. Calculated stresses and strains under maximum load (F=6.0 kN) based on E= 10.000 MPa

When comparing the measured results to the elastic calculation, the following can be observed: The Strains, measured on the tension side are comparable to the elastic calculations (145 versus 150 μm/m). On the compression side the measured strains are -55 μm/m, so somewhat smaller than the -90 μm/m calculated. A reason for this could be sought in the positioning of the sensors in the compression side (bridge deck). The compression sensors were not installed in the woven Flax fibres but in the Non-Woven Hemp fibres (due to limited availability of the sensors at the time of production). The differences in material stiffness between these two fibre materials may cause part of this difference in the strain response. (Until now insufficient data on the compression side is available. For this reason this paper focusses on the tension side results.)

### 4.3 Load test 15-3-2017

A similar test was performed on March 15, 2017. Figure 10 gives an overview of the strain results during the time of the measurements from the sensors located at the tension side. Again 20 weights of 0.3 kN were placed in the middle of the bridge. In addition to that a group of 6 students increased the load to 9.5 kN by walking onto the bridge at about 14.32 hrs.

![Figure 10. Resulting strains of load test 15-03-2017](image)

Figure 10. Resulting strains of load test 15-03-2017

On the tension side the maximum strains at 6.0 kN loading are 167 μm/m. Compared to the results of 1-12-2016 this shows a (167 μm/m /145 μm/m) 15% increase, or a reduction in the stiffness of 15 % at sensor 3-4,
which is positioned in the middle of the bridge (underside). At 9.5 kN, with the additional load of the students, the maximum strain is about 250 μm/m. This still shows a more or less elastic behaviour.

4.4 Non-elastic time dependent behaviour

It can also be observed in figure 8 that at the end of the test (1-12-2016) there are still remaining strains: When the loads where decreased, the strains did not return to zero. The maximum remaining strain in tension is almost 30 μm/m. This seems to correspond with the hysteresis behaviour that was observed in earlier material tests, see figure 2. The 30 μm/m corresponds to 0.003 %.

Apart from the more or less elastic behaviour and this material hysteresis, also a time dependent behaviour can be observed. For example it can be seen is that the strains keep increasing slightly in time while the loading does not increase. At the 6.0 kN load the strains (at 2-5) increase from +163 μm/m to +167 μm/m. This is consistent with the behaviour seen in material creep tests. Preliminary results of ongoing creep tests on the bio-composite material subjected to different stress levels at TU/e indicate that at low stress levels (< 5MPa) the creepfactor k_{def} has a value of about k_{def} = 0.78. This can be regarded as a reduced stiffness in time, calculated as:

\[ E_{\text{mean,fin}} = E_{\text{mean initial}} / (1 + k_{\text{def}}) \]

\[ E_{\text{mean,fin}} = 12.5 \text{ GPa} / (1+0.78) = 7.0 \text{ GPa} \]

Figure 11 a shows results of a creep test performed at a stress-level in bending of 5 Mpa

![Figure 11a](image1)

**Figure 11a**: Strain – time relation showing the creep slope, resulting from creep test at TU/e. b: Reduction in stiffness at increased moisture levels measured at TU/e.

Another reason for a reduction in stiffness over time can be sought in the influence of an increased moisture content. Figure 11b shows results of earlier test at TU/e, in which a large reduction in stiffness was measured with increasing moisture content. In this case the test samples were thin (2 mm), cut and unprotected, allowing for easy moisture absorption in the fibres. The moisture content of the bridge in situ has not yet been measured therefore the quantification of this influence is not yet possible. Comparing the initial strains from three different test dates gives another indication of the strain behaviour in time. Figure 12 shows the results of the (tension) strains of sensors 2-1 to 2-7, only loaded by the bridges self-weight.

![Figure 12](image2)

**Figure 12**: Measured strains without any additional load measured at 1-12 and 15-12 in 2016 and 15-3-2017.
The initial large strains at 15-12-2016 compared to the Nul-situation at 1-12-2016 can not sufficiently be explained by temperature strains. Table 1 shows the measured temperatures at the time of the tests. The temperature strain increase from this is estimated at about 50 -100 μm/m (based on a calculated temperature expansion coefficient using [4]).

<table>
<thead>
<tr>
<th>date</th>
<th>temperature Underside Bridge (Celsius)</th>
<th>Strain Δε (with αt = 10x10⁻⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-12-2016</td>
<td>5,2</td>
<td></td>
</tr>
<tr>
<td>15-12-2016</td>
<td>8,5</td>
<td>6,60E+01</td>
</tr>
<tr>
<td>15-3-2017</td>
<td>16</td>
<td>2,16E+02</td>
</tr>
</tbody>
</table>

Table 1: Measured temperatures and estimation of temperature strains at three different test dates

5. Discussion and conclusions

The measured strains in the load test at the test facility and after the initial installation of the bridge show a good correlation with elastic models. The measured strains, especially at the tension side of the bridge, almost exactly match the elastic behaviour. Further tests show elastic results during these tests but when compared with the other test show a long term behaviour over time that cannot be explained by elastic models. Based on earlier material tests, influences of creep, moisture and temperature are all expected to contribute to this time dependent behaviour. However at this stage, insufficient test results and data are available to further pin point and quantify each of these different contributions in more detail. The future goal of this research is constantly monitoring of the bridge and access the data through internet. It is expected when more data from more test become available, as well as more material tests, (for example more exact determination of the temperature expansion coefficient of the material, as well as measuring the moisture content in situ) combined with a more detailed FEM modelling will provide more insight.

6. References


