# Monitoring high temperatures in the VARTM production process of a novel flax fiber-reinforced composite footbridge with FBG sensors

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## Abstract

This research investigates the application of fiber Bragg grating (FBG) sensors in monitoring the vacuum-assisted resin transfer molding (VARTM) process for the production of a 15m flax-reinforced polyester footbridge. The footbridge employs a continuous cross-section with a sandwich construction. The fibers in the upper and lower faces, and the vertical webs, are oriented in various directions. Contrary to the classic face-core-face sandwich panel, the footbridge is infused as one element. Fibers are wrapped around polyurethane foam cores serving as non-structural permanent formwork. The foam core guarantees that debonding is prevented especially in the connection areas, making it difficult for resin-dominated crack propagation to occur. However, high temperatures can develop while curing in this two-flanged web structure due to the insulation properties of the foam cores used as permanent formwork that confine the webs from both sides. This study takes into account critical quality parameters such as residual strains, voids presence, and peak exotherm temperatures. A careful material selection was also carried out. Temperatures and residual strains were monitored throughout the production process, during injection and curing, for a total of 7 days. A summary of the results at several sensor points is provided with a discussion.

**Keywords**: Fiber-reinforced polymers (FRP), FBG sensors, VARTM, footbridges, natural fibers, flax-fibers, bio-composites, temperature monitoring, residual stresses.

## 1. Introduction

The demand for sustainable infrastructure solutions has become increasingly imperative in today's world. With a focus on minimizing environmental impact while ensuring structural integrity, the exploration of innovative materials and monitoring techniques has gained significant attention.

Fiber-reinforced polymers (FRPs) offer a range of desirable properties including high strength-to-weight ratio, stiffness, flexural strength, high durability, resistance to corrosion, and customizable performance characteristics. Traditionally, glass fibers dominate as the primary reinforcement material in FRP composites, comprising over 90% of use cases. However, research suggests that natural fibers, particularly flax, exhibit promising mechanical properties and can potentially challenge glass fibers in various applications [1], [2].

Utilizing natural fibers (NFs) as reinforcement for composites presents numerous advantages such as low cost, low density, high abundance, and acoustic and thermal insulation properties. Compared to synthetic fibers, manufacturing processes involving NFs are less energy-intensive. With a growing emphasis on reducing raw material consumption, there is increasing interest in plant-based natural fibers.

While laboratory-scale studies have extensively investigated flax properties, there's a notable gap in research and practical applications for outdoor load-bearing structures. Challenges in scaling up from laboratory to practical implementation hinder both production and design validation processes. Pioneering efforts include a fully composite footbridge constructed in 2016 at Eindhoven University of Technology, spanning the Dommel River with a 14-meter length [3]. Although short-term material degradation tests were conducted, conclusive long-term evaluations are lacking. Another notable application is the construction of a composite movable bridge in Ritsumasyl, The Netherlands, with an overall length of 66 meters. This innovative bridge features an asymmetrical movable swing component with a 22-meter free main span and a 12-meter counterweight section [4].

This paper delves into the utilization of Fiber Bragg Grating (FBG) sensors in monitoring the VARTM production process of a 15-meter flax-reinforced polyester footbridge. The footbridge in question is part of a 4-year research project called Smart Circular Bridge (SCB). The project seeks to promote and explore the potential of natural fiber-reinforced composites for load-bearing applications.

The end goal was to establish a valid and functioning structural health monitoring (SHM) system as part of the bridge management system (BMS). 82 strain sensors (FBG), complemented by 8 thermocouple (TFBG) sensors, were strategically embedded to monitor temperatures, and residual strains were monitored throughout the production process, during infusion and curing, for a total of 7 days. A summary of findings from various sensor points is presented with a concise discussion.

In summary, this research contributes a methodology for enhancing the quality and reliability of large-scale composite structural elements through the use of FBG sensor and their integration in production monitoring.

## 2. Materials and Methods

The Almere footbridge spanning 15 meters, has been realized utilizing roughly 3.2 metric tons of flax fibers. Collaboratively developed within the SCB framework - a consortium comprising 5 universities, 7 companies, and 3 municipalities - the footbridge debuted at the Floriade Expo in Almere, The Netherlands on April 22, 2022. Successively, the footbridge was integrated into a newly developed residential area.

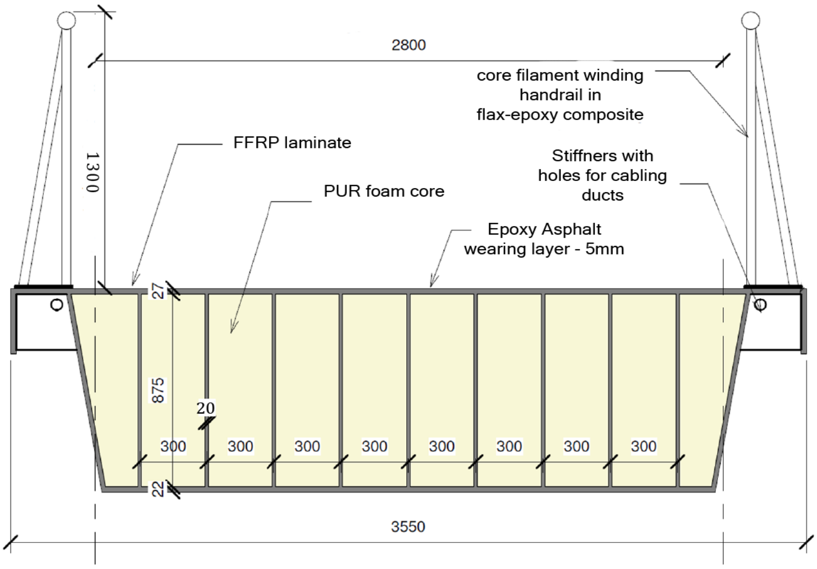
Figure 1: The Almere footbridge.

**2.1 Footbridge design**

The bridge's structure encompasses a bio-composite deck and railing, alongside abutments featuring approach ramps.

The deck comprises a multi-cell, trapezoidal continuous sandwich cross-section with longitudinal vertical webs, terminated by a transverse support plate at each end. With dimensions of 3.55 m in width, 0.92 m in height, and a 15m span, the footbridge accommodates varying panel thicknesses, ranging from 20 mm for the webs, 27 mm for the deck, and 22 mm for the bottom panel. For the fiber orientation, the multi-layered laminate panels were built with a combination of 40 % [0°], 30 % [+45°/-45°], and 30 % [0°/90°]. For the webs, a symmetric layup of 50 % [+45°/-45°] and 50 % [0°/90°] was used – more information on the design methodology can be found in Shahmirzaloo et al [2]. Fibers are wrapped around PUR foam cores serving as non-structural-permanent formwork, running in all directions and thus limiting the possibility of resin-dominated crack propagation.

Figure 2: Bridge cross-section details.




Both abutments consist of a sheet pile wall, two bored piles, and a steel beam that connects and supports the bridge. Vertical support forces from the bridge are directed to the bored piles through the steel beam, while the sheet piles handle horizontal support forces in both longitudinal and transverse directions. To provide access, concrete drag slabs are placed on a sand bed between the sheet pile walls on both sides of the abutments.

The railing concept has been developed and realized by Fibr Gmbh with a novel coreless filament winding technique [5] also using flax fibers.

Table 1: Components of the resin mixture used in the study [2].

| Element | Producer - Component | Concentration |
|---|---|---|
| Polyester | Polynt - 1580 IB | 96.6 % |
| Curing Agent | Nouryon - Butanox LPT-IN | 2 % |
| Accelerator | Nouryon - Nouryact CF-12N | 1 % |
| Inhibitor | Akzo Nobel – NLC-10 | 0.4 % |

### 2.2 Materials Selection

The chosen resin is a partially (24%) unsaturated bio-based polyester system (Polynt 1580 IB). The polyester resin is combined with a peroxide curing agent (Butanox LPT-IN, Nouryon), an accelerator (Nouryact CF-12N, Nouryon), and an inhibitor (NLC-10, Akzo Nobel). An optimization of the accelerator package was conducted at Nouryon Chemical Spa, resulting in the formulation outlined in Table 1. The Nouryact CF-12N, (accelerator) for polyester curing, supplied by Akzo Nobel, is cobalt-free. This makes it more environmentally friendly, additionally exhibiting low sensitivity to moisture. Fiber selection was determined by the current market availability, The fibers chosen are indicated in Table 2.

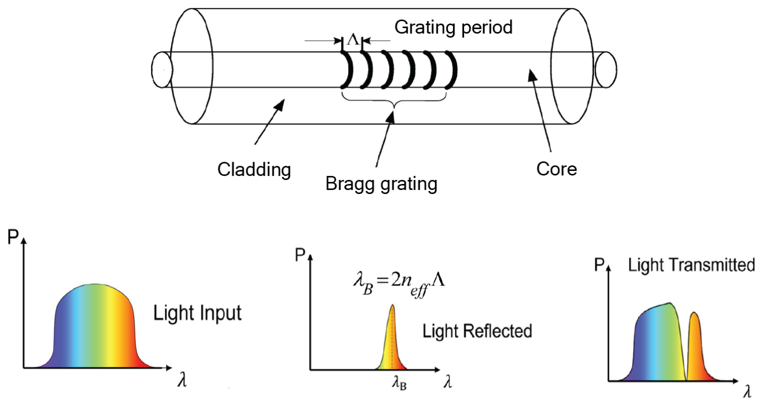
Table 2: Selection of flax fibers.

| Fiber Orientation | Supplier | Density (g/m²) |
|---|---|---|
| [0] | Bcomp | 280 |
| [+45/-45] | Bcomp | 350 |
| [0] | Lineo | 330 |
| [0/90] | Terre de Lin | 800 |

### 2.3 Fiber-optic Bragg grating (FBG) sensors for strain monitoring

An FBG monitoring system is based on the measured shift of the Bragg wavelength caused by the measurand (strain or temperature). The strain directly affects the physical elongation and causes changes in the refractive index of the fiber, while temperature changes directly cause the subsequent thermal expansion of the fiber as well as the modifications to its refractive index. In addition, several FBGs can be inscribed along with the same optical fiber, thus obtaining an array of gratings with different Bragg wavelengths [6]. This can prove useful in the creation of a discrete measuring system with multiple sensing points within a single fiber, limiting the number of sensor lines.

Figure 3: Schematic diagram of the functional principle of FBG sensors.




#### *2.3.1 Mechanical and Temperature Sensitivity*

A fiber-optic Bragg grating (FBG) functions similarly to an electrical resistance strain gauge (RSG) although in the optical domain. The RSG has a strain gauge factor (k-factor) representing the proportionality factor between the resistance change and the applied strain. Likewise, the FBG has an equivalent optical strain gauge factor or strain calibration factor $S_\varepsilon$. This factor establishes the relationship between the shift in Bragg wavelength and the strain within the optical fiber core. The strain measured along the fiber's axial direction $\Delta\varepsilon_3$ can be written as:

$$\Delta\varepsilon_3 = \frac{\Delta\lambda_B}{\lambda_{B,0}} \cdot \frac{1}{S_\varepsilon} \tag{1}$$

With $\lambda_B$ the measured Bragg wavelength, $\lambda_{B,0}$ the initial (reference) Bragg wavelength, and $\Delta\varepsilon_3$ the strain in the fiber's axial direction. Focusing on the longitudinal strain, the wavelength shift of an embedded optical fiber can be attributed to three distinct contributions. The mechanical strain, the thermo-optic effect, the thermal expansion of the FBG, and the thermal expansion of the composite wherein the fiber is embedded. This will cause an additional excess strain or compression if the coefficient of thermal expansion (CTE) of the FRP laminate is smaller than that of silica[7]. Given that the temperature can be accurately monitored, the mechanical strain along the fiber direction can be deduced, so that (1) can be transformed to [8], [9]:

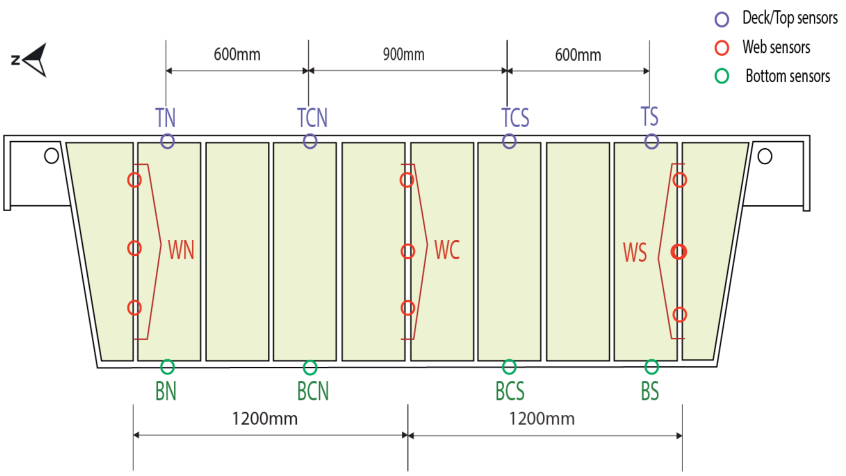
$$\Delta\varepsilon_{3,mech} = \frac{1}{S_\varepsilon}\left[\ln\frac{\lambda_B}{\lambda_{B,0}} - S_{T1}(\Delta T - \Delta T_0) - S_{T2}(\Delta T^2 - \Delta T_0{}^2)\right] - (\alpha_S - \alpha_f)(\Delta T - \Delta T_0) \tag{2}$$

With $S_{T1} = 6.36\cdot10^{-6}$, $S_{T2} = 7.59\cdot10^{-9}$, $S_\varepsilon = 0.777$, $\alpha_f = 0.55\cdot10^{-6}$; $\Delta T = T - T_{ref}$, the temperature difference between the reference during calibration, $T_{ref}$, and an arbitrary time during the measurement T; $\Delta T_0 = T_0 - T_{ref}$, the temperature difference between the zero point of the measurement $T_0$ and the reference during calibration $T_{ref}$ ( usually $T_{ref} = 22.5°C$ ). With $\alpha_s$ the CTE of the laminate.

### *2.3.2 Experimental setup for production monitoring: BMS sensor schemes*

Central to this research is the integration of FBG sensors into the production process, facilitating real-time monitoring of structural health. With 82 strain sensors strategically embedded throughout the footbridge, complemented by 8 thermocouple sensors (TFBG). This methodology not only enhances the quality control of large-scale composite structural elements but also establishes a framework for long-term structural health monitoring (SHM) within the bridge management system (BMS). Sensors schemes and locations are shown in Figure 4, Figure 5, and Figure 6.

Figure 4: Bridge cross-section with FBG sensors location.




## 3. Quality Parameters in the VARTM Process

The VARTM production process presents several challenges, especially for the production of large-size elements. Therefore, it is important to examine critical quality parameters, including residual strains, voids presence, and peak exotherm temperatures, to ensure the reliability and longevity of the footbridge. Furthermore, insights gleaned from smaller-scale tests provide valuable context for interpreting full-scale results, offering a comprehensive understanding of the production process and the performance of the footbridge [2].

The combination of the peak exotherm of the unsaturated polyester resin (50-70°C) with the insulation properties of PUR foam cores, utilized as non-structural permanent formwork, can lead to high temperatures in the two-flanged web structure as the heat dissipation is very slow, potentially affecting the quality of the final product. For this reason, the temperatures inside the web needed to be monitored throughout the production process of the footbridge. The temperatures during injection and curing were monitored for a total of 7 days (long curing at room temperature).

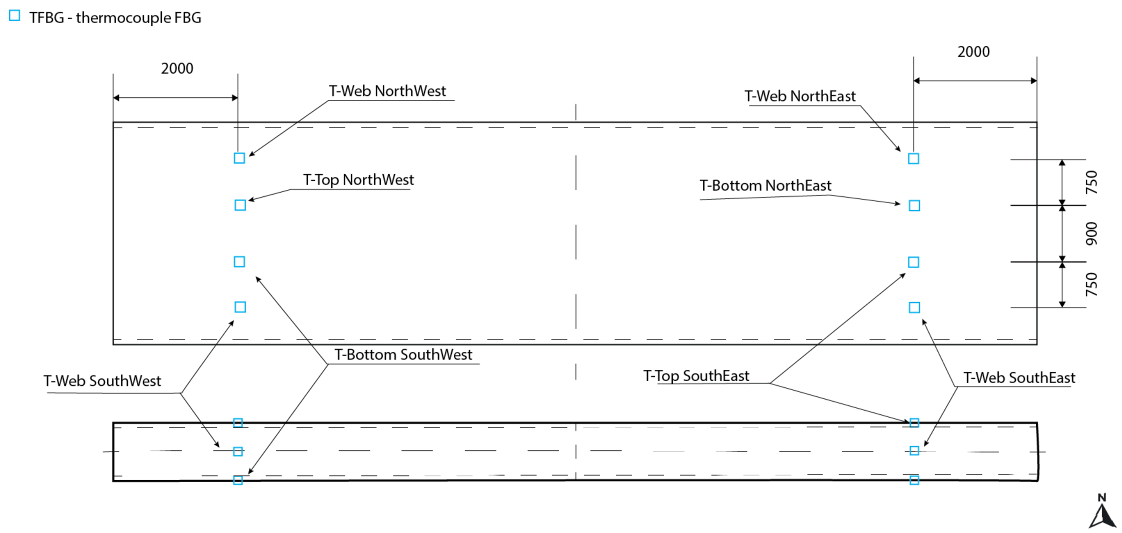
The negative impacts of high temperatures can be attributed to several factors.

In general, residual strain and stresses can arise during the curing process of composite laminates due to low transverse thermal conductivity. This can trigger detrimental exothermic reactions and sharp temperature spikes, particularly in thicker components during injection. Consequently, it results in inconsistent thermal profiles, impacting the degree and quality of curing, chemical shrinkage, and overall mechanical performances [10].

Monitoring peak exotherm temperatures is crucial due to the reduced water boiling points under vacuum, potentially leading to void creation and swelling stresses. Void presence reduces interlaminar shear strength (ILSS) due to decreased cross-sectional area and initiation of failure from larger voids [11]. Anisotropic moisture absorption in natural fibers, like flax, can cause unmatched swelling stresses at the fiber-matrix interface, leading to debonding and delamination. Proper drying of fibers is essential to control this phenomenon. Pre-conditioning flax fibers at high humidity levels [12] during manufacturing can improve moisture durability, but careful evaluation of water interaction with resin and components is necessary.

In summary, addressing factors such as thermal management during curing, void reduction, moisture content control, and careful evaluation of fiber pre-conditioning can mitigate detrimental effects in composite manufacturing and improve their long-term service life.

Figure 5: TFBG (thermocouples) sensors scheme and locations.



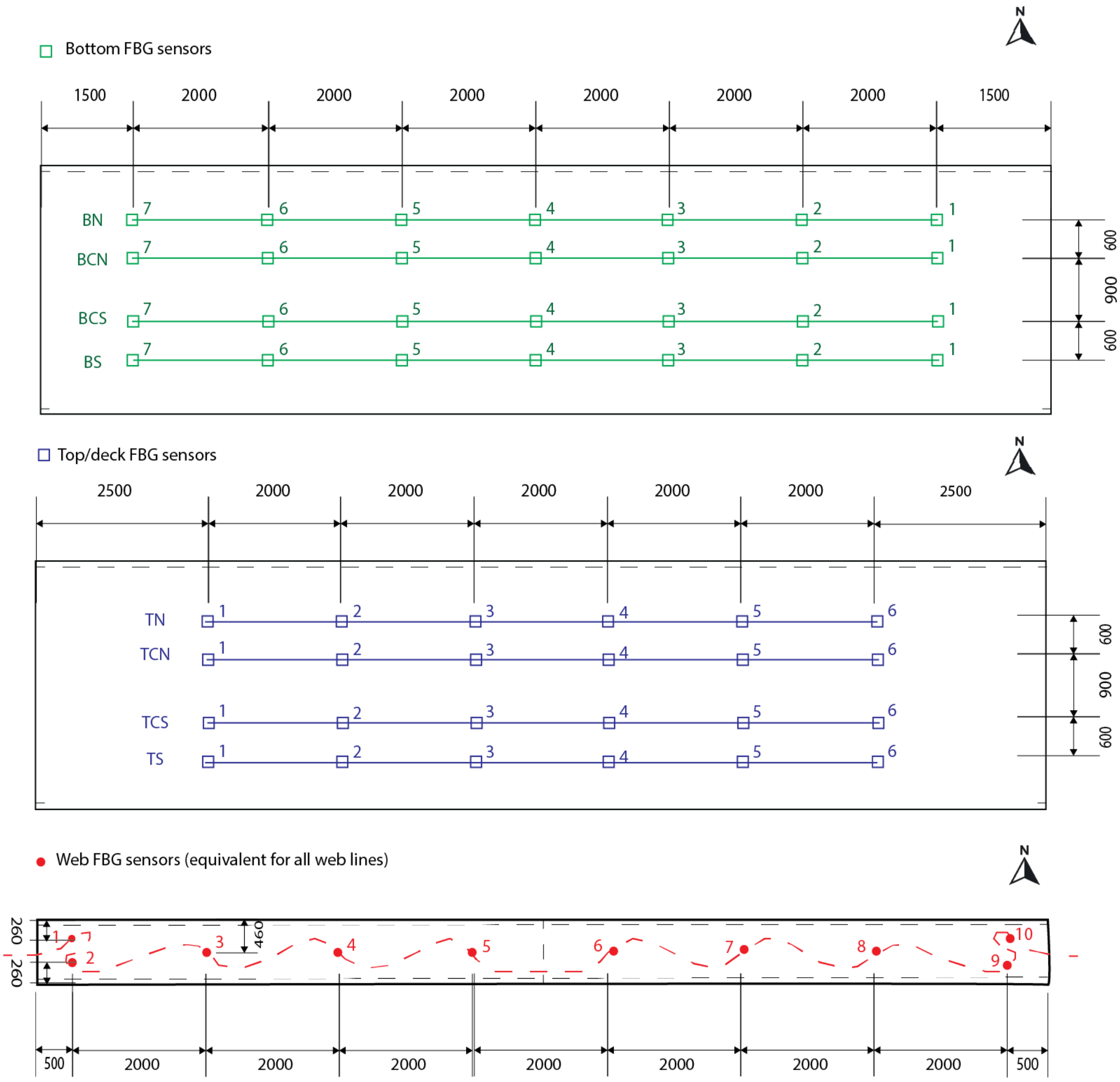

## 4. Experimental Results

The VARTM technique employs a single-sided vacuum-sealed mold along with vacuum pressure to pull the resin into the mold. The footbridge is infused upside down, with the deck surface in contact with the steel mold ensuring the right geometrical precision and the desired pre-camber. While the bottom surface is in contact with the air.

Figure 7 shows the temperature profile for the two monitored cross-sections. Results are aligned for the two locations. It can be noticed that high temperatures develop sharply for all web sensors, lasting for several days. After the measurement was disconnected, all web TFBG still showed values higher than ambient temperature. T-Bottom-NorthEast was lost during the production and no data was available. The other TFBG sensor in the bottom laminate shows temperature spikes but quickly dissipates them through the air, without showing particularly high peaks. For the TFBG sensors in the deck, the temperature rises sharply but likely the conduction with the steel formwork and then the air helped to reduce the temperature spike in a reasonable time. It has been shown that the convection coefficient has a remarkable impact on the curing process [10].

During the manufacturing of composites, curing and solidification of the resin mixture at high temperatures result in thermal expansion, imposing compressive stresses on the fibers. The different

Figure 6: FBG strain sensors schemes and locations.



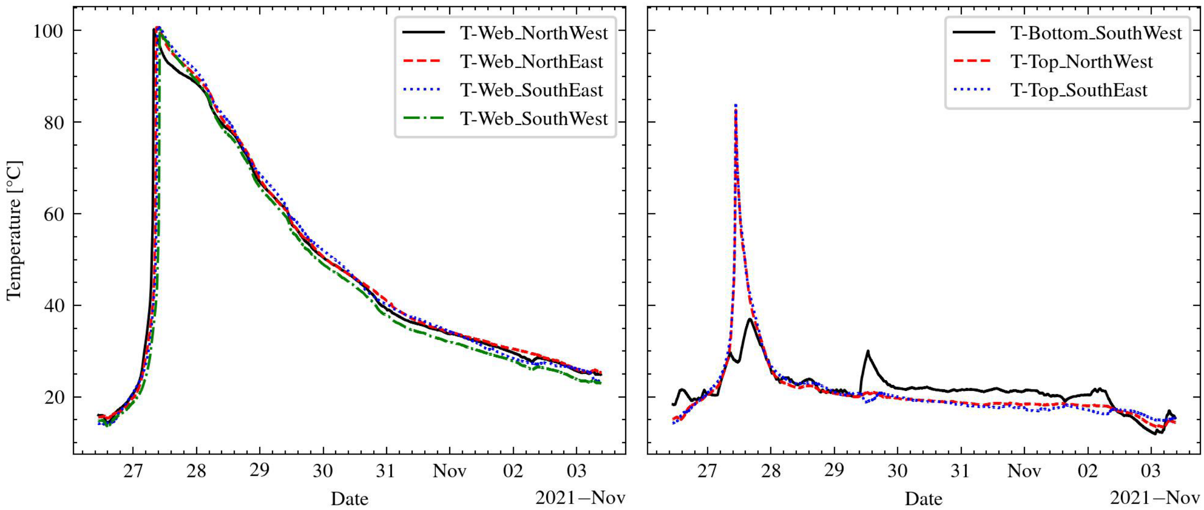

thermal expansion between fibers and resin creates residual stresses during cooling, notably prevalent in multidirectional composites due to the anisotropic characteristics of plies.

Effective load transfer occurs shortly after gelation begins, with induced stresses gradually solidifying within the material. Before gelation, when the matrix is in its liquid state, there is no indication that frictional stresses from chemical shrinkage are transmitted and locked within the material. Additionally, while it's acknowledged that the creation of residual stresses primarily occurs during variations in the cooling phase, residuals are measured from the onset of gelation until the curing process is complete, as done by Mulle et al [13]. Finally, it is assumed that vitrification initiates at the onset of the cooling phase.

Higher local temperatures may lead to uneven distribution of residual stresses. Lower fiber volume fractions (FVF) in certain areas, as indicated in [2], can exacerbate this issue, due to the higher presence of resin locally. Previous researchers have also raised this issue [8]. Therefore, careful analysis of each sensor's data is necessary. In this work, a detailed analysis of residual strains was not feasible for all FBG sensors to maintain conciseness. Thus, the results for the other FBG sensors may vary depending on environmental factors, sensor location, and FVF, and likely not align with the results here presented.

As shown in section 2.3.1, to obtain the residual strains there are three contributions to the total strain acting on an embedded optical fiber. Therefore, the 7 TFBG sensors are used to monitor the temperature and compensate for the thermal-optic effect and thermal expansion (silica and composite) of the nearest strain sensors, making the temperature compensation more accurate. The corresponding temperatures and residual strains are shown in Figure 8. Here, the residual strain development is reported for 3 FBG sensors with the corresponding closest thermocouple.

Figure 7: TFBG sensors data during infusion and curing for 7 days.




## 5. Conclusion

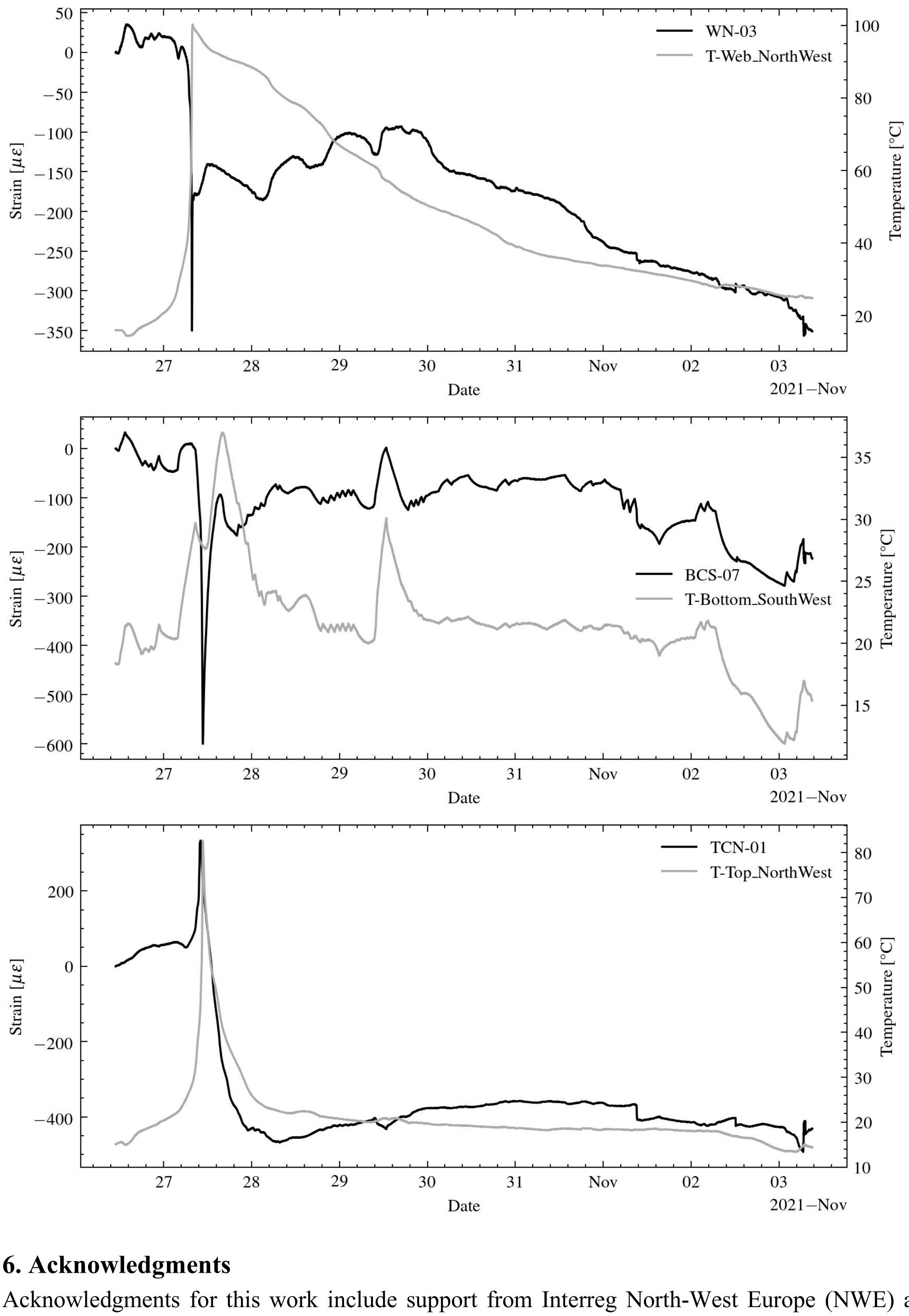
In conclusion, this study explores the application of Fiber Bragg Grating (FBG) sensors in monitoring the Vacuum-Assisted Resin Transfer Molding (VARTM) process for the production of a 15-meter flax-reinforced polyester footbridge. By strategically embedding FBG sensors throughout the footbridge and complementing them with thermocouples, comprehensive data on the production process and structural behavior were captured in real-time.

The research emphasizes the importance of monitoring critical quality parameters such as residual strains, void percentage, and peak exotherm temperatures during the VARTM process. Reveals that high temperatures can develop, particularly in the two-flanged web structure due to the insulation properties of the foam cores used as permanent formworks. These high temperatures, while staying above air temperatures for several days, can impact the quality of the final product, necessitating careful monitoring and management during the curing process.

Experimental results demonstrate the effectiveness of the FBG sensor system in capturing temperature profiles and residual strains throughout the production process. The integration of FBG sensors not only enhances the quality control of large-scale composite structural elements but also establishes a framework for long-term structural health monitoring within the bridge management system.

In conclusion, addressing factors such as thermal management during curing, void reduction, moisture content control, and careful evaluation of fiber pre-conditioning can mitigate detrimental effects in composite manufacturing and improve their long-term service life. Overall, this research contributes to advancing the understanding and application of FBG sensors in monitoring the production process of sustainable infrastructure solutions, and in the application of natural fibers for load-bearing applications.

Figure 8: Residual strains for 3 FBG sensors with the temperature recorded by the closest thermocouple on 7-day period.




## 6. Acknowledgments

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