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Bending Analysis of Glass Fiber Reinforced Composite Using Distributed Fiber Optic Sensing System

D. Blaha[1,*], Z. Padovec[1], K. Doubrava[1], R. Kottner[2], C. Novotný[1], N. Schmidová[1], M. Růžička[1], P. Balík[1]

[1] *Division of Strength and Elasticity, Fac. of Mech. Engineering, Czech Technical University in Prague; Technická 4, 166 07 Prague, Czech Republic*

[2] *ACO Industries Tábor s.r.o.; Průmyslová 1158, 391 01 Sezimovo Ústí, Česká republika*

[*] *David.Blaha@cvut.cz*

Abstract: In this study, we conducted a bending analysis of a glass fiber reinforced composite plate with a central hole, using a distributed fiber optic sensing system and other reference methods. The focus was to investigate the change in strain near the hole under bending stress. Our findings provide valuable insights into the behavior of such composites under prescribed load, contributing to their safer and more efficient use in various applications.

Keywords: distributed fiber optic sensing system; strain measurement; glass fiber composite; bending analysis.

1 Introduction

In recent years, water treatment solutions and technologies have been developed to address the growing demand for storing and treating water. The key components of water treatment systems are pressure vessels, which are used to store and treat water. The pressure vessels are typically made of steel, but due to their high weight and susceptibility to corrosion, there is a growing interest in using composite materials for their construction. One of the potential solutions is the use of glass fiber reinforced composited (GFRP) for their high strength to weight ratio. However, the behavior of GFRP under stress is complicated and require detailed analysis to ensure their safe and efficient use especially in critical places such as near holes or other stress concentration points.

A distributed fiber optic sensing system (DFOS) is a powerful tool for measuring strain distribution along the length of a optical fiber. In comparison to conventional measurement methods, DFOS provides dense network of points for strain measurement. In the 1998, Froggatt et al. [5] achieved spatial resolution up to 0.6 cm with tunable laser source to measure strain in the optical fiber. The DFOS system is based on the principle of Rayleigh scattering and is capable of measuring strain with high spatial resolution. The DFOS system is used in various applications, such as structural health monitoring, geotechnical monitoring, and civil engineering [2].

In the Munzke et al. study [3], the authors used a DFOS sensor embedded between layers to monitor the strain distribution in a composite pressure vessel. The monitoring system detected damage 17 000 cycles before the vessel burst. In the Karapanagiotis et al. study [4], the authors successfully embedded a DFOS sensor in a composite pressure vessel to monitor the strain distribution along the length of the vessel including dome and cylinder area.

2 Methods

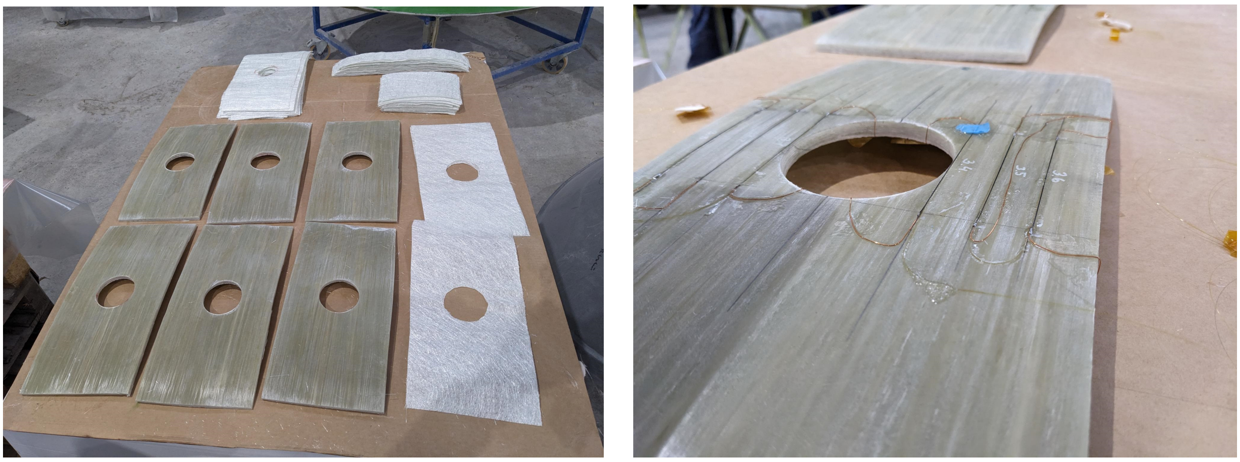
The measurement is performed on a composite plate with a central hole. Strain measurements are performed using a distributed fiber optic sensing system (DFOS) and a conventional strain gauges. These methods are used to measure the strain distribution along the hole of the composite plate. The DFOS system is based on the principle of Rayleigh scattering and is capable of measuring strain with high spatial resolution. The strain gauges are used as a reference method. The results from both methods are compared with FEM analysis.

2.1 Sensor installation

The composite plate was made of glass fiber reinforced polyester resin. The sample is 400 mm long, 200 mm wide and 9.76 mm thick. The thickness corresponds to 19 layers of glass fiber. The central hole has a diameter of 80 mm.

The strain gauges were installed to the surface of the composite plate near the central hole in the direction of loading. The DFOS sensor was installed in parallel with the strain gauges, but on the opposite side of the hole. The DFOS sensors were installed in two configurations. The first configuration is a sensor installed on the surface of the composite plate. The second configuration is a sensor installed under the covering glass layer. The sensoric optical fiber was welded to the connector with Fitel S179 fusion splicer and calibrated with Luna software according to the manual [1].

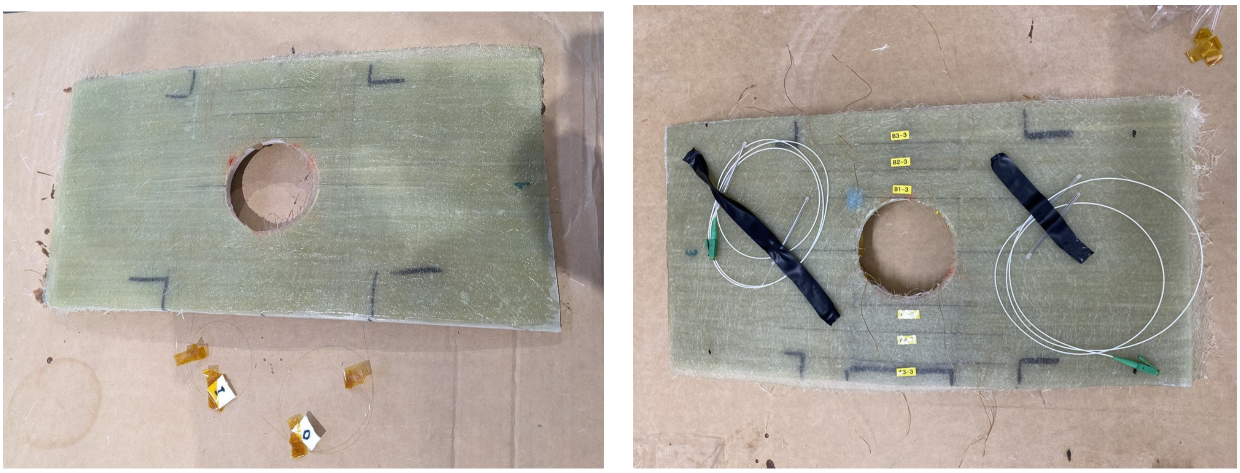
The carbon fiber sensors (CFS) were installed under the covering glass layer. The CFS sensors were installed in the same configuration as the DFOS sensors. The CFS sensors were used to measure the strain. The results from CFS sensors are presented in the Schmidova et al. study [6].



(a) Prepared samples for FO and CFS sensor's installation

(b) Prepared fiber optic and carbon fiber sensors on the plate

Fig. 1: Prepared samples for sensor's installation before covering glass layer.



(a) prepared sample with covering glass layer

(b) prepared sample with FO connectors

Fig. 2: Prepared samples after sensor's installation.

2.2 Testing

A setup for four-point bending test is following. The distance between the upper supports is 120 mm and the distance between the lower supports is 320 mm. The strain gauges are installed on the upper (compression) side of the plate. The DFOS sensor is installed on both sides of the plate, one on the compression side and one on the tension side.

The testing was subjected to four-point bending on universal testing machine Heckert FPZ100/1. The samples were loaded with a ramp of 1 kN and then unloaded repeatedly. Then the samples were destructively loaded up to 10 kN.

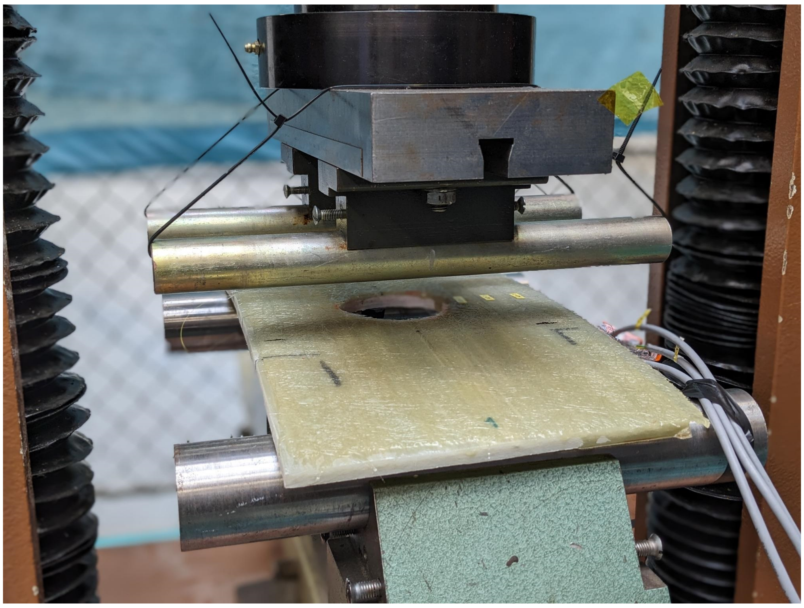


Fig. 3: 4-Point bending test setup.

2.3 FEM analysis

The FEM analysis was performed using the Abaqus software. The composite plate was modeled as a shell element with a thickness of 9.76 mm. The material properties were set to correspond to the glass fiber and polyester resin. The boundary conditions were set to simulate the four-point bending test.

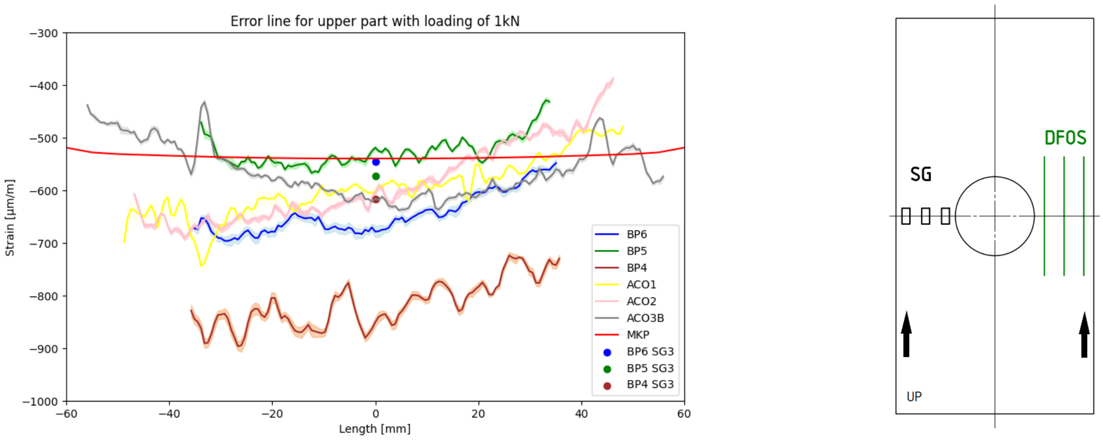
3 Results

Before showing the results, the DFOS data was processed using Python scripts. The data was aranged into separate lines corresponding to the sensor's position on the plate. The bottom side of the plate is loaded in tension and the upper side is loaded in compression. Each figure shows the strain distribution along the sensor's path complet with the sensor's schema. Zero value on the length axis corresponds to the center of the hole. In the figures, there is plotted the mean strain distribution (colored-line) with its standard deviation (colored-area).

Mean deviation was calculated as the percentage difference between the DFOS sensor and the FEM analysis along the sensor's path. The DFOS sensors installed on the surface are named BP4, BP5, BP6, and the DFOS sensors installed under the covering glass layer are named ACO1, ACO2, ACO3A, ACO3B.

The results from the DFOS system show that the strain distribution near the hole is non-uniform. The strain gauges show similar results as the DFOS sensors. The FEM analysis confirms the results from the DFOS system and strain gauges.

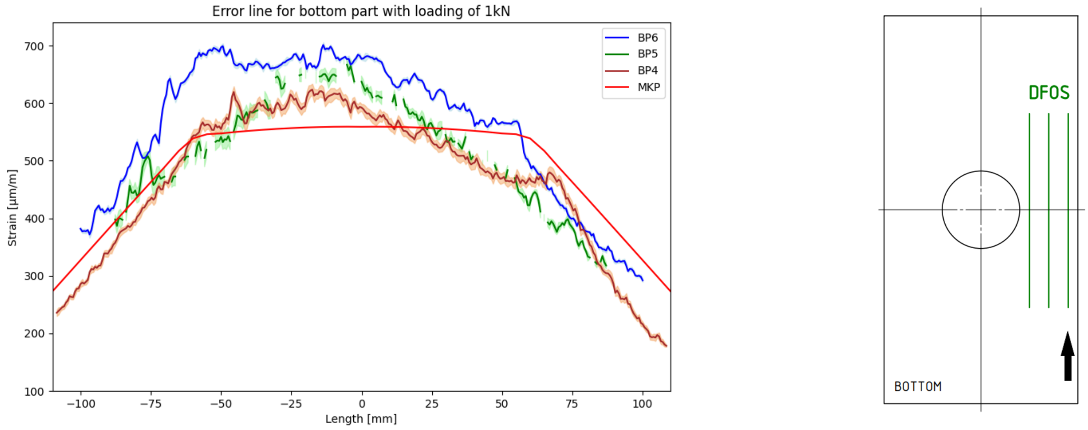
In the Figure 4 and Figure 5 are shown the results from all sensors from upper and bottom side in the plane near the edge. It is clear that sensors on the bottom side show better agreement with the FEM analysis. The sensors on the upper side show more variance in the strain distribution. On the compression side (UP), the mean deviation between the DFOS sensor and FEM analysis ranges from 4.2 to 33.9 %. On the tension side (BOTTOM), the mean deviation between the DFOS sensor and FEM analysis ranges from 10.8 to 13.6 %.



(a) strain results at compression side

(b) sensor's schema

Fig. 4: Results from all sensors from upper side in the plane near the edge.



(a) strain results at tension side

(b) sensor's schema

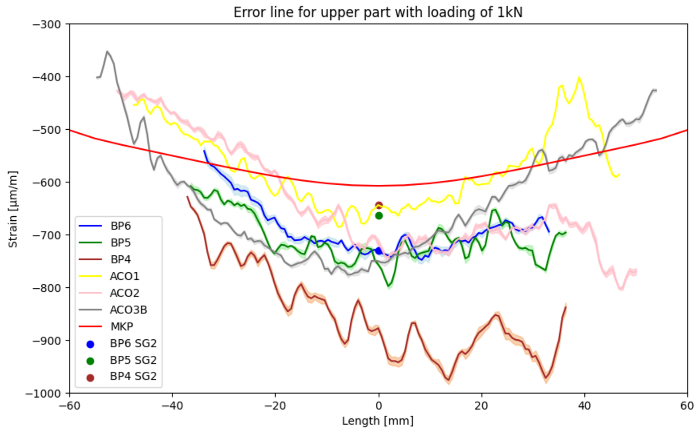
Fig. 5: Results from all sensors from bottom side in the plane near the edge.

The results from the sensors in the middle of the plate are shown in the Figure 6 and Figure 7. The mean difference between the DFOS sensor and FEM analysis on the compression side (UP) varies from 8.1 to 30.2 %, see Figure 6. The mean difference on the tension side (BOTTOM) varies from 7.7 to 10.8 %, see Figure 7.

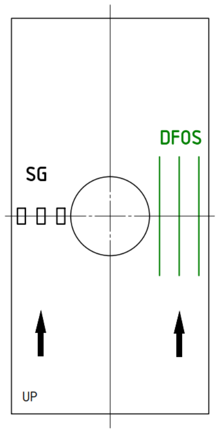
The results from the sensors close to the hole are shown in the Figure 8 and Figure 9. The mean difference between the DFOS sensor and FEM analysis on the compression side (UP) varies from 15.2 to 25.6 %, see Figure 8. The mean difference on the tension side (BOTTOM) varies from 8.5 to 13.3 %, see Figure 9. The sensor ACO3A and ACO3B are excluded from the mean difference calculation due to its closer position to the hole of the plate, which causes the higher deviation from the FEM analysis near the hole area. The trend in the data corresponds across sensors, but probably due to the uneven surface of the composite plate makes the data less reliable.

Based on assumption that the strain concentration points are near the hole, there were installed additional sensors in the plane directly next to the hole. The results are shown in the Figure 10. It is clear that the sensors next to the hole show higher strain values in compare to sensors close to the hole. Even a distance of 10 mm between the sensors near the hole causes a difference of 27 % in the most critical location.

The strain results loaded up to 10 kN are shown in the Figure 11 and Figure 12. The loading up to 10 kN did not cause visible damage to the composite plate. After unloading, only a residual strain of about 100 microstrains was observed in the place around the hole after unloading. The results from the DFOS system are in good agreement with the results from the strain gauges and FEM analysis for the tension side of the plate. The results from the compression side of the plate show more variance. The difference on compression side

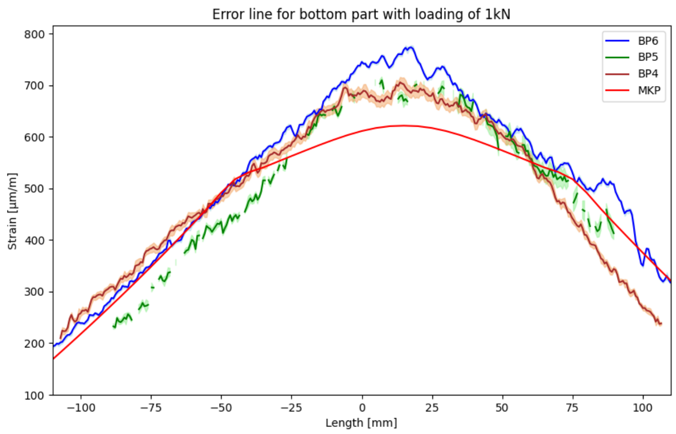


(a) strain results at compression side

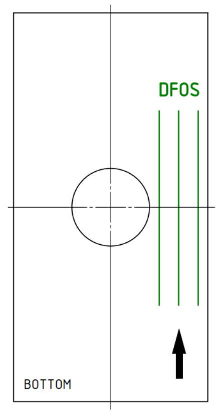


(b) sensor's schema

Fig. 6: Results from all sensors from upper side in the plane in the middle.

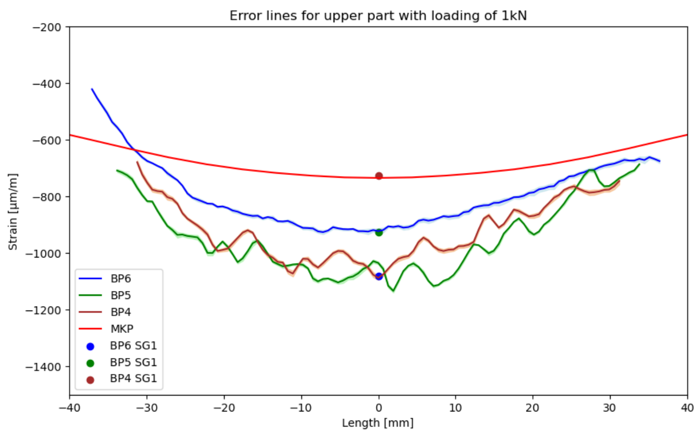


(a) strain results at tension side

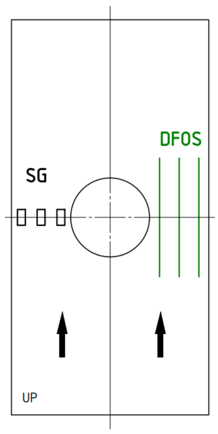


(b) sensor's schema

Fig. 7: Results from all sensors from bottom side in the plane in the middle.

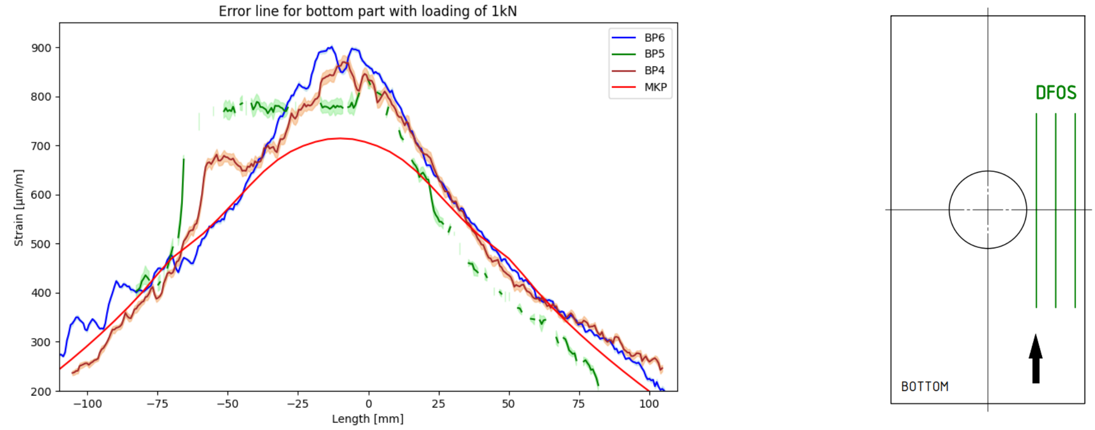


(a) strain results at compression side



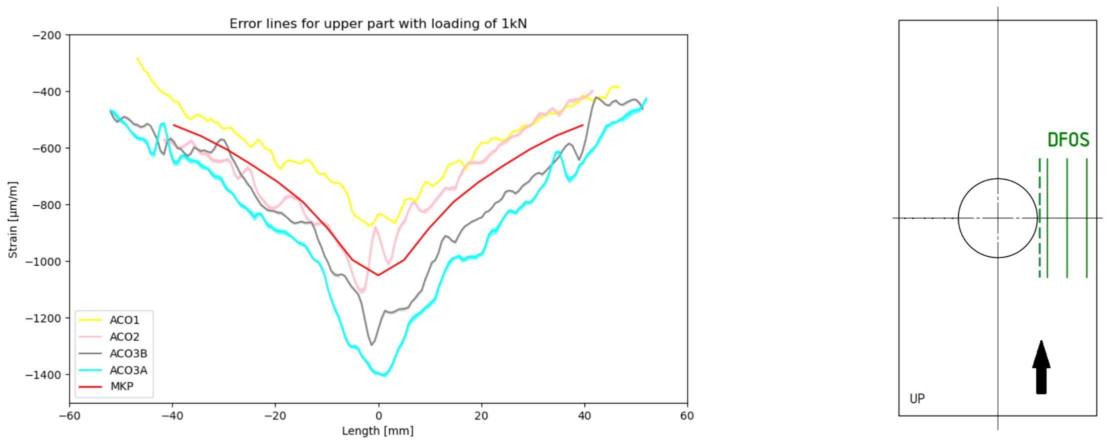
(b) sensor's schema

Fig. 8: Results from all sensors from upper side in the plane close to the hole.



(a) strain results at tension side (b) sensor's schema

Fig. 9: Results from all sensors from bottom side in the plane close to the hole.



(a) strain results at compression side (b) sensor's schema

Fig. 10: Results from all sensors from upper side in the plane next to the hole.

(UP) between the DFOS sensor and FEM analysis varies from 9.3 to 19.8 %, see Figure 11. Mean difference is 16.4 %. The difference on tension side (BOTTOM) varies from 0 to 14.6 %, and the mean difference is 6.7 %, see Figure 11.

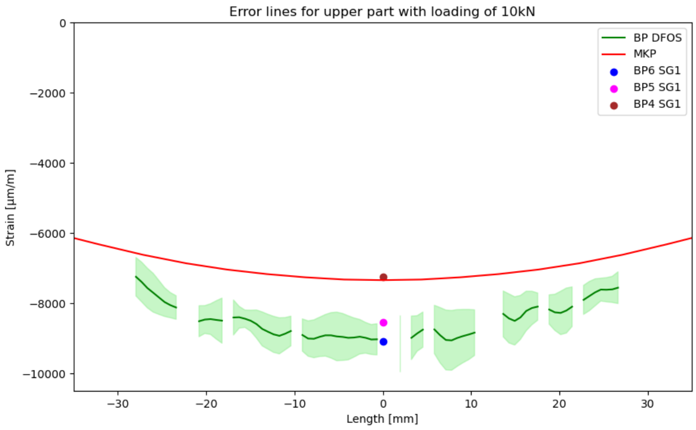
Conclusion

The results of the bending analysis of the GFRP composite plate with a central hole show that the strain distribution near the hole is non-uniform. The results from the DFOS sensors are in good agreement with the results from the strain gauges and FEM analysis on tension side, but show more variance on the compression side. The results from the strain gauges range across the variance of the DFOS sensors.

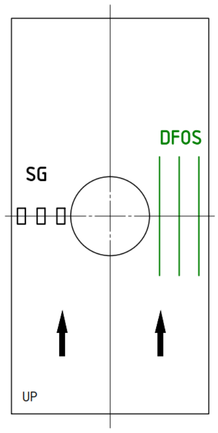
The sensors installed under the covering glass layer showed better agreement with the FEM analysis than the sensors installed on the surface of the composite plate. This can be attributed to the uneven surface of the composite plate, which makes the data less reliable. This can be reason why the sensors BP4, BP5, BP6 show more variance in the strain distribution than the sensors ACO1, ACO2, ACO3A, ACO3B. It is important to note that the sensors ACO1, ACO2, ACO3A, ACO3B are installed under the covering glass layer only on tension side of the plate, which can cause bigger deviation on compression side.

Loading up to 10 kN did not cause visible damage to the composite plate, although residual strain was observed after unloading.

Applicability of the DFOS system for strain measurement in the composite plate was confirmed, particularly

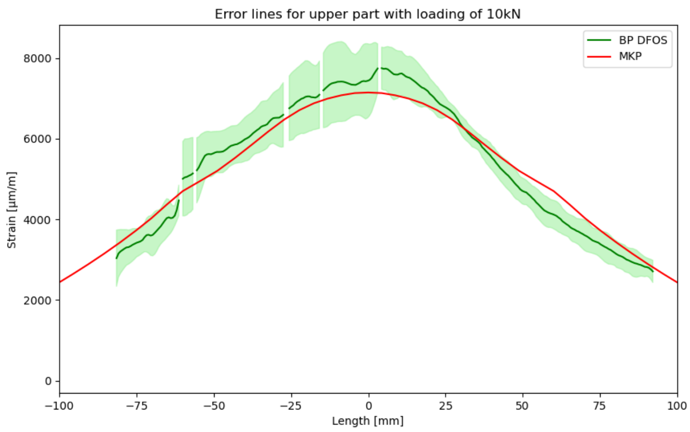


(a) strain results at compression side

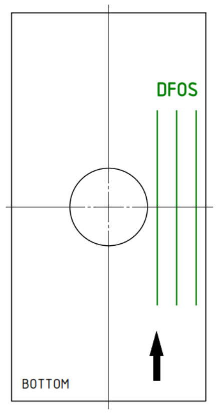


(b) sensor's schema

Fig. 11: Results from all sensors from upper side in the plane close to the hole.



(a) strain results at tension side



(b) sensor's schema

Fig. 12: Results from all sensors from bottom side in the plane close to the hole.

for the strain concentration points. The method provides valuable insights into the behavior of such composites, contributing to their safer and more efficient use in water treatment applications.

Future work will focus on the development of a connectors and housing for the DFOS and CFS sensors to make them more robust and easier to install. The sensor's ability to measure damage in the composite plate will be tested in the future.

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