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# Distributed fibre optic sensing of decommissioned wind turbine blades under bending

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ABSTRACT: The decommissioning of wind turbine blades (WTBs) presents significant environmental challenges due to their non-biodegradable composition. To promote sustainable reuse and repurposing, it is essential to establish effective structural health monitoring (SHM) techniques that can accurately assess the residual performance of decommissioned WTBs. This study investigates the feasibility and applicability of distributed fibre optic sensing (DFOS) as an advanced monitoring tool for evaluating the structural integrity of decommissioned WTBs intended for reuse in civil engineering applications. A four-point bending test was conducted on a WTB segment, with DFOS deployed alongside other monitoring techniques, including strain gauges, and digital image correlation (DIC). The DFOS measurements demonstrated strong agreement with those obtained from strain gauges and DIC, with negligibly small variations in strain magnitude, validating its accuracy and reliability for continuous strain monitoring. The results further confirmed sufficient load-bearing capacity of the WTB segment, indicating its potential for second-life structural applications. This study highlights the capability of DFOS in providing high-resolution, distributed strain measurements, offering a promising approach for assessing the suitability of decommissioned WTBs for reuse. Future research aims to incorporate material characterisation studies and long-term monitoring to establish standardised frameworks for the sustainable repurposing of WTBs, contributing to a circular economy in the wind energy sector.

KEY WORDS: Decommissioned wind turbine blades; Repurposing; Four-point bending test; Distributed fibre optic sensing.

## 1 INTRODUCTION

Wind energy has become a cornerstone of sustainable energy solutions worldwide, significantly contributing to the reduction of carbon emissions. In Ireland, the expansion of onshore and offshore wind farms is expected to play a critically significant role in achieving the country's 2030 renewable energy targets, potentially reducing its carbon emissions by 51% [1]. However, as wind energy industry grows and matures, a growing challenge is the decommissioning of the wind turbine blades (WTBs). By 2025, approximately 11,000 tons of WTBs are expected to be decommissioned in Ireland alone [2]. These blades are predominantly made from glass fibre reinforced polymer (GFRP) composites, which are non-biodegradable and pose significant disposal challenges, often ending up in landfills and leading to environmental degradation [3].

Despite the environmental challenges, WTBs possess unique structural properties, including high strength-to-weight ratios and resistance to harsh environmental conditions, making them promising candidates for reuse and repurposing in civil engineering applications [4]. Previous studies have explored various repurposing strategies. For example, Martini and Xydis (2022) reviewed the common practice of WTB reuse and recycling in the United States, which included whole and partial blade reuse, and grinding material reuse [5]. In another study, Hasheminezhad et al. (2024) further reviewed its reuse for construction and infrastructure applications [4], such as powerline poles [6], slow-traffic bridges [7], picnic tables [8], playground [9], etc.

However, despite the growing interest in repurposing WTBs, a critical challenge lies in understanding the residual structural performance after years of service. Long-term exposure to environmental influences, such as UV radiation, moisture, and cyclic loading, can degrade the mechanical properties of the GFRP composites used in WTBs, which may influence their structural integrity and impact their long-term performance and suitability for reuse in civil engineering applications.

To enable the safe and sustainable reuse and repurposing of decommissioned WTBs, effective condition monitoring and structural health assessment is essential. While traditional monitoring methods, such as strain gauges, provide valuable insights, they are often limited to their discrete measurements. In contrast, distributed fibre optic sensing (DFOS) offers a high-resolution, continuous, and long-term monitoring solution capable of capturing detailed strain distributions over large structural elements. DFOS has been successfully implemented in various infrastructure applications such as tunnels [10], but its feasibility and applicability for monitoring the residual structural performance of decommissioned WTBs remains largely unexplored.

This study aims to evaluate the feasibility of DFOS as a monitoring technique for assessing the residual performance of a decommissioned WTB segment subjected to four-point bending tests. The segment was instrumented with DFOS, alongside other monitoring techniques such as strain gauges, linear variable differential transformers (LVDTs), and digital image correlation cameras to enable a comparative assessment of measurement accuracy and reliability. By examining the strain distribution and mechanical behaviour of the WTB segment, this study aims to determine the suitability of DFOS for structural health monitoring in second-life applications of decommissioned WTBs. The findings will contribute to the development of robust monitoring frameworks for WTB reuse

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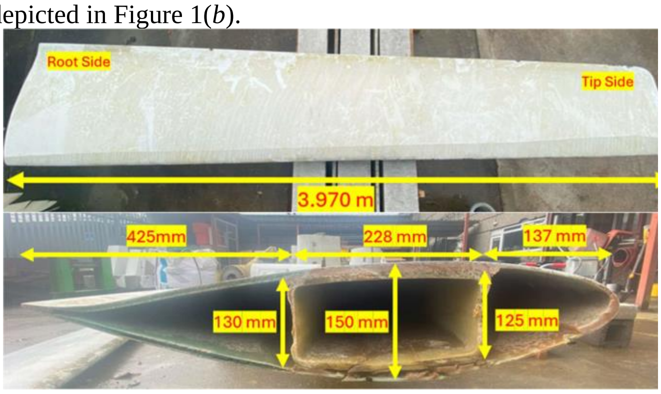
in civil engineering, supporting a circular economy in the wind energy sector and enhancing the sustainability of wind turbine decommissioning.

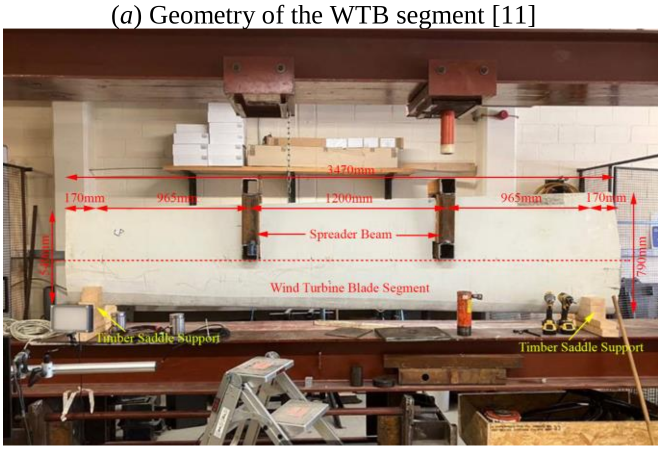
## 2 METHODOLOGY

### 2.1 *Wind turbine blade preparation*

The decommissioned wind turbine blade used in this study was sourced from a V42/600 wind turbine manufactured by Vestas in Denmark. Each turbine has a power rating of 600 kW and consists of three blades. The turbines have a rotor diameter of 42m, and each blade has a total length of 21 meters from root to tip. A 4-meter long segment was cut from the tip side for laboratory testing. In the initial preparation stage, the geometry of this blade segment was measured using vernier callipers, as illustrated in Figure 1(*a*). Surface stains were cleaned to facilitate a visual inspection for any potential damage. Subsequently, the blade segment was divided into 500 mm-long sections using a measuring tape and a chalk line. To accurately identify the location of the spar on the tip side, the final 500 mm portion at the blade tip was removed. The centre of the blade segment was then marked, with 600 mm measured on each side of the centreline to designate the positions for the spreader beams. A line was drawn connecting the top spar on the root side to the top spar on the tip side of the blade segment. To accommodate the installation of spreader steel beams, which are designed to transfer loads onto the spar cap, 110 mm square sections were cut from both the high-pressure and low-pressure sides of the blade aerofoil at the points where each 600 mm mark intersected with the spar cap line. This process is depicted in Figure 1(*b*).




(*a*) Geometry of the WTB segment [11]




(*b*) WTB segment preparation for testing

Figure 1. Geometry of the WTB segment

### 2.2 *Loading arrangement*

The blade was positioned in the edgewise direction with the trailing edge facing upward and was supported by two timber saddles, each placed 170 mm from the ends to avoid areas of local skin damage. Loading was applied using two hydraulic jacks acting on both spreader beams, simulating a four-point bending test. Load cells beneath each jack recorded the applied force. Two four-point bending tests were conducted on the blade segment. In test 1, a total load of 30kN was applied, while in test 2, the total load reached 50kN. The objective was to maintain loading within the blade's elastic range, enabling multiple repetitions if necessary. In both tests, loading was applied stepwise: for the 30kN test, a designed step loading of 2-5kN was used, whereas for the 50kN test, increments of 10kN were used. Figure 2 illustrates the loading system. The four-point loading was carried out by manual handling of two hydraulic jacks due to the dysfunction of the automatic system. The loading details of both tests were shown in Figure 3.

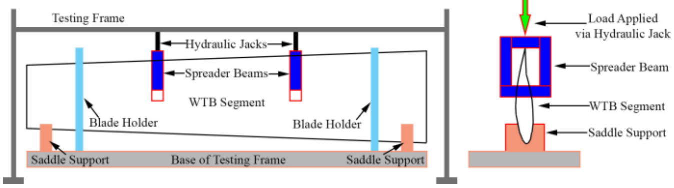
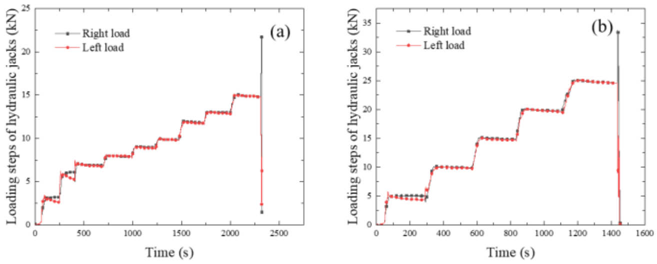



Figure 2. Illustration of the four-point bending test




Loading record of test 1   Loading record of test 2

Figure 3. Loading details of both tests

### 2.3 *Monitoring system setup*

To monitor the strain and displacement development of the WTB segment under four-point loading tests, a comprehensive monitoring system was implemented to capture multiple sets of displacement measurements, enabling a thorough assessment of its mechanical performance. This system incorporated diverse techniques, including strain gauges, LVDT, DIC) and DFOS. The setup of each monitoring system is detailed below. A general view of the installed monitoring systems on the WTB segment is shown in Figure 4.

Strain gauge and LVDT: Two strain gauges were deployed on the back of the WTB segment, as shown in Figure 4. The strain gauge fixed at the upper part of the blade segment is 80 mm from the top and the other gauge fixed at the lower level is 80mm from the bottom of the segment. Both strain gauges were deployed in the middle span of the blade segment. Three LVDTs were installed at three distinctive locations on the back of blade segment, as demonstrated in Figure 4. The LVDT mounted on the left was placed at a distance of 63mm below the bottom of the left spreader beam, while the one mounted on the right was at a distance of 70mm from the bottom of the right spreader beam. The middle one was fixed at 430mm from the top of the blade in the vertical direction.

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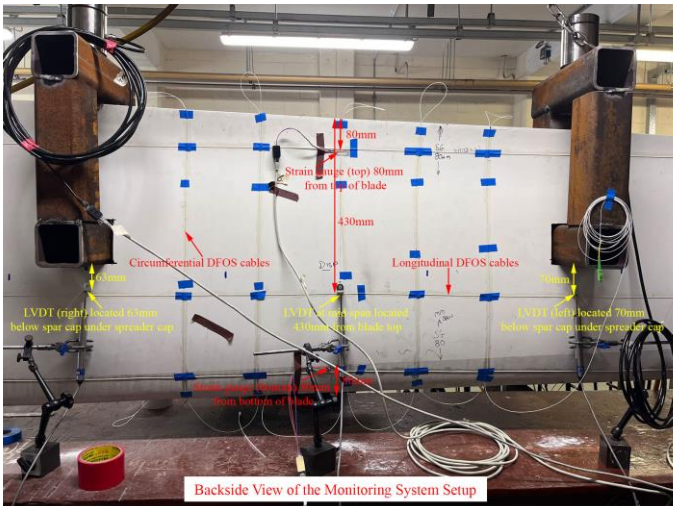



Figure 4. Monitoring system setup on the WTB segment

DIC and DFOS: One DIC camera was positioned to capture and monitor the deformation and displacement of the front side of the WTB segment. Line gauges and reference points were marked at key locations to facilitate deformation tracking. These markers were symmetrically aligned on the front face with the two strain gauges and three LVDTs positioned on the back of the segment, as shown in Figure 5. To get continuous strain measurements of the WTB segment, a Brillouin-based DFOS system was deployed. DFOS cables were installed on both the front and back surfaces of the segment, with two fixed loops: one horizontal and one vertical, as shown in Figures 4 and 5. The data logger used in this experiment was the VISION dual interrogator, manufactured by Omnisens, which integrates Brillouin Optical Time Domain Reflectometry (BOTDR) and Brillouin Optical Time Domain Analysis (BOTDA), enabling short- to long-distance strain measurements over a single fibre.

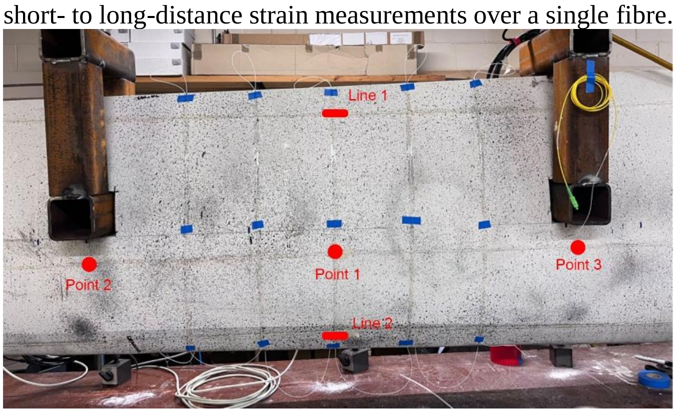
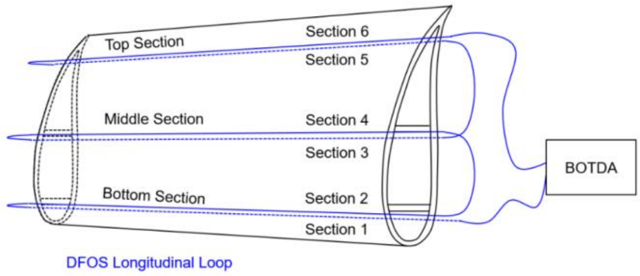


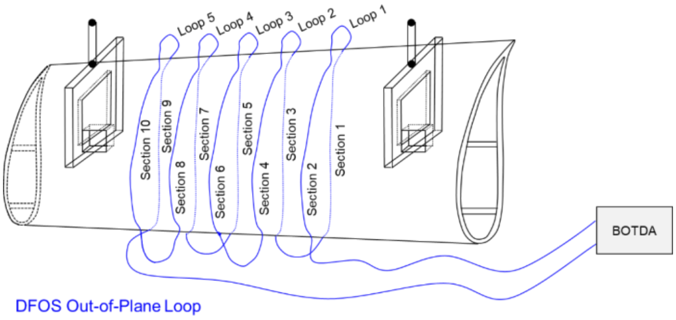

Figure 5. Line gauges and points to mark locations for DIC

### 2.4 *DFOS instrumentation details*

Theoretically, the four-point bending of the WTB segment is expected to induce the highest strain in its top and bottom regions, while the central portion is supposed to experience the lowest strain magnitude. Consequently, the monitoring systems are strategically positioned around the top and bottom areas to capture the most significant strain responses. To ensure consistency and comparability in the monitoring program, DFOS was deployed at locations corresponding to the strain gauges and LVDTs, as illustrated in Figure 6. The front and back surfaces of the WTB segment were instrumented with a single loop of longitudinal DFOS cable, which was virtually divided into three segments on the front and three on the back (Figure 6(a)). In addition, an out-of-plane loop comprising five loops was installed at the mid-span of the segment and virtually segmented into ten sections on both the front and back surfaces (Figure 6(b)). Figure 6 provides a schematic representation of the DFOS instrumentation design for the WTB segment.




(*a*) Deployment of DFOS longitudinal loop




(*b*) Deployment of DFOS out-of-plane loop

Figure 6. DFOS deployment on the WTB segment

The DFOS cables used for monitoring strain development in the WTB segment are single-mode fiber optic cables. These cables were affixed to the front and back surfaces of the WTB segment using Loctite EA 3421 adhesive. For the longitudinal loop of DFOS cables, the top section was installed horizontally along DIC marker Line 1, as indicated in Figure 4-6, rather than being aligned parallel to the top edge of the WTB segment. The middle and bottom sections were also affixed horizontally. The vertical spacing between the top and middle section is 295 mm, while the distance between the middle and bottom sections is 210 mm, with the bottom section positioned 80 mm from the lower edge of the segment. The deployment sequence of the longitudinal loop followed the following order: Section 1-Section 2-Section 4-Section 3-Section 5-Section 6.

For the out-of-plane loop of DFOS cables, five sub-loops were installed on both the front and back surfaces of the WTB segment. The deployment sequence followed the order: Section 2-Section 1-Section 3-Section 4-Section 6-Section 5-Section 7-Section 8-Section 10- Section 9. The spacing between adjacent sub-loops was approximately 190 mm. Loop 1 was positioned 170 mm from the right load-spreader beam, while Loop 5 was located 188 mm from the left load-spreader beam.

Once the DFOS cables were installed, they were left undisturbed for approximately 48 hours to allow the adhesive to cure fully and ensure a secure bond between the cables and the segment surface, preventing slippage. Following the curing period, laser beams were used to verify the integrity of the DFOS deployment. Once the installation was confirmed to be intact, the formal testing phase commenced.

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# 3 MONITORING RESULTS

## *3.1 DFOS measurements*

Figure 7 presents the monitoring results obtained using DFOS under test 1 and test 2 for the longitudinal loops, alongside the strain gauge (SG) and DIC measurements for comparison. As previously discussed, the middle section of the WTB segment (Section 3 and Section 4) is theoretically expected to exhibit the lowest strain magnitude, which is corroborated by the results in Figure 7. Given the minimal strain observed in these sections, their performance will not be further analysed in this paper.

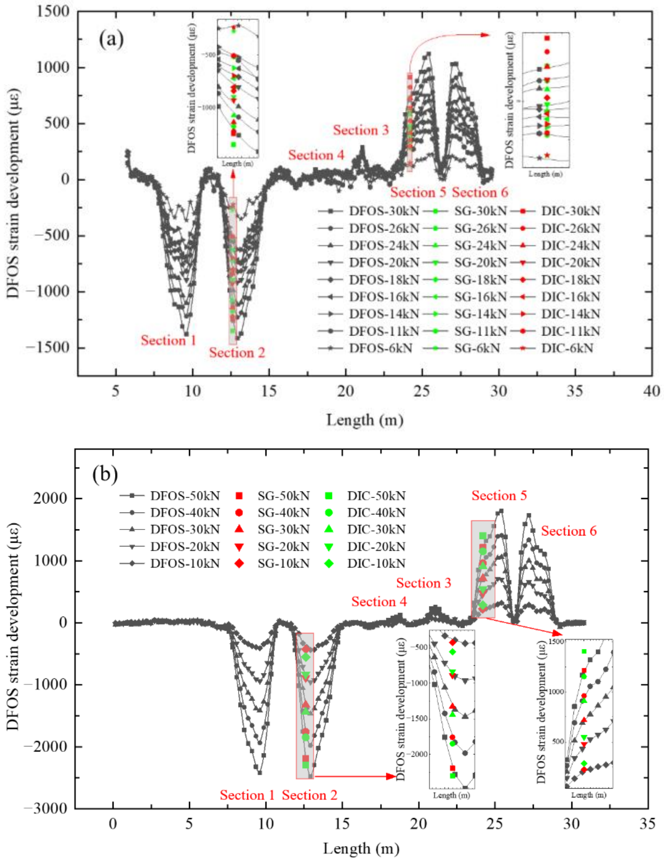


Figure 7. DFOS monitoring results of longitudinal sections under (a) test 1 and (b) test 2

Figure 8 presents enlarged graphs of the measurements obtained in Section 2 and Section 5, corresponding to locations where the DFOS sensors were positioned adjacent to two strain gauges. These graphs provide further insights into the bending behaviour of the WTB segment and facilitate a comparative analysis of different monitoring techniques. As illustrated in Figure 6, Section 1 and Section 2 were affixed to the back and front surfaces of the turbine blade, respectively, at the same height. Theoretically, the bending patterns observed in these areas should be similar under both test 1 and test 2, a hypothesis that is confirmed by the results presented in Figures 8(*a*) and 8(*c*). A comparable trend was observed in Sections 5 and 6, further validating this expectation. The consistency in bending patterns across these sections underscores the repeatability and reliability of the DFOS system employed in this study.

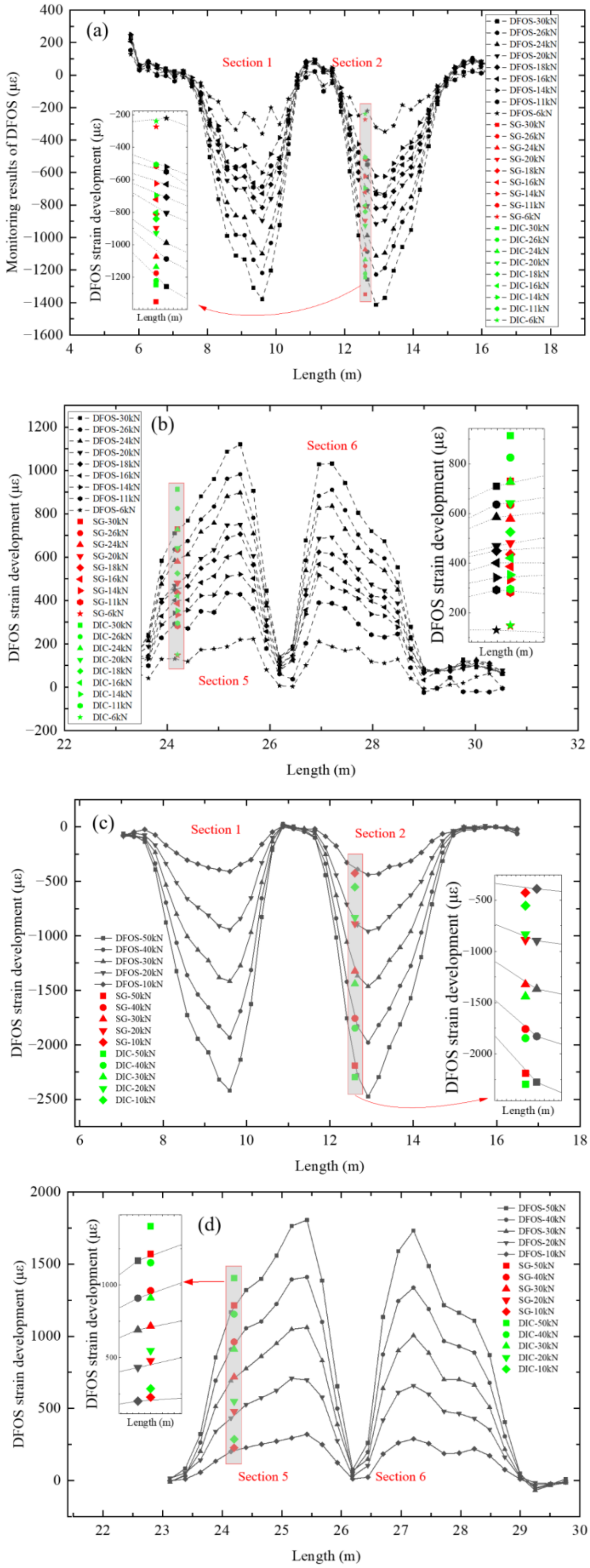


Figure 8. Enlarged graphs of section 2 and section 5 under test 1 (a and b) and test 2 (c and d)

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### 3.2 *Test results comparison*

Figure 9 presents a comparative analysis of the monitoring results obtained using different techniques. The detailed values recorded by the strain gauge, DIC, and DFOS at the top and bottom area of the WTB under test 1 and test 2 are summarised in tables 1 and 2, corresponding to the conditions where total loadings of 30kN and 50kN were reached, respectively.

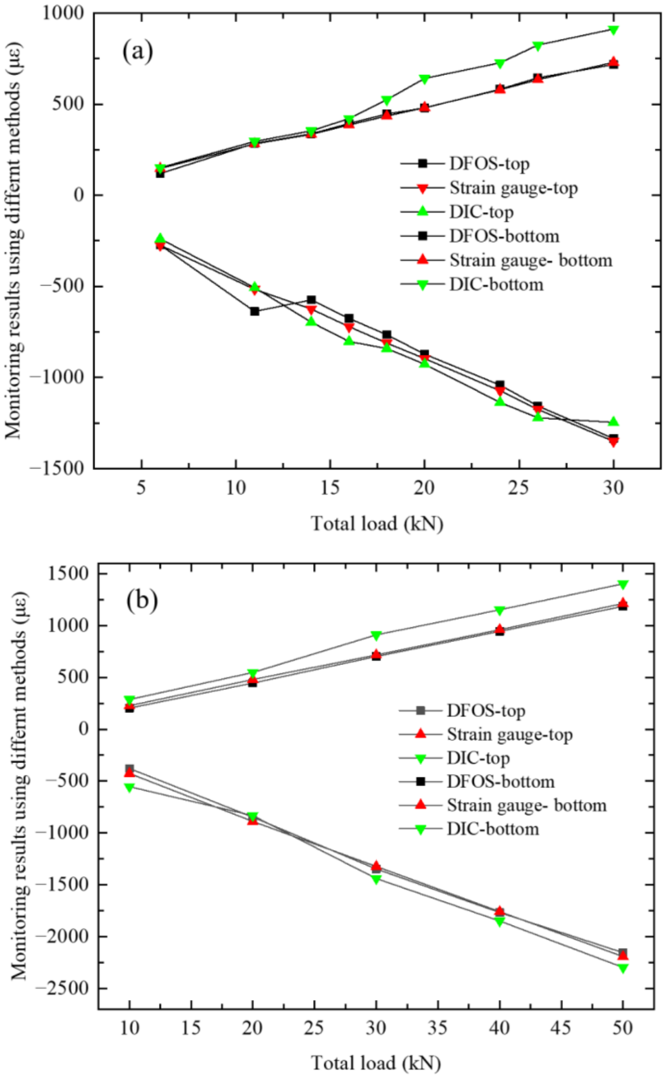


Figure 9. Comparison of monitoring results under (a) test 1 and (b) test 2

Figure 9 illustrates that measurements obtained using different monitoring techniques exhibit consistent deformation patterns in the turbine blade under both test 1 and test 2. The results indicate that the upper region of the blade experienced tensile stress, while the bottom region was subjected to compressive stress. Furthermore, as the external loading increased, the measured strain values exhibited an approximately linear increase, confirming the expected mechanical response of the WTB structure.

Overall, the DFOS measurements in both tests exhibited strong agreement with the results obtained from strain gauges and DIC, confirming its reliability. However, fluctuations were observed in the first two measurements of DFOS-bottom under test 1, which may be attributed to inaccuracies in the manual control of the loading increment. Despite these initial variations, the results affirm the effectiveness and reliability of DFOS as an innovative structural health monitoring technique for analysing the performance of decommissioned WTBs for repurposing.

Table 2. Monitoring results under test 2

| Strain/με | 10kN | 20kN | 30kN | 40kN | 50kN |
|---|---|---|---|---|---|
| DFOS-top | -379.0 | -846.8 | -1346.8 | -1766.2 | -2153.2 |
| SG-top | -426 | -888 | -1323 | -1758 | -2191 |
| DIC-top | -553.3 | -832.1 | -1439.7 | -1847.9 | -2296.4 |
| DFOS-bottom | 204.6 | 445.2 | 702.5 | 943.8 | 1185.1 |
| SG-bottom | 228 | 479 | 717 | 960 | 1213 |
| DIC-bottom | 286.6 | 548.1 | 909.7 | 1152.3 | 1403.1 |

Table 1. Monitoring results under test 1

| Strain/με | 6kN | 11kN | 14kN | 16kN | 18kN | 20kN | 24kN | 26kN | 30kN |
|---|---|---|---|---|---|---|---|---|---|
| DFOS-top | -272.6 | -637 | -574.2 | -675.8 | -765.1 | -871.5 | -1041.4 | -1155.9 | -1334.4 |
| SG-top | -274 | -516 | -624 | -721 | -811 | -896 | -1073 | -1175 | -1350 |
| DIC-top | -239.6 | -506.7 | -696.2 | -802.2 | -840.5 | -927.3 | -1136.4 | -1221.2 | -1246.1 |
| DFOS-bottom | 119.6 | 284.7 | 337.4 | 393.8 | 446.4 | 479.5 | 581.8 | 644.7 | 717.2 |
| SG- bottom | 147 | 282 | 334 | 386 | 435 | 481 | 579 | 634 | 729 |
| DIC-bottom | 150.9 | 295.5 | 353.2 | 420.6 | 524.8 | 641.4 | 727.2 | 824.3 | 912.3 |

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## 4 CONCLUSION

This study evaluated the suitability and applicability of distributed fibre optic sensing for monitoring the second-life performance of decommissioned wind turbine blades in reuse and repurposing scenarios. Four-point bending tests were conducted on a decommissioned WTB segment, with DFOS deployed alongside strain gauges, digital image correlation, and linear variable differential transformers to assess its residual structural performance. The results revealed consistent strain measurements obtained from DFOS, strain gauges, and DIC, with only negligible differences in magnitude, confirming the accuracy and reliability of DFOS in capturing strain distributions in the WTB.

Through comparative analysis, this study confirms that DFOS is a viable and effective monitoring technique for assessing the structural behaviour of decommissioned WTBs, supporting their reuse in civil engineering applications. The tested blade exhibited adequate static load resistance and beam-like behaviour under bending loads, indicating its suitability for structural applications such as bridges and other load-bearing elements. Considering the growing demand for sustainable construction materials, the reuse of decommissioned WTBs, coupled with advanced sensing techniques like DFOS, can contribute to a circular economy in the wind energy sector, reducing waste generation and environmental impact.

However, to ensure the long-term reliability and safety of decommissioned WTBs in civil infrastructure, further research is recommended. Future studies should incorporate material characterisation tests to better understand the degradation effects of aging, UV exposure, and cyclic loading on GFRP composites. Additionally, long-term monitoring under real-world environmental conditions is necessary to validate the feasibility of DFOS for field applications. These steps will help establish standardised design and assessment frameworks, facilitating the widespread adoption of repurposed WTBs in civil engineering applications.

## ACKNOWLEDGMENTS

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