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Structural performance testing of a composite demonstrator made with recyclable composite materials

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ABSTRACT: Currently, wind energy is the largest contributor to Ireland's renewable electricity supply. In Ireland, there were approximately 275 MW of new wind farms connected in 2023. The typical design life span of a wind turbine is 25 years. Most parts of a wind turbine can be reused or recycled, such as steel towers, copper cables, and electrical equipment. However, the blades currently can't be easily recycled, which can cause a high volume of composite waste. By 2030, composite waste from the wind industry is expected to exceed 130,000 tonnes/year. Therefore, it is vital to develop novel wind turbine blades that contribute to the material circularity. In this research, the structural performance of a composite demonstrator, which represents the main structure of a wind turbine blade, is studied. This 5-m long demonstrator was manufactured using glass fibre and Elium® resin, a recyclable material. To ensure the manufactured demonstrator can withstand the design forces, it underwent a series of static loadings, which are introduced by a hydraulic actuator, in the large structures laboratory at the University of Galway. The T-bolt connectors of the demonstrator failed under a load of 36.1 kN. Based on the observations and strain gauge recordings, there is no damage occurred in the thermoplastic composite components. These preliminary test results show that it is positive to use thermoplastic materials in wind turbine blade manufacturing.

KEY WORDS: Composite Materials; Experimental Testing; Renewable Energy; Structural Performance; Wind Energy; Wind Turbine.

1 INTRODUCTION

Ireland's Climate Action Plan 2024 [1] set a target to achieve net-zero emissions no later than 2050. To accomplish this ambition, installation of 5 GW of offshore wind generation by 2030 is proposed. With this rapid expansion of the offshore wind energy sector, concerns are raised about the sustainability of wind turbines, which typically have a design life of 20 to 25 years. When a wind turbine reaches its end of life, most of its metallic components (nacelle, tower, etc.) can be recycled. However, it is still challenging to recycle its rotor blades, which are mainly made with thermoset resins and glass fibre. It is estimated that there will be about 130,000 tonnes/year of composite waste generated from the wind energy sector by the end of 2030 [2].

As a recyclable and sustainable material, there is a rising interest in using thermoplastic resin in composite structure manufacturing. Kravtsova *et al.* [3] found it practical to recycle pultruded unidirectional thermoplastic composites. It was concluded that the number of recycling rounds does not change the chemical composition of the material. The mechanical properties of acrylic and epoxy composite materials were compared by Arwood *et al.* [4]. No significant differences were observed between the two composite materials. Cousins *et al.* [5] recycled glass fibre from a thermoplastic wind turbine blade spar using a dissolution process. More than 90% of thermoplastic resin was recovered and the tensile strength of the recycled glass fibre had no degradation. Through a techno-economic analysis, the manufacturing costs of a thermoplastic wind turbine blade, which is 61.5 m long, were found to be 4.7% less than that of a thermoset epoxy blade [6].

Structural testing is an efficient way of validating the performance of a rotor blade and ensuring its safe operation. In the recent years, there have been a number of research studies focusing on the structural testing of thermoset composite rotor blades [7]-[10]. Regarding thermoplastic wind turbine blades, Murray *et al.* [11] tested two wind turbine blades, one thermoplastic and one thermoset. It was observed that the two blades performed similarly under the same loading conditions.

However, there is still a lack of experimental data on the rotor blades, especially for kilowatts-scale wind turbines, that are made with recyclable thermoplastic resin. Hence, the structural performance of a thermoplastic wind turbine blade demonstrator is experimentally studied in this research. Firstly, the feasibility of producing a large composite structure using glass fibre and thermoplastic resin is evaluated by manufacturing a 5 m demonstrator. The challenges are identified during the manufacturing process. Secondly, the manufactured thermoplastic composite demonstrator is physically tested to determine its static and dynamic properties. The workability of using thermoplastic resin in wind turbine blades are evaluated based on the test results.

2 MATERIALS AND METHODS

2.1 Aim and Objectives

The main aim of this research is to study the structural response of a wind turbine blade, made with thermoplastic resin and glass fibre, under static loading. To achieve this goal, the following objectives are accomplished:

- To manufacture a 5 m wind turbine demonstrator using thermoplastic resin and glass fibre.
- To test the demonstrator physically under static loading and evaluate its structural performance based on the results.

2.2 *Wind Turbine Blade Demonstrator*

The demonstrator studied in this research is derived from the 13 m rotor blade of a Vestas V27 wind turbine (Figure 1). The blade was made with glass fibre and thermoset resin and its structural performance was studied through experimental testing and numerical modelling [8]. More details about the blade can be found in the research work of Finnegan *et al.* [8]. As the blade is mainly exposed to flexural forces during operation, most wind turbine blades are designed with a spar. As presented in Figure 1, there is a box-shaped spar inside the 13 m wind turbine blade. The spar box is the strongest component of the rotor blade. It dominates the blade's structural performance. The root of the spar is the most critical region of the blade since it experiences the highest bending moment. Hence, a 5 m demonstrator is designed from the root region of the spar box. This demonstrator has similar structural details as the one manufactured and tested in the research work of Jiang *et al*. [12]. In this research, the demonstrator is manufactured using glass fibre and Elium®, a type of thermoplastic resin that is suitable for building large composite components.

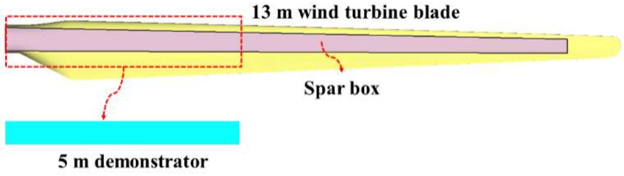


Figure 1. Concept of the wind turbine blade demonstrator.

Figure 2 exhibits the components of the demonstrator, which consists of 2 spar caps, 2 webs and 22 T-bolt connectors. The two webs have a constant thickness of 6 mm along the demonstrator length. They were manufactured using a combination of unidirectional and tri-axial woven glass fibre with Elium® resin. The spar caps were made with unidirectional glass fibre. The caps have a thickness of 15 mm.

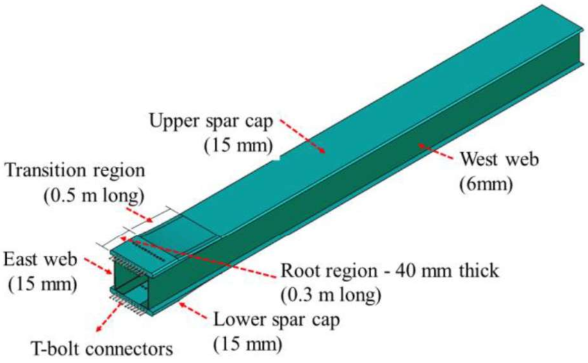


Figure 2. Components of the wind turbine blade demonstrator.

The T-bolt connectors are used to connect the demonstrator to a support frame in the laboratory, whereas on-site they would be used to connect the blade to the wind turbine hub that is installed at the forward end of the nacelle. They were embedded in the root of the spar cap. To accommodate the T-bolts connectors, the spar cap's root thickness is increased to 40 mm. A CNC machine was utilised to drill the holes that take in the connectors.

Figure 3. The vacuum-assisted resin transfer moulding process (for the spar cap).

The thermoplastic composite components were manufactured using the vacuum-assisted resin transfer moulding (VARTM) technique. Figure 3 shows the infusion progress of the spar cap. There was no difficulty experienced during manufacturing, indicating the feasibility of using thermoplastic instead of thermoset resin in large composite structure manufacturing. Moreover, the thermoplastic composite components were cured under ambient temperature, which consumed less energy compared to the oven-cured components. All the components were assembled using

Figure 4. The assembled demonstrator.

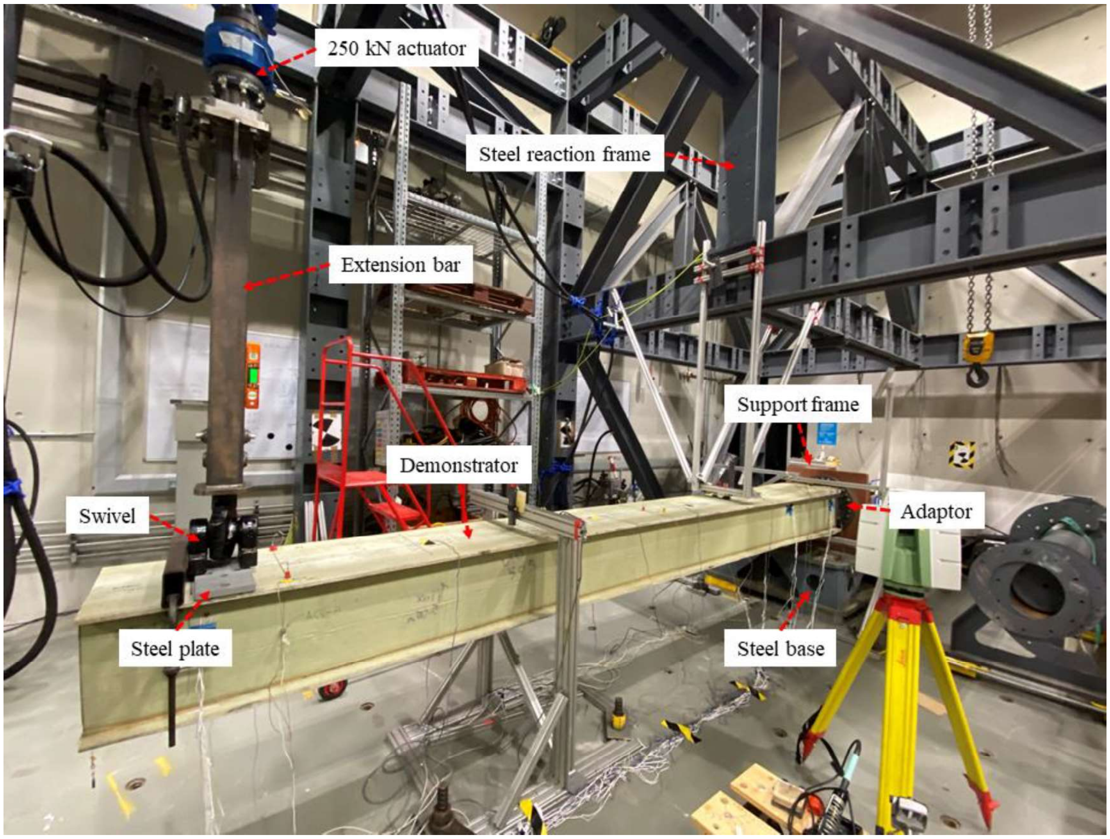


Figure 5. Test setup in Large Structures Testing Laboratory, University of Galway.

methacrylate adhesives. Figure 4 shows the manufactured thermoplastic wind turbine blade demonstrator.

2.3 *Test Programme*

2.3.1 Test Setup

The thermoplastic demonstrator was tested in the large structures testing laboratory, located at the University of Galway. Figure 5 demonstrates the test setup. The root of the demonstrator was mounted on a steel adaptor, which was fixed to the strong concrete floor through a support frame and a steel base. This setup ensured that the demonstrator was tested as a cantilever. The demonstrator was loaded vertically near the tip of the cantilever (4.75 m from its root). A 250 kN hydraulic actuator was used to apply the loads. The actuator was mounted on a steel reaction frame. The force was transferred to the demonstrator through an extension bar. To ensure the force is applied vertically, a swivel, which can rotate freely around the pin, was installed at the end of the extension bar, as shown in Figure 5.

2.3.2 Instrumentations

To monitor the structural responses of the demonstrator, strain gauges, displacement sensors and accelerometers were installed. The instrument layouts on the spar caps and webs are displayed in Figure 6 and Figure 7, respectively. The locations of the instruments were placed according to the previous demonstrator tests [12]. This can allow a direct comparison of the performance of the two demonstrators. The demonstrator's deflections were measured by 3 displacement sensors. On the upper spar cap, 2 linear variable differential transformers (LVDTs) and 1 string pot were installed at the locations of 1.5 m and 3.5 m from the root, as well as at the tip. The

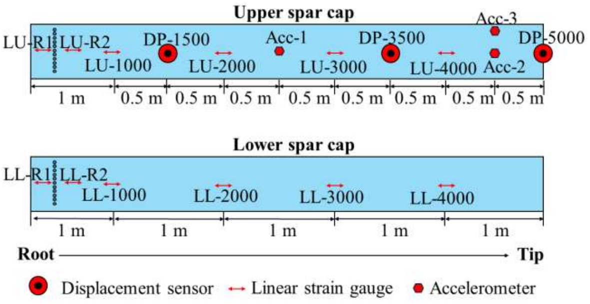


Figure 6. Instrument details on the spar caps.

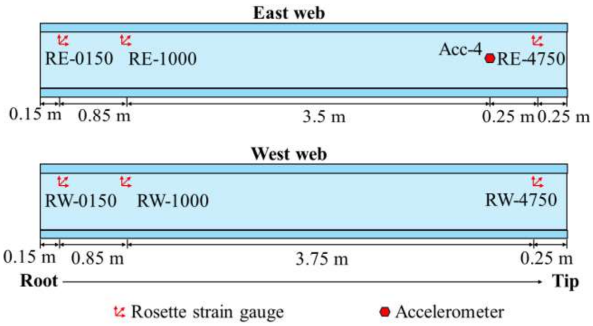


Figure 7. Instrument details on the webs.

demonstrator's vibration responses were recorded by the 3 single-axis accelerometers on the upper spar cap and 1 single-axis accelerometer on the east web at 4.5m from the root.

Regarding strain development of the thermoplastic composite components, 12 linear and 6 rosette strain gauges were attached to the spar caps and webs, respectively. The linear strain gauges were installed along the centre line of the spar caps, while the 6 rosette strain gauges were placed 50 mm under the upper spar cap as the horizontal strain near the cap is higher than that around the centre of the web. Strain gauge recordings can indicate the failure of the composite components in addition to visual inspections.

Besides the instruments on the demonstrator, additional strain gauges and LVDTs were installed on the steel adaptor to ensure it did not fail during testing. As shown in Figure 8, 2 linear strain gauges were installed on the upper and lower sides of the adaptor to monitor the tensile and compressive strains in the steel component. If the values exceed the yield strain of steel, the test would be terminated. The rotation of the whole fixture system was monitored by 2 LVDTs, which were installed on the upper and lower edges of the adaptor's front surface.

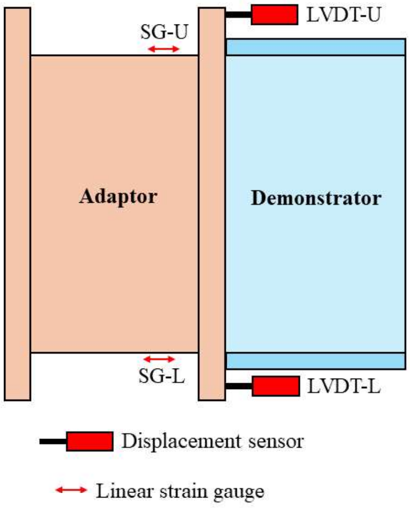


Figure 8. Instrument details on the adaptor.

2.3.3 Test programme

Dynamic and static tests were performed in the test programme. The tests were prepared and executed according to the IEC [13] and DNV GL [14] standards. The main objective of the dynamic test is to acquire the demonstrator's natural frequencies. The demonstrator underwent a free vibration when a transient impact, introduced by a hammer, was applied to its tip region. Its responses were recorded by the 4 accelerometers. By applying the fast Fourier transform (FFT) analysis, the demonstrator's natural frequencies were calculated. The dynamic tests were repeated 3 times in both horizontal and vertical directions.

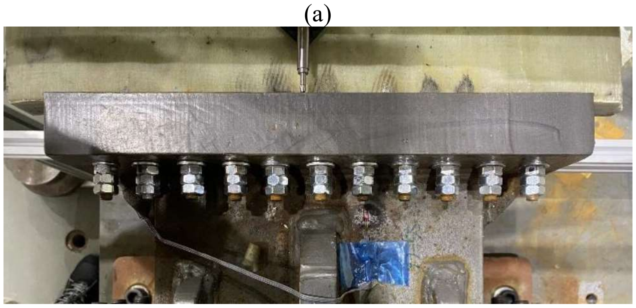
In the static tests, the demonstrator was bent with loads applied near the tip region, at 4.75 m from the root. A steel plate was placed below the swivel to distribute the force and avoid local stress concentrations. The objective of the static tests was to load the demonstrator to failure to find its bending capacity.

Table 1. The maximum static load applied in each load case.

Load Case #	Maximum Load [kN]	Observation
1	4.9	No damage
2	9.8	No damage
3	14.3	No damage
4	19.1	No damage
5	23.9	No damage
6	28.8	No damage
7	33.4	No damage
8	36.1	Nut failure
9	35.4	T-bolt failure

This value is compared to the design load, 32 kN, obtained from a finite element analysis. According to numerical results, there is composite failure around the root under a force of 32 kN. The load was applied manually and carefully under displacement control to avoid any dynamic effect. There were 9 load cases considered in the tests, with the maximum loads listed in Table 1. From load cases 1 to 8, the loads were applied gradually with an increment of around 4.8 kN, which was adopted based on the observations from the previous tests of another demonstrator [12]. Between each load cases, the force was unloaded to zero. In load case 8, five nuts on the T-bolt connectors were observed to be damaged at a load of 36.1 kN. Hence, more nuts were installed on the connectors to avoid nut failure. Figure 9 shows the change of root connections before and after load case 8.

(a)



(b)

Figure 9. Root support strengthening, (a) load case 1 to 8, and, (b) load case 9.

3 RESULTS AND DISCUSSION

3.1 Natural Frequencies

Dynamic tests were carried out before the static tests to obtain the natural frequencies of the undamaged structure. FFT analyses were applied to the recorded accelerations and the results are displayed in Figure 10. The demonstrator's first natural frequencies in the vertical and horizontal directions are 14.0 Hz and 12.3 Hz, respectively. This indicates that the demonstrator has a higher stiffness in the vertical direction than in the horizontal direction. The damping ratios in vertical and horizontal directions are 1.8% and 2.5%, respectively.

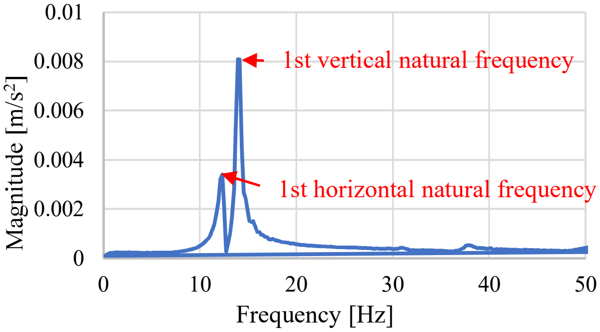


Figure 10. FFT analysis result of dynamic tests.

3.2 Static testing results

In the first 7 load cases, there was no damage observed on the demonstrator. In load case 8, five nuts on the upper side T-bolt connectors failed under tensile force. The damaged nuts were replaced, and more nuts were installed to strengthen the root connection, as shown in Figure 9. In load case 9, the upper spar cap's T-bolt connectors experienced tensile failure at a load of 35.4 kN. As shown in Figure 11, 10 out of 11 bolts failed while the remaining one deformed significantly. No damage was observed on the thermoplastic composite components. Given that nuts and bolts failed under similar loads, 36.1 kN versus 35.4 kN, it can be concluded that the critical components of the demonstrator are the T-bolt connectors. Increasing either the size or steel grade of the connector will improve the connection's capacity and the demonstrator's structural performance. Given that the predicted capacity of the demonstrator is 32 kN, the static tests verify that this thermoplastic structure behaves as expected.

Figure 11. Failure of the T-bolt connectors.

The deflection corresponding to the maximum load of each load case are plotted in Figure 12. In the first 8 load cases, the deflection increases with the load. The maximum deflection, 89 mm, occurred at load case 8. However, after strengthening the root connection after load case 8, the tip deflection dropped about 17% under a similar load in load case 9. The increase in stiffness shows that the increasing the number of nuts per bolt can effectively increase the stiffness of the whole system.

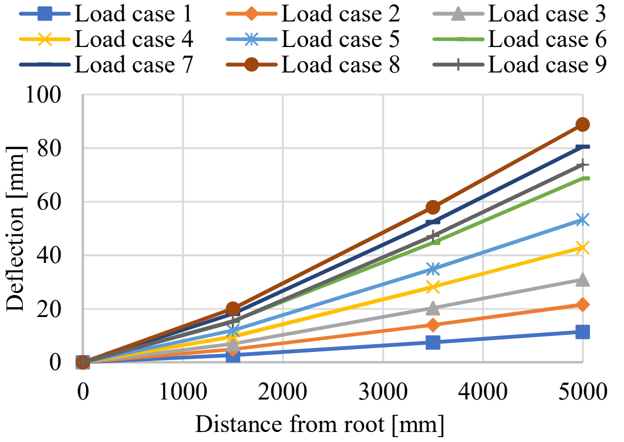


Figure 12. Deflection along the demonstrator.

The strain developments on the upper and lower spar caps are shown in Figure 13. Despite the root developing the highest moment, the maximum tensile and compressive strain occurred at 1 m from the root, with values around 0.01. This is mainly due to the root thickness of 40 mm being higher than the spar cap thickness of 15mm for the rest of the regions. Moreover, the embedded steel T-bolt connectors also contribute to the root stiffness, resulting in relatively low strain values. The maximum strain on thermoplastic composites was less than its typical ultimate strain capacity of 0.02, which would suggest that there was no damage to the composite material. Different from the observations on the behaviour in deflection, similar strain values were found in load cases 8 and 9. It further evidences that the composite components were not damaged, and the T-bolt connectors were the only parts to experience failure.

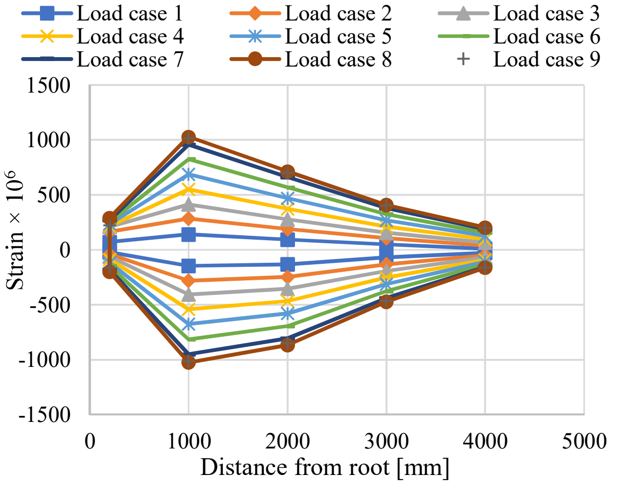


Figure 13. Measured strain values on the upper and lower spar caps.

4 CONCLUSIONS AND IMPACTS

In this research, a wind turbine blade demonstrator was manufactured using glass fibre and thermoplastic resin. To evaluate its structural performance, the 5 m composite demonstrator was physically tested in the large structures testing laboratory of University of Galway. A series of dynamic and static tests were conducted. Based on the test results, the following conclusions can be drawn:

- It is practical to manufacture large composite structures using thermoplastic resin.
- The T-bolt connectors are the critical components of the demonstrator, while other components remain safety.
- The demonstrator's thermoplastic composite parts withstood the design load.
- Thermoplastic resin is a promising material for wind turbine blades.

The study provides preliminary test data that contributes to the feasibility evaluation of using thermoplastic materials in wind turbine blade manufacturing. In the future, a full-scale 13 m wind turbine blade that is made using thermoplastic composites will be tested under static and fatigue loads. The test results will further validate the capability of thermoplastic blades in the wind energy sector.

Currently, the research work carried out on studying the large thermoplastic composite structures, especially for wind turbine blades, is very limited. This research demonstrates that it is highly feasible to use thermoplastic resin in wind blade manufacturing, which is in line with the conclusion proposed by Murray *et al.* [11]. Using recyclable materials in wind turbine blade manufacturing would increase the sustainability in wind energy sector. It will facilitate the decarbonisation progress of energy system and benefit the development of a circular economy. A recyclable wind turbine blade will allow for the expansion of new end-of-life solutions for large composite structures, increasing circularity in the supply chain and reducing waste. It will contribute to the wider government of Ireland's objectives of achieving 80% renewable electricity and a 51% reduction in greenhouse gas emissions by the end of this decade.

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