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Development of Natural Fiber Wind Turbine Blades using Design Optimization Technology

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Abstract
Recently, as the life cycle of wind turbines has arrived around the world and wind blades are discarded, environmental damage is accelerating due to waste from FRP wind blades emitted. To reduce the environmental load of these FRP wind blades, it is intended to develop wind blades using natural fibers, which have recently been expanded in various fields.
A wind blade has a wind load in the form of cantilever beam, and even a fatigue load is structurally vulnerable while driving during the life of a product. In addition, natural fibers have less mechanical properties than FRP, so there have not been many cases of application to load-bearing structures. However, with the recent development of technology, the need to develop wind blades using natural fibers has emerged as the number of applications to yachts and ships has increased and demands for environmental impact reduction have occurred worldwide.
In this study, the annual energy production is maximized by using the aerodynamic optimal design technique for the development of 30 kW class and 7.4 m wind blade using natural fibers, and the blade weight is minimized by using the structural optimal design technique.
Hyper-X is a design optimization program for specialized composite structures and has accumulated excellent results in design optimization on various fields such as aerospace, aviation, automobiles, and wind power industries. This study is to examine the possibility of practical use by optimizing weight and strength of wind blade structure by applying Hyper-X to wind blade structural design compared to FRP.

Keyword: design optimization, natural fiber, flax fiber reinforced plastic, wind blade, wind turbine

1. INTRODUCTION

In recent years, natural disasters caused by global warming are gradually increasing, and as international environmental regulations are strengthened, eco-friendly technologies that can reduce CO_2 generation are emerging. For wind, annual deployment must surge to around 180 GW, according to IRENA's Transforming Energy Scenario. Under the IEA's Net Zero by 2050 scenario, annual run rates for wind would need to be even steeper, reaching 160 GW by 2025 and then 280 GW by 2030, 3 times the volume built in 2020. Lifecycle analysis shows that the carbon emissions payback period for wind is far shorter than for coal-based plants about 5.4 months for a 2 MW onshore turbine and 7.8 months for a 6 MW offshore turbine, as of 2016 and even outperforms hydro and solar generation [3].
However, recently, the disposal of wind power generator that have reached their life cycle is becoming a serious issue. Although more than 80% of total wind turbine mass is made up of recyclable materials, such as steel, iron, copper and aluminum, according to NREL, anywhere from 11-16% is composed of carbon fibre or fiberglass composites, plastics and resin, primarily for rotor blades which have a life expectancy of up to 25 years and are currently difficult to recycle commercially [10, 11]. These environmental demands, along with various studies for incineration, landfill, and recycling of synthetic composite materials, are increasing requirements to apply the more easily recyclable materials for wind blades from the beginning of design process.
Natural fibers like flax, hemp and jute shown in Fig. 1, offer several economical, technical and ecological advantages over synthetic fibers in reinforcing polymer composites [1,4]. Since natural fibers can be obtained naturally, they are cheaper, recyclable, and require low energy during production than conventional glass or carbon fibers [8].
The present study intends to investigate the substitutability of the glass-fiber reinforced plastic (GFRP) to the flax-fiber reinforced plastic (FFRP) for small wind power generators by developing 7.4m wind blades [13, 15].

Design Optimization was performed throughout blade aerodynamics and structural design stages. In this study, the usefulness of DO in blade design was confirmed by overcoming the weakness of the mechanical properties of natural materials to some extent.

(Flax) *(Kenaf)* *(Jute)* *(Sisal)*

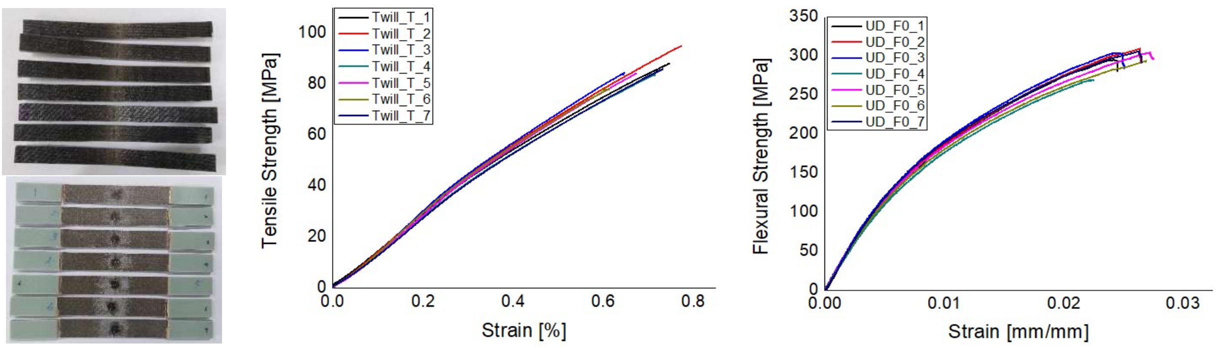
Fig. 1 *Reinforcing natural bast fibers*

2. MATERIAL PROPERTIES OF NATURAL FIBER, FLAX

Carbon fibers and glass fibers, which are previously mainly used as reinforced fibers of composite materials, generate a large amount of CO_2 in the manufacturing process, and are highly resistant to the environment, so even when discarded after use, carbon fibers and glass fibers are hardly permanently decomposed. Natural fibers not only absorb a large amount of CO_2 in the process of cultivating materials, but also have complete biodegradability when made of a composite material combined with biodegradable natural resin and have excellent eco-friendliness because they are completely eco-friendly.
Natural fibers have excellent impact performance and are not far behind in weight-to-weight strength and rigidity compared to glass fibers, so they can be fully used as a composite fiber reinforcement material for manufacturing wind turbine blades. Jute, flax, hemp, etc. have high cellulose contents, and if the cellulose content of natural fibers is high, mechanical strength is high. The flax fiber reinforced composites (FFRP) are used for the wind blade structural design. Due to the low weight requirement to the wind blades, an epoxy resin is utilized as structural matrix material in this study. Epoxy provides a higher level in facture toughness, strength and stiffness of the composite and influences the fatigue life of the composites [12, 13].
The material test is performed according to ASTM D3039/D3039M to obtain material properties. The test results of tensile and flexural strength are shown in Fig. 2. Table 1 shows the material properties of the glass/epoxy fabric and flax/epoxy fabric used to the specimen test [2, 16].

Table 1. *Material properties*

Material Property(UD)	Glass/epoxy fabric	Flax/epoxy fabric
Elastic modulus [GPa]	44.20	19.13
Flexural modulus [MPa]	38113.0	15726.67
Tensile strength [MPa]	1143.0	193.2
Compressive strength [Mpa]	778.73	131.77
Flexural strength [MPa]	1161.82	234.61
Poisson’s ratio	0.29	0.42
Shear strength [MPa]	63.66	26.88



(Specimens) *(Tensile strength)* *(Flexural strength)*

Fig. 2 *The specimens(FFRP) and the measured properties*

3. AERIDYNAMIC DESIGN OPTIMIZATION OF 30KW WIND BLADE

The main requirements of blade design are the cost-effectiveness and reliability of the structure. Design optimization (DO) replacing the GFRP into FFRP has been performed to develop a 7.4 m length blade for 30kW wind turbine with a low wind speed, high efficiency, and low rotational speed. DO is applied to both aerodynamic design to maximize the annual energy production, and the structural design to minimize the weight, by using FFRP.

3.1 Optimum planform and aerodynamic performances

Various NACA and DU foils were reviewed for blade cross-sectional design with a rated output power of 30 kW at a rated wind speed of 9m/s, NACA 44xx and 64xx foils with high lift to drag ratios are selected for blade design with DU foil. As a result of the comparison analysis, the performance of NACA 64xx foils are showed better aerodynamic performance than 44xx, NACA 64xx foils are selected for 30 kW, 7.4m blade design.

In addition, in order to secure the best power coefficient, the analysis is performed by applying the optimal design technique for the code length and twist angle. The result of the optimal design has the effect of maximizing the power coefficient not only improving the efficiency of the blade but also reducing noise by delaying surface separation at the boundary layer of the blade cross-section.

The cord length and twist angle are optimized at TSR 7 using an optimization design technique maximizing the power coefficient as the objective function to optimize the design variables. As a result, power coefficient of 0.5 and an output of 30 kW are obtained at a rated wind speed of 9 m/s. Fig. 3 shows the optimized wind blade shape.

Fig. 3 *Optimum planform of 30 kW wind blade*

Fig.4 shows that the maximum power coefficient Cp and TSR (tip speed ratio) result by applying the code length and twist obtained from the optimal design. The max. Cp shows 0.5 at TSR 7. In Fig. 5, the maximum thrust is 6047.1 N at 8.8 m/s of wind speed and rotation speed of 70 rpm.

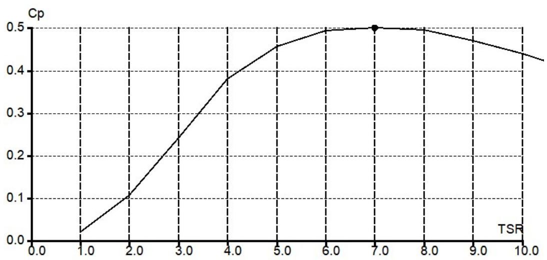


Fig. 4 *Power coefficients as a function of TSR*

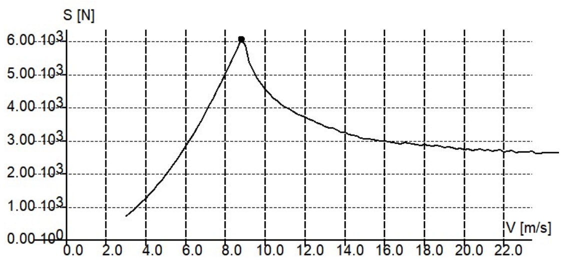


Fig. 5 *Thrust force as a function of wind speeds*

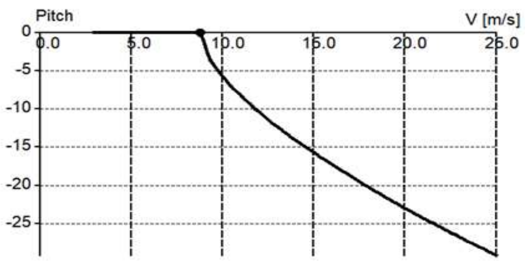


Fig. 6 *Pitch angle control over the rated wind speed*

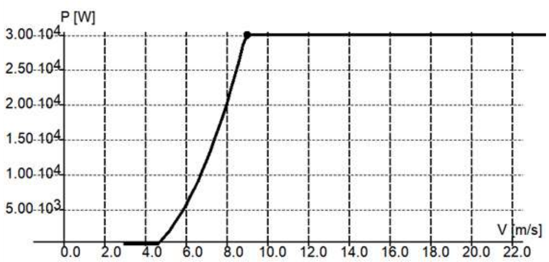


Fig. 7 *Power curve of the 30 kW wind turbine*

Fig. 6 calculates the pitch control angle to maintain the rated output power of 30 kW after the rated wind speed 8.8m/s. Fig. 7 shows the power curve of the 30 kW wind turbine, as a result of aerodynamic analysis, it shows that the result of producing a rated output of 30 kW at 8.8 m/s of the rated wind speed, and the rated rotation speed of the rotor is calculated as 72 rpm. Fig. 8 shows the trend of AEP (annual energy production) according to the change in Weibull parameter, and when shape parameter 2 and scale parameter 9, AEP is calculated as 13.814 Megawatt.

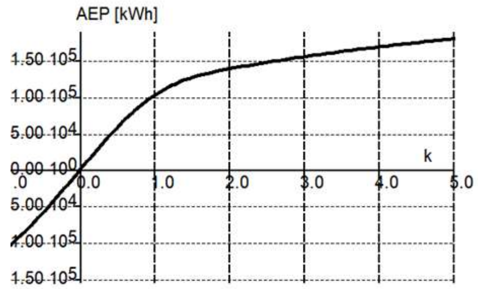


Fig. 8 *AEP vs. Weibull shape parameter k*

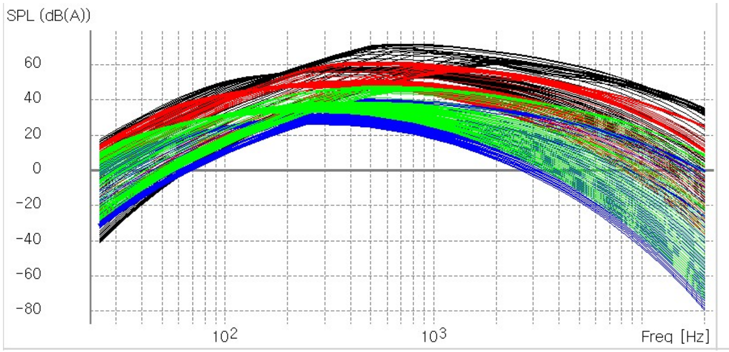


Fig. 9 *NACA 64xx and DUxx at the rated speed of AOA –3 to 2 5 degrees*

3.2 Blade noise analysis

A high-efficiency wind blade with power coefficient of 0.5 is developed using an optimal design technique. A high efficient blade shows low noise level to reduce environmental noise and low-frequency noise using the optimal design technique. Lloyd E. Jones and others revealed that increasing efficiency has less aerodynamic loss, resulting in less turbulence and noise reduction due to separation delays, reducing up to 5dB ranging below 1,000kHz [7, 14]. The amount of noise was quantitatively analyzed through two-dimensional noise analysis for the blade.

In Fig. 9, noise analysis is performed by applying the air inflow speed at the position of each blade of NACA 64xx and DU foil applied to the design at a rated rotation speed of 72 rpm and a rated wind speed of 8.8m/s. About 70dBA of noise is generated at the end of the blade, and the noise of other foils on the blade root side is less than 60dBA.

4. DESIGN OPTIMIZATION OF THE WIND BLADE STRUCTURE

There are amount of possibility to reduce weight in a blade design varying the overall geometry shape, cross section type and thickness and basic architectural layout as well as selecting lighter material. In order to confirm the replacement of the natural fiber reinforcement, we are focused on the weight reduction of wind structures through composite material design optimization. The composite material design optimization is performed by using HyperX [5].

4.1 DO problem formulation

The optimization problem to minimize weight has been formulated to satisfy the limit state functions describing the strength to withstand even extreme winds and gravity load, stiffness to ensure the aerodynamic stability of the blade such as tip clearance between blade and the tower. The fatigue limit state function for more than 20 years and 10s cycles as constraints [9].

- **Object Function** : Minimize Weight
- **Design Variables** : dimension, ply shape
- **Constraint** : Maximum deflection & failure criteria
    - Fiber failure : Max. strain, Tsai-Hill, Modified Tsai-wu
    - Matrix failure : Max. stress, Puck Criteria, In-plane Shear, Von Mises

The design load for the structural design of the wind blade is calculated according to the IEC standard, and the Flap-wise forces (Fx) with respect to span wise location is shown in Fig. 10. The flapwise forces are distributed each cross section of the blade structured in Fig. 11. Fig. 12 shows the FEM model used for structural optimization design.

In order to confirm the usefulness of the optimal design for applying natural fibers, even their low material properties in stiffness and strength, the three case studies are investigated by applying FFRP and GFRP differently to the skin and load carrying laminate flapwise (shear web and spar cap) of the blade. The cross section structure of the wind turbine blade is shown in Fig. 12.

Case 1) All FFRP for skins, shear web and spar cap
Case 2) All GFRP for skins, shear web and spar cap
Case 3) FFRP skin, GFRP to shear web and spar cap

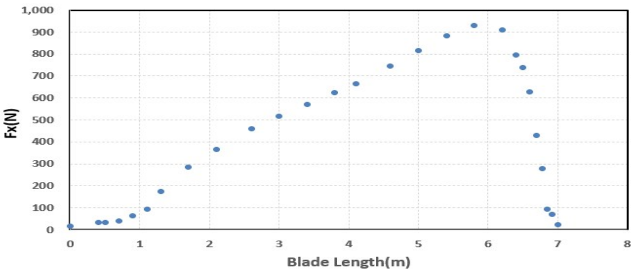


***Fig. 10** Flap-wise forces (Fx)*

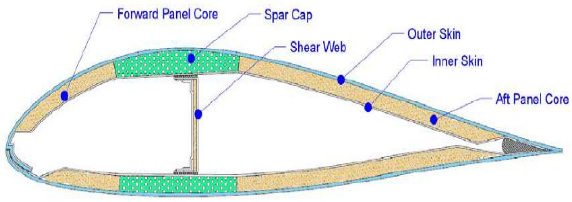


***Fig. 11** Cross section **structure** of the wind blade*

***Fig. 12** Finite element model of the 7.4m blade*

4.2 Composite failure criteria and optimization results

First, the more traditional ply approaches such as max strain, max stress, and quadratic interaction (for example, Tsai-Wu). These failure theories use the same primary material moduli and strain/stress allowables. Second, physically based approaches that attempt to distinguish between fiber and matrix failures. Third, category of composite strength prediction are the laminate approaches. A laminate approach does not attempt to define stress/strain allowables at the ply level, but instead at the laminate level and has the advantage of being capable of more accurately capturing the effects of percent plies in the different layup orientations.

We can achieve thinner and more efficient blade profiles that will yield a higher energy output. The dimension and ply shape of each design case is optimized by using Hyper-X, respectively. The optimum displacement and weight are determined under the design conditions that satisfy all failure criteria, including the Puck failure criterion.

The structural optimization results are presented on Table 2. The original blade is a GFRP blade manufactured by the conventional method. All three design cases subjected to aerodynamic and structural DO have the same planform with longer maximum chord length of 913.5 mm than the original blade (577 mm) from the aerodynamic performance point of view.

***Table 2.** Design study case and results of blade*

Case	Skin	Shear web & Spar Cap	Max. deflection for 200rpm (mm)	Total weight (kg)	Strength and stability criteria satisfied?
Original	GFRP	GFRP		135 (131.1%)	Yes
Case 1	FFRP	FFRP	630 (99.1%)	145 (140.8%)	Yes
Case 2	GFRP	GFRP	636 (100.0%)	103 (100.0%)	Yes
Case 3	FFRP	GFRP	499 (78.5%)	132 (128.2%)	Yes

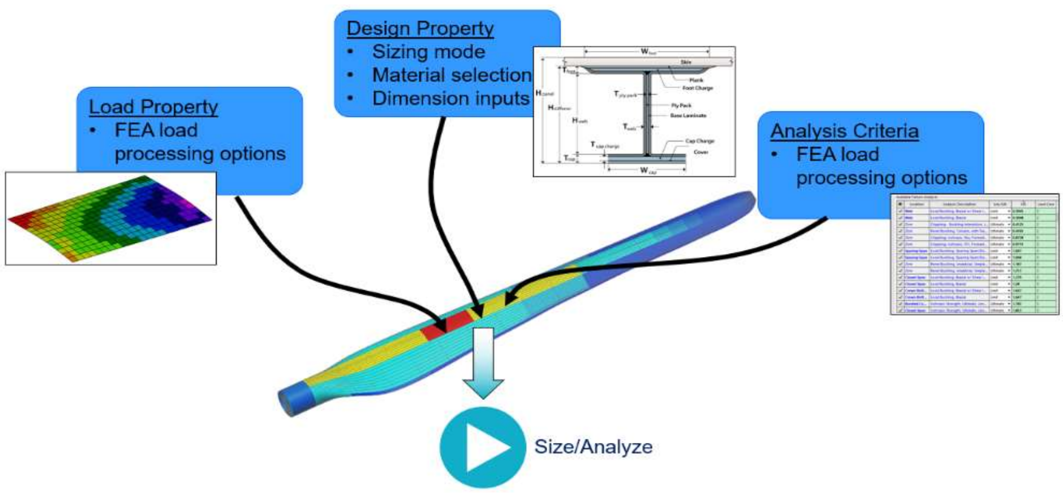


***Fig. 13** Sizing and lay up design optimization by HYPER-X* [5]

The GFRP design (Case 2) has the same material and cross section type as the original, but the weight is greatly reduced by 31.1% from lay-up dimension and shape optimization. Although the deflection is maximum for the GFRP design (Case 2), all design cases satisfied with design constraints defined by the allowable max. deflection and composite failure criteria. In the case of all FFRP design (case 1), the weight is 145 kg, but it also satisfies all design constraints and increased by only about 7.4% compared to the original blade despite the difference in weak physical properties. On the other hand, compared to Case 1, which uses all FFRP with relatively weak material properties, the blade (case 3) with GFRP applied only to the shear web and spar cap has a similar weight to the original blade.
The replacement of GFRP with the natural flax reinforced composite (FFRP) blade by structural design optimization is reasonable for adoption in conventional wind turbines. The 7.4% weight increase of the FFRP blade leads to an increase in the load on the main shaft and main bearings, but it is technically tolerable and has a much higher advantage in terms of environmental protection.

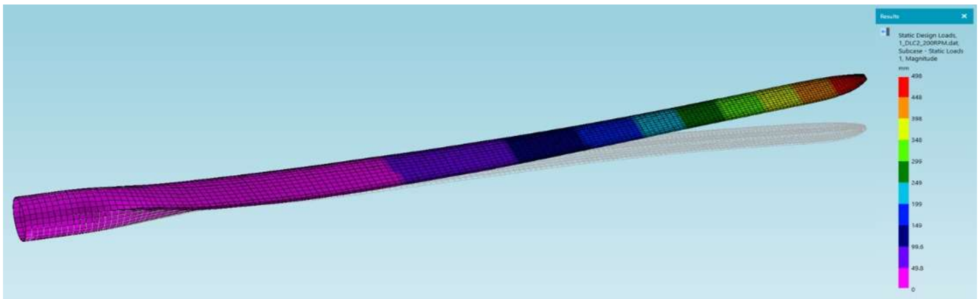


Fig. 14 *Deflection of blade*

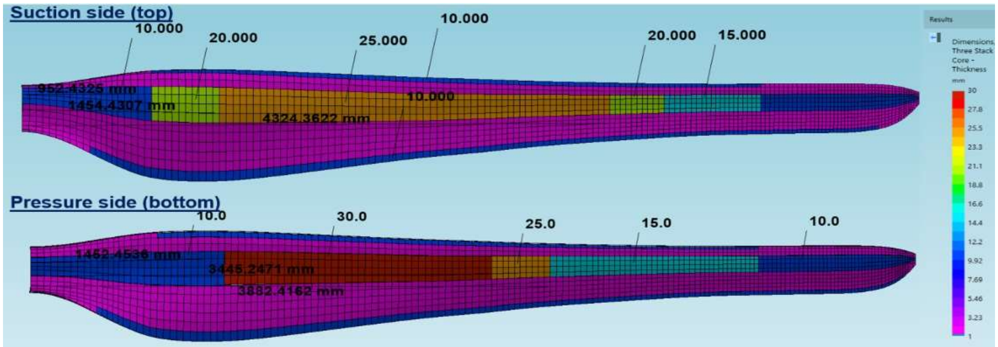


Fig. 15 *Optimized thickness of the blade*

5. CONCLUSIONS

It has been confirmed that natural fibers can be applied to wind blade such as high-loaded structures by applying structural optimization technology to apply eco-friendly natural fibers instead of GFRP.
To reduce the environmental load of these FRP wind blades, it is intended to develop wind blades using natural fibers, the wind blade with a low wind speed, high efficiency, and low rotational speed of 30 kW with power coefficient of 0.5 is developed. As a result of noise analysis, the noise level at the tip of the blade is interpreted as 70dBA. The structural optimal design for 30 kW wind blade with natural flax fiber is performed using Hyper-X, and the applicability is investigated by comparing them with all GFRP wind blade and the FFRP/GFRP mixed wind blade.
Natural fiber reinforced composite blade is found to be 40.8% (FFRP blade, case 1) and 28.2% (FFRP/GFRP, case 3) heavier than the GFRP blade (case 2), respectively. But the FFRP balde (case1) is only 7.4% heavier than the original GFRP wind blade. An increase of 7.4% in weight of natural fiber composit blade compared to the original GFRP blade leads to an increase in load such as main shaft and main bearing, but it is considered to be technically tolerable and can be applied to wind turbines

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