Wear Behavior Analysis and Life Prediction of Floating Sloar Power Structures

unseong Kim*, Seongmin Kang *, SongYi Jeong, Yongseok Choi* and Kyungjun Lee *

* Department of Mechanical Engineering, Gachon University, Gyeonggi-do 13120, South Korea

1. Introduction

Recent extreme weather events have led to a surge in interest and demand for eco-friendly energy sources. According to the world energy outlook 2024, floating solar power generation is emerging as a key technology in the global energy transition, with an expected high growth rate of over 30% annually for the next decade. This is attributed to the unique advantages of floating solar, including increased land use efficiency, improved power generation efficiency due to water surface cooling effects, and water resource conservation. Floating solar power generation is a method of producing electricity by installing solar panels on water surfaces such as seas, lakes, and reservoirs. Typically, solar panels are mounted on floating structures supported by buoys. This approach overcomes the limitations of narrow inland environments and is known to achieve 3-5% higher power generation efficiency compared to land-based solar power due to the cooling effect of the water surface. However, floating solar structures installed in areas such as Saemangeum have reported structural damage due to wave action and wind forces. Although the design life is known to be 20 years, there are reports of solar structures being damaged after only a few months of use. This poses a serious threat to the stability and economic viability of floating solar power generation. To address these issues, this study introduces a new floating solar structure developed by TM Solution and evaluates its performance from various angles. This structure has significantly improved durability in extreme environments by addressing the problems of existing structures. Research methods include optimal design and vulnerability analysis using finite element analysis (ABAQUS), wear resistance evaluation of corrosion-resistant steel through wear experiments, and structural analysis under complex load conditions using VOF flow analysis. Through this research, we present analysis methodologies for floating solar structures and wear life prediction methods, which are expected to be widely used in the robust design of future floating solar structures. In particular, the floating solar structure developed in this study is expected to significantly improve the safety of solar power plants by exhibiting stable durability compared to existing structures under extreme load conditions. This is expected to contribute to achieving global carbon neutrality goals.

2. Experimental procedure

A comprehensive structural analysis was conducted on a floating solar structure model using the finite element analysis program ABAQUS. The model consisted of HDPE (High-Density Polyethylene) floats and steel square tubes, representing a typical configuration for floating solar installations. Our study incorporated deflection analysis, stress analysis, and wear testing to provide a holistic evaluation of the structure's performance and long-term durability. The initial phase of our research focused on deflection analysis, assessing the structure's deformation under its own weight when subjected to wave action. We examined three distinct boundary conditions: fixing 6 side parts out of 9 floats, securing 6 front and rear parts, and anchoring 2 diagonal end parts. These scenarios allowed us to simulate various real-world installation configurations. Throughout this analysis, we accounted for gravitational loads to accurately represent the structure's self-weight. Following the deflection analysis, we conducted a stress analysis considering three key design parameters, with the aim of developing a structurally sound and economically viable design. The first parameter we investigated was the thickness of the structure's square tubes. Given that floating solar structures typically comprise dozens to hundreds of units, the tube thickness significantly impacts economic efficiency. We evaluated the relationship between stress increase and weight reduction when decreasing the square tube thickness from 3.2mm to 1.8mm. The second parameter involved the addition of V-shaped truss reinforcements at the base of the structure supporting the floats. Lastly, we explored the effect of installing reinforcements by interconnecting the square tubes on the float sides. To address the issue of wear caused by wave-induced twisting between square tubes, we simulated the contact pressure on the external paint layer and internal corrosion-resistant coating. By applying an axial force of 3500N to the square tubes in our model, we calculated a contact pressure of 31.92MPa. To validate this in physical testing, we used a 6.37mm diameter SUS316L ball to replicate the equivalent pressure, determining that a 3kg load produced the same 31.92MPa contact pressure. We then employed a 2-body abrasion tester to conduct reciprocating wear experiments at an initial velocity of 3mm/s. This allowed us to determine the wear gradients of the paint layer, corrosion-resistant coating layer, and base layer. By comparing these experimental results with the theoretical wear rate of 0.12mm per minute derived from our analysis, we estimated the actual wear life of the structure to be approximately 0.1 years.

3. Results and discussion

A comprehensive analysis of the floating solar array's structural integrity was conducted under standard gravitational load (1g) conditions with diagonal support configuration, incorporating both structural modifications and wear testing. The primary focus was on the structure's strength-to-weight ratio and long-term durability assessment. Initial analysis centered on reducing the square tube cross-section thickness from 3.2mm to 1.8mm. Results showed an increase in maximum stress levels from 262.1 MPa to 334.3 MPa (22% increase), indicating the onset of plastic deformation. Simultaneously, a mass reduction of 44% was observed, with the total structural weight decreasing from 1,694 kg to 953 kg. This configuration was adopted as the base model for subsequent analyses due to the disproportionate relationship between stress increase and mass reduction. Additional structural improvements were explored using this base model. V-shaped truss reinforcements installed between the lower structural elements resulted in a 16% reduction in maximum stress, with a 6% increase in overall mass. Connecting previously separate reinforcement elements along the float sides led to a 39% decrease in maximum stress, with an 11% increase in total mass. When both reinforcement types were simultaneously applied, a 44% reduction in maximum stress was achieved with a 17% increase in overall mass. Wear experiments were conducted on the structure's coating layers to assess long-term durability. Results showed wear rates of 5.65 μm/min for the paint layer, 1.3 μm/min for the corrosion-resistant coating, and 0.99 μm/min for the base iron layer. These results correlated with the hardness values of each layer: 21.2 Hv for the paint layer, 115.9 Hv for the corrosion-resistant coating, and 185.7 Hv for the base layer. The wear rates were validated using the Archard Equation, which establishes an inverse relationship between wear rate and material hardness. In the wear experiments, the coating layer was completely removed within a range of 17.5 to 39 minutes. This variation in removal time is attributed to the non-uniform thickness of the paint layer and corrosion-resistant coating across the structure. When compared with analytical results, this indicated that the coating layer would be fully worn away in approximately 0.1 years under simulated real-world conditions.

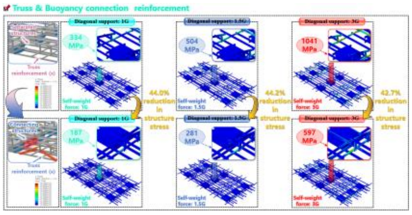

Fig. 3 Analysis results according to presence or absence of reinforcement

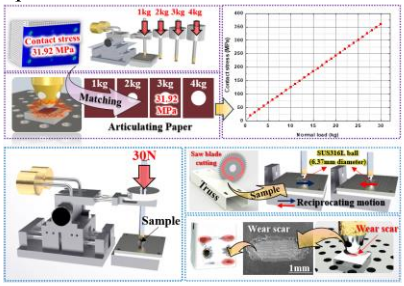

Fig. 4 Wear test process

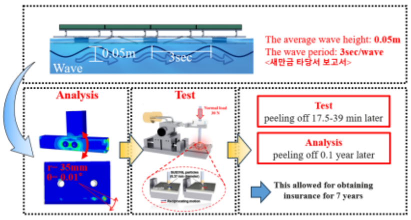

Fig. 5 Predicting wear life

Conclusion

The comprehensive structural and wear analysis of the floating solar array under various configurations yields several significant insights. The study demonstrates that strategic structural modifications can substantially enhance the integrity and efficiency of floating solar installations. The initial reduction in square tube thickness, while resulting in a minor increase in stress levels, led to a disproportionately larger decrease in overall mass, optimizing the strength-to-weight ratio. The combination of V-shaped truss reinforcements and interconnected reinforcement elements along the float sides proved most effective in stress reduction, showcasing a synergistic effect that significantly outperformed individual modifications. Complementing the structural analysis, the wear experiments provided crucial insights into the long-term durability of the system. The observed wear rates for different layers and their correlation with material hardness values offer valuable data for predicting the lifespan of protective coatings. The rapid wear of the coating layers, with complete removal occurring within 17.5 to 39 minutes under accelerated test conditions, translates to an estimated 0.1 years in simulated real-world conditions. The research emphasizes the value of advanced computational modeling and wear testing in the development of innovative solar energy solutions. While the results are promising, real-world implementation would require further investigation into factors such as dynamic loading conditions, long-term fatigue effects, and environmental impacts. In conclusion, this study provides a solid foundation for the advancement of floating solar array design, potentially contributing to the broader adoption and increased reliability of this emerging renewable energy technology. The combination of optimized structural design and enhanced material durability is key to developing floating solar arrays that can withstand the harsh conditions of aquatic environments while maintaining long-term efficiency and cost-effectiveness.

Reference

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ACKNOWLEDGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MIST) (No. 2018R1A5A7025522).

This work was supported by Korea Institute for Advancement of Technology(KIAT) grant funded by Korea Government(MOTIE) (P0020612, 2023 The Competency Development Program for Industry Specialist).