Structural analysis and design for the development of floating photovoltaic energy generation system

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Abstract. In this paper, we discussed the structural analysis and design for the development of floating photovoltaic energy generation system. Series of research conducted to develop the system from the analysis and design of the structural system to the installation of the system discussed. In the structural system supporting solar panels PFRP materials and SMC FRP materials used. A unit module structure is fabricated and then the unit module structures are connected each other to assemble whole PV energy generation complex. This system connected directly to the power grid system. In addition, extensive monitoring for the efficiency of electricity generation and the soundness of the structural system is in progress for the further system enhancement.

1. Introduction
Fossil fuel is one of the major energy resources used around the world nowadays. However, over consumption of fossil fuel leads to environmental issues. In 2012, Korea adopted the renewables portfolio standard (RPS) to promote the development, use, and diffusion of new and renewable energy. The RPS requires the production of energy from renewable energy resources such as wind, solar, biomass, geothermal, etc [1].

According to the literature review conducted in the study, various types of floating photovoltaic (PV) energy generation systems installed on the idle water surface of dam, reservoir, and sea in USA, Europe, and Asia [2]. For the analysis and design of the system, materials to use, methods to design, design requirements, structural configurations, mooring system including buoy, etc should be predetermined. For the structural system, the glass fiber reinforced polymer plastic (FRP) members manufactured by the pultrusion process and specially produced L-shaped member manufactured by the sheet molding compound (SMC) process are used, respectively [3]. Because of the durability and the construction cost due to lightweight, glass fiber reinforced polyester composite (FRP) structural members having high corrosion resistance and high specific strength and stiffness selected. In general, the pultruded FRP material is considered as an orthotropic material (transversely isotropic more strictly) in the structural analysis and design.

2. Mechanical properties of FRP members
For the FRP material, various manufacturing techniques are developed. In the construction industries, pultrusion process is one of the most cost effective manufacturing processes because of its mass production capability. In general, the mechanical properties of FRP materials are closely related to the
material production processes. Prior to analysis and design of structural system, manufacturing process of the FRP member and its mechanical properties need to determine. Figures 1 and 2 show some of manufacturing processes.

![Figure 1. Pultrusion process.](image1)

![Figure 2. Continuous filament (tape) winding process.](image2)

2.1. Manufacture of pultruded structural members
The FRP members to fabricate solar panels supporting structural system produced by the pultrusion process. For fabricating the structure to support the solar panels, L-shaped member produced by the SMC process also used.

2.2. Mechanical property of FRP
To determine the mechanical properties of the FRP structural I-shape members and SMC L-shape members, coupon specimens have taken along the reinforcing fiber direction and along the transverse direction, respectively. Uniaxial tension test on the coupon specimens is conducted and the load is applied up to the point of specimen failure. Average test results are given in tables 1 and 2, respectively [3].

| Location | Tensile strength [MPa] | Modulus of elasticity [GPa] | Poisson’s ratio [mm/mm] |
|----------|------------------------|-----------------------------|-------------------------|
| Flange   | 385.01                 | 34.23                       | 0.34                    |
| Web      | 451.52                 | 31.04                       | 0.28                    |

| Table 2. Material property of SMC (FRP) [3]. |
|---------------------------------------------|
| Tensile strength [MPa] | Modulus of elasticity [GPa] | Poisson’s ratio [mm/mm] |
|------------------------|-----------------------------|-------------------------|
| 80.00                  | 14.33                       | 0.25                    |

3. Analysis and design

3.1. Structural analysis
In the analysis of structural system supporting the solar panels and resting on the buoys, the finite element method (FEM) is used. FEM software, MIDAS CIVIL 2012 [4], is used for the structural analysis. In addition, GTSTRUDL version 29 [5] is also used for the analysis. Because the structural system with buoys rests continuously on the water surface with hogging and sagging movement, the fluid-structure interaction (FSI) analysis also performed by using ADINA system finite element
software [6]. From the structural analysis by the finite element analysis (FEA), the maximum stress and the location where the maximum stress occurs in the member found. Loads for the analysis is consisted of the wind load, snow load, load induced by the mooring system, and self-weight of the structural system including weight of workers during construction and maintenance of the system in service.

3.2. Structural design
For the design of floating photovoltaic energy generation structural system relevant specification need to be developed. In USA pre-standard specification is developed and submitted to American Composite Manufacturers Association in 2010. This design method is based on the load and resistance factor design method (LRFD) which may be considered as one of the limit state design methods (LSD) (refer to figure 3). Eurocomp design code and handbook published in 1996 is also available at present (refer to figure 4). In addition, FRP composite manufacturers also developed and continuously revised the design manual, mostly based on the allowable design method (ASD), for their own pultruded FRP (PFRP) materials as shown in figures 5 and 6, respectively.

![Figure 3. ASCE pre-standard (LRFD).](image1)

![Figure 4. Eurocomp design code and handbook.](image2)

![Figure 5. Extren design manual (Strongwell).](image3)

![Figure 6. Pultex pultrusion design manual (Creative pultrusions).](image4)
4. Connection system
For the pultruded structural members, connection of members for fabricating the structural system is important. Unlike the connection of steel or aluminium members, because of welding of FRP member is not possible, bolting, gluing, gluing with bolting may only be applicable. In the study, bolted connection of PFRP members for the fabrication of structural system adopted based on the test results conducted by Lee et al [7-9] and Woo et al [10].

4.1. Member connection
In the fabrication of structural system supporting the solar panels (unit module), bolted connection between the FRP members with gusset plates used as shown in figure 7. Stainless steel bolts, nuts, and washers also used as shown in figure 7. To reduce the number of connection points, L-shaped member produced by the SMC process also used as shown in figure 8.

![Figure 7. Gusset plate (PFRP angle) [11].](image)

![Figure 8. L-shape member produced by the SMC process [3].](image)

4.2. Module connection
In the design of floating PV energy generation structural system, a unit module structure is designed, and then the unit modules are connected each other by C-shape connection devices to assemble the floating PV generation complex (refer to figures 9 and 10 [2]). By this way, we can reduce the stress in structural member in the unit module. In addition, it leads to easy of handling during fabricating, launching, and towing at the job site. Moreover, it is also possible to reduce the construction cost in terms of PFRP material, equipment, and labor cost.

![Figure 9. C-shape device [2].](image)

![Figure 10. Module connection with C-shape device [2].](image)
5. Buoy and mooring system

5.1. Buoy
In the development of the system, two types of buoy manufactured considering the cost and durability. Expanded polystyrene (EPS) is filled inside the polyethylene (PE) drum as shown in figure 11. This type of buoy is cheaper but not durable. Filament winding FRP composite drum (FFRP), made by using E-glass fiber and polyester resin, filled inside the drum with expanded polystyrene also produced as shown in figure 12. This buoy is highly durable but expensive compared with buoy made by PE drum.

![Figure 11. Buoy (PE).](image1)

![Figure 12. Buoy (FFRP).](image2)

5.2. Mooring system
Planning and designing of mooring system are important because it directly related to the construction cost. In the design, it is necessary to consider the change of water level, the environmental condition of location to install, etc. In addition, the loads induced by the mooring system need to consider in the design of structural system as mentioned earlier. Figure 13 shows one of mooring systems used in the study.

![Figure 13. Mooring system.](image3)

6. Efficiency of energy generation
Comparison of yearly energy generation between land-fixed type and tracking type floating photovoltaic energy generation system conducted. Summary of comparison result is in table 3. In the development and installation of the system, energy generation efficiency evaluated by comparing the system installed on the ground as given in table 4. The system installed on the water is slightly more efficient than the system installed on the ground.
Table 3. Comparison of energy generation efficiency [3].

| Installation site       | Type of PV generation | Energy generation capacity [kW] | Yearly energy generation [MWh] | Operation ratio [%] |
|-------------------------|-----------------------|---------------------------------|-------------------------------|---------------------|
| Samcheon-po, Korea      | Land fixed            | 100.00                          | 113.03                        | 12.90               |
| Hapcheon, Korea         | Floating with tracking| with 100.00                     | 125.00                        | 14.27               |

Table 4. Comparison of monthly energy production between the floating type and land type system [9].

| Month                   | Floating (0.93 kW) ① | Land (20 kW)② | (20kW/0.93kW) ③ | (②/①) | ①/③ |
|-------------------------|-----------------------|---------------|-----------------|--------|------|
| June (21-30)            | 20.4                  | 313.0         | 15.34           |        | 1.33 |
| July                    | 52.6                  | 931.0         | 17.70           |        | 2.97 |
| August                  | 55.8                  | 1042.0        | 18.67           |        | 2.99 |
| September               | 46.5                  | 1124.0        | 24.17           |        | 1.92 |
| October (1-10)          | 12.2                  | 397.0         | 32.54           |        | 0.37 |

7. Installation site

Figure 14 shows a unit module of floating type photovoltaic energy generation structure. The structure installed at the Tongyeong bay located in the south coast of Korea [1]. A tracking-type floating photovoltaic energy system with 100kW generation capacity installed as shown in figure 15. The structure installed at the Hapcheon dam in Korea. It composed of four unit modules with 24.8 kW generation capacity per each unit module [1]. Figure 16 shows 1MW class floating photovoltaic energy generation structure at cooling water intake channel of power plant in Dangjin-si, Chungcheongnam-do, Korea [1]. The floating photovoltaic energy generation structural system is installed at Otae reservoir, Sangju-si, Gyeongsangbuk-do, Korea (refer to figure 17) [1].

The generation systems installed at different locations showed here for illustration purposes. However, many of similar structural system installed at different sites and they are in service. The electricity generated by the system supplied directly to the power grid system of Korea [1].

Figure 14. Tongyeong bay.  
Figure 15. Hapcheon dam.
8. Conclusion

In this paper, series of research conducted to develop the floating PV generation system discussed from the analysis and design to the installation. Materials used to fabricate the structural system supporting the solar panels are PFRP profile and SMC FRP members. Mechanical properties of the members determined by the coupon specimen tests. In the fabrication of the structuring system to support the solar panels, a unit module structure designed and fabricated, and then the unit module structures are connected each other to assemble the whole PV generation structural complex.

The floating PV generation system directly connected to the power grid system so that the electricity generated by the system can supply. Extensive monitoring for the efficiency of electricity generation and the behavior of structural system is in progress for further development and structural enhancement.

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