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추적식 수상 태양광발전 구조물의 시공 및 안전성 평가

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Installation and Safety Evaluation of Tracking-type Floating PV Generation Structure

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Abstract: Pultruded glass fiber reinforced polymeric plastic (PFRP) and FRP member manufactured by sheet molding compound (SMC) have superior mechanical and physical properties compared with those of conventional structural materials. Since FRP has an excellent corrosion-resistance and high specific strength and stiffness, the FRP material may be highly appreciated for the development of floating-type photovoltaic (PV) power generation system. In this paper, advanced floating PV generation system made of PFRP and SMC is designed. In the design, it includes tracking solar altitude by tilting photovoltaic arrays and tracking solar azimuth by spinning structures. Moreover, the results of the finite element analysis (FEA) are presented to confirm stability of entire structure under the external loads. Additionally, installation procedure and mooring systems in the Hap-Cheon Dam are discussed and the measurement of strain under the actual circumstances is conducted for assuring stability of actually installed structures. Finally, by comparison with allowable stress, appropriate safety of structure is confirmed to operate the system.

Key Words: PV, PV generation, PFRP, FRP, SMC, Tracking-type PV power generation, Installation, Solar energy, Design, Mooring

1. INTRODUCTION

The photovoltaic energy generation system (PV) is one of suitable techniques to mitigate environmental problems associated with the fossil fuel. To generate solar energy efficiently, construction of the photovoltaic energy generation system (PV) needs wide enough site. However, since the facility site is mostly located on land, some problems such as an increase in total construction cost due to high cost of land use, environmental disruption such as devastation of ecological system, etc. have occurred. To solve or mitigate such problems, floating type photovoltaic energy generation system was developed by using pultruded glass fiber reinforced polymeric plastic (PFRP) members (Choi, 2010; Choi, 2013).

PFRP has superior material properties compared with those of conventional structural materials. Especially, PFRP has an excellent corrosion-resistance and high specific strength and stiffness (Babero, 1998; Bank,

주요어: 태양광발전, 수상태양광발전, PV패널, PFRP, SMC, 유리섬유복합재, 추적식 태양광발전, 계류, 시공

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2006) which is highly appreciated for the design and fabrication of the floating type photovoltaic energy generation system.

In previous study, FRP compression members produced by SMC (sheet molding compound) process was suggested for structural members of floating PV system. Structural members manufactured by SMC has advantages for increasing constructability by reducing the number of connecting bolts (Choi, 2013).

In this paper, advanced floating PV generation system made of PFRP and SMC is designed. In the design, it includes tracking solar altitude by tilting photovoltaic arrays and tracking solar azimuth by spinning structures. Moreover, results of the finite element analysis (FEA) are presented to confirm stability of entire structure under the external loads. Additionally, installation procedure and mooring systems in the Hap-Cheon Dam are discussed and the measurement of strain under the actual circumstances, wind, wave, and loading; mainly due to worker engaged in the maintenance of the system, is conducted for assuring stability of actually installed structures.

Fig. 1 Pultruded FRP Members

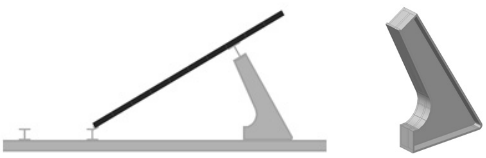


Fig. 2 SMC Compression Members (Choi, 2013)

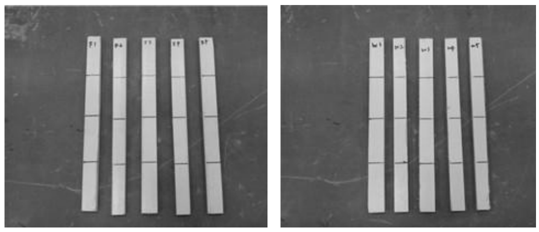
2. TRACKING-TYPE FLOATING PV GENERATION SYSTEM

2.1 Material Properties of Structural Members

To identify the material properties of main structural members, tensile tests were conducted for PFRP members according to KS M ISO 527-4 (2002). For testing tensile strength, two strain gages are attached to the surface of specimens with longitudinal and transverse directions. Each specimen is installed and loaded using the universal testing machine with 1,000*kN* capacity as shown in Fig. 3. The specimens were loaded up to failure with a speed of 3*mm/min* according to the displacement control method.

For the tensile tests of I-Shape PFRP members, test specimens were taken in the longitudinal direction (i.e., axis direction of the member) in the flange of the member and they are shown in Fig. 4.

Fig. 3 Tensile Tests of PFRP



(a) Flange (b) Web

Fig. 4 PFRP Specimens for Tensile Tests

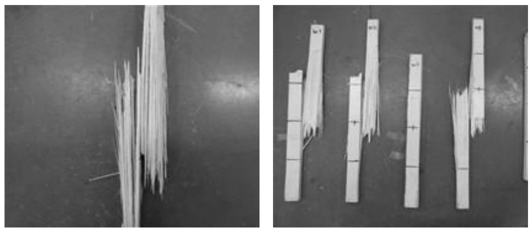


Fig. 5 Failed PFRP Specimen

From the results of tensile tests, brittle failure was occurred along the fiber direction of the specimen. From the test results, material properties of PFRP specimens are estimated and presented in Table 1.

In addition, the mechanical properties of SMC members are also presented in Table 2.

Table 1. Material Properties of PFRP (KS M ISO 527-4)

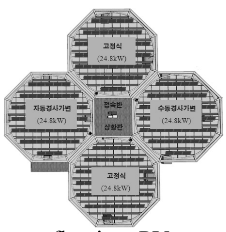
Specimen Designation		Tensile Strength (f_{Pt}, MPa)	Young's Modulus (E_P, GPa)	Poisson's Ratio (ν_P)
Flange	F-1	401.34	32.04	0.31
	F-2	387.40	34.54	0.37
	F-3	404.90	35.24	0.30
Average		397.88	33.94	0.33
Web	W-1	461.79	30.41	0.28
	W-2	466.41	29.74	0.26
	W-3	438.54	29.28	0.15
Average		455.58	29.81	0.27

Table 2. Material Properties of SMC Member (Choi, 2013)

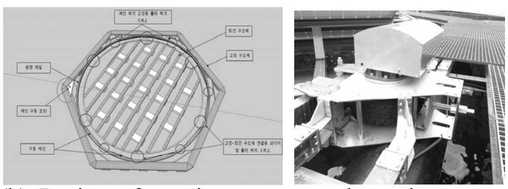
Material	Tensile Strength (f_{St}, MPa)	Young's Modulus (E_{SMC}, GPa)	Poisson's Ratio (ν_{SMC})
SMC	80.00	14.33	0.25
	Flexural Strength (f_{Sf}, MPa)	Specific Gravity	
	182.00	1.88	

2.2 Design of PV Module

The entire tracking-type floating PV generation system consists of four octagonal generation modules and one square control module as shown in Fig. 6. There are three types of generation modules, i.e., fixed-angle type, passive-tilting type, and automatic (active)-tilting type, and each module has 24.8kW generation capacity.



(a) Tracking-type floating PV generation system



(b) Design of rotating system and rotating motor

Fig. 6. Design of Floating PV Generation Structure

PV modules are rotated by the guide rails and rollers on the edge of rotating-structure. Rotation of the system was performed by the motors which are installed on the contact points of PV module and control module.

(1) Fixed-angle type

In the fixed-angle type, PV panels are placed on PFRP and SMC members and connected by bolts as shown in Fig. 7.

The fixed-angle type has better stability and cost effectiveness than other types. Especially, this type has advantages in highly windy areas like island or coastal areas. Although the fixed-type has a lower generation efficiency than the other types, it has advantage in installation and maintenance (Yoon, 2014).

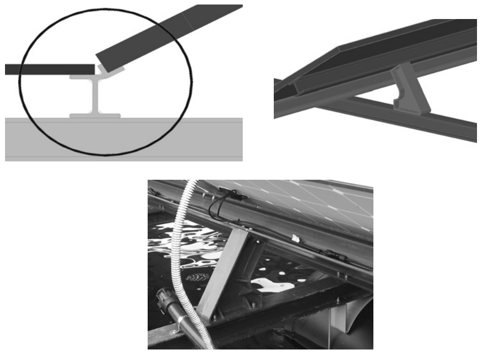


Fig. 7 Fixed-angle Type PV Generation Structure

(2) Passive-tilting type

In the passive-tilting type, PV panels are connected on rotating steel bar and placed on SMC members with angle changable parts as shown in Fig. 8.

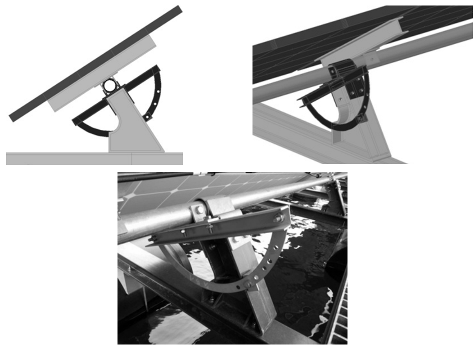


Fig. 8 Passive-tilting Type PV Generation Structure

Considering the location of the sun in each month of the year, the angle of the passive-tilting type is changed manually in every month or season. Although generation efficiency of this type is lower than the automatic-tilting type, it was found to be more efficient, about 20%, than the fixed-angle type (Yoon, 2014).

(3) Automatic-tilting type

The automatic-tilting type is designed to find and track solar altitude and azimuth automatically according to pre-programmed algorithm. Since this type makes PV panels orthogonally receive the sun rays automatically based on the information from solar sensors, this type is highly efficient for generation than the other types (Yoon, 2014).

On the back of PV panels, rotating systems actuated by hydraulical power are installed as shown in Fig. 9.

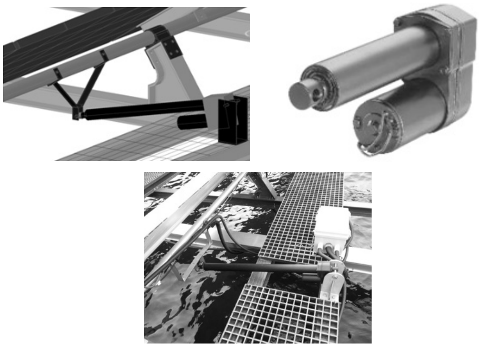


Fig. 9 Automatic-tilting Type PV Generation Strusture

2.3 Design of Mooring Structure

The mooring system is significantly important to maintain floating-structures, because the circumstances on the water surface such as water level and wave are persistently changing and directly affect to generation efficiency. Depending on shapes of structures and situations of installation site, the type of mooring system is determined by conducting the suitability analysis (Yoon, 2014).

For obtaining structural stability and constructability as well as maintaining constant tension of mooring cable independent from water level, the mooring system is designed as shown in Fig. 10.

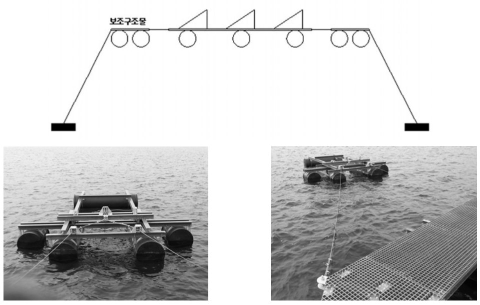


Fig. 10 Design of Mooring System

3. THE FINITE ELEMENT ANALYSIS

3.1 Modeling for the FEA

Since the floating type PV structures are constructed on the water surface, structural safety after completion of construction is crucial. Therefore, the finite element analysis (FEA) was conducted to investigate the safety on the floating circumstance using MIDAS CIVIL 2009 program. 3D-frame element; each node has 6 DOF, was used for FEA modeling and it is shown in Fig. 11.

The fixing-structures located out of the edge of the rotating-structures are considered as a separated structure from rotating-structure, just as a guide to rotation. Accordingly, modeling for analysis is conducted for rotating-structure only.

In the structural modeling it is assumed that loads on fixing-structure are independent from the rotating-structure located inside and connection on the edge is assumed to be hinge to prevent from arising the moments due to external forces. In addition, boundary conditions are assumed as elastic spring in which the spring constant is evaluated from the buoyance force of the buoy, and reactions are obtained from displacement applied.

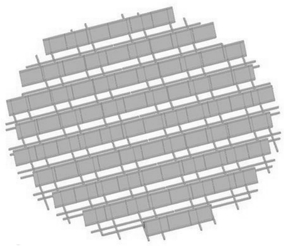


Fig. 11 FEA Modeling

Characteristics of members of the system are presented in Table 3 and the arrangements of members are shown in Fig. 12.

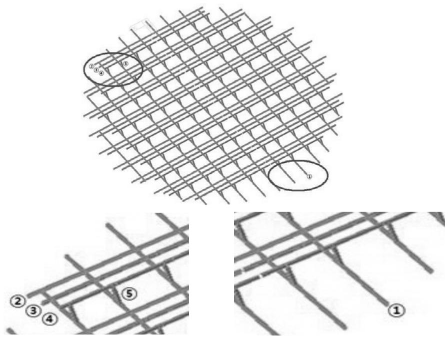


Fig. 12 Location of Member

To conduct the FEA, material properties given in Table 1 are used and self-weight of the rotating-structure including PV panels, footholds, and floating parts are applied. In addition, snow loads, wind loads with 50m/s, and the designed wind speeds are applied to structures for the FEA and they are given in Table 4, Table 5, and Table 6, respectively.

Table 3. Characteristics of Members for the FEA

Location	Member Type (Unit : mm)	Area (cm^2)
①	H-100×100×10×10	28.00
②	H-100×100×10×10	28.00
③	H-124×100×10×14 (Considering connection)	34.00
④	H-100×100×10×10	34.00
⑤	H-100×100×10×10 (SMC with Max. cross-section)	30.00

Location	Asy (cm^2)	Asz (cm^2)	Ixx (cm^4)	Iyy (cm^4)	Izz (cm^4)
①	16.67	10.00	9.67	449.33	167.33
②	16.67	10.00	9.67	449.33	167.33
③	20.00	12.40	16.21	825.72	200.83
④	20.00	12.00	11.67	811.33	288.83
⑤	16.67	12.00	10.33	690.00	167.50

To conduct the FEA, material properties given in Table 1 are used and self-weight of the rotating-structure including PV panels, footholds, and floating parts are applied. In addition, snow loads, wind loads with 50m/s, and the designed wind speeds are applied to structures for the FEA and they are given in Table 4, Table 5, and Table 6, respectively.

Table 4. Self-weight

Load	Magnitude
PV Module	220.73N/EA
Floating Object	392N/m
Foot Panel (Synthetic Lumber)	7.059N/m

Table 5. Details of Wind Load

Wind Velocity (m/s)	50
Roughness Coefficient	D
Gust-effect Factor	1.0
Importance Factor	1.10
Topographic Factor	1.30
Pressure Exposure Coefficient	1.13
Design Wind Velocity ($m/\sec$)	62.15

Table 6. Details of Snow Load

Snow Load (S_g)	0.5
Roof Snow Load Coefficient (C_b)	0.5
Exposure Coefficient (C_e)	0.8
Thermal Factor (C_t)	1.2
Importance Factor (I_s)	1.0
Slope Factor (C_s)	1.0
Snow Pressure (kN/m^2)	0.24

3.2 Results of the FE Analysis

From the results of the FEA presented in Table 7 and Fig. 13, near the center of the structure is the most critical in the entire structure and the flexural stresses are much closer to the allowable stress than the tensile stresses, the shear stresses, and the compression stresses. Consequently, design of structure is conducted by considering the flexural stress of the members.

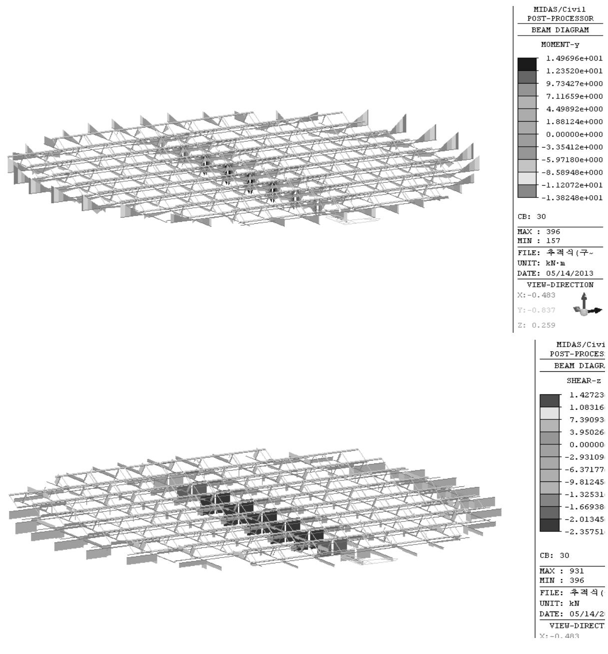


Fig. 13 Result of the FEA

Table 7. Result of the FEA

Me-mber	Stress (MPa)			
	Tension		Compression	
	Max. (σ_t)	Allowable (σ_{ta})	Max. (σ_c)	Allowable (σ_{ca})
①	19.94	231.76	17.10	154.50
②	5.55		7.05	
③	40.36		1.95	
④	7.15		22.66	
⑤	2.31	140.00	4.43	140.00

Me-mber	Stress (MPa)			
	Shear		Flexure	
	Max. (σ_s)	Allowable (σ_{sa})	Max. (σ_f)	Allowable (σ_{fa})
①	11.09	26.37	81.47	185.40
②	14.74		153.84	
③	22.47		122.00	
④	16.83		102.74	
⑤	8.00	80.00	130.04	140.00

4. INSTALLATION OF TRACKING-TYPE FLOATING PV GENERATION SYSTEM

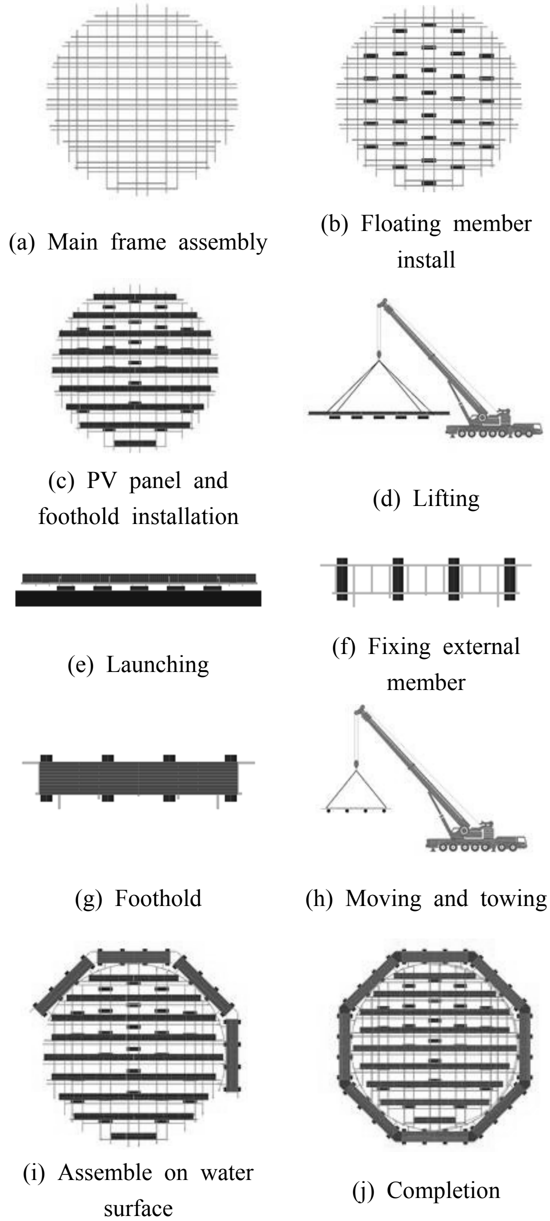
Since the tracking-type floating PV generation system is installed on the water surface, by considering the installation site, work procedure must be simplified. First of all, main structure and mooring structure which are manufactured in advance are assembled on the ground site, floating parts and PV panels are installed continuously in sequence.

After completion of work process in the ground site, assembled structure is lifted and floated on the water surface by crane. Floated structures are connected with boats and towed to the selected installation site. And then remained structures such as the footholds and the fixing-structures are assembled and towed in the same way as shown in Fig. 14.

In the installation site on the water surface, each structure is assembled to a complete single PV module (unit module) and then each generation module and control module are connected together.

Finally, depending on the type of modules, actuation parts such as hydraulic pump and rotation motor are installed to each module and all sorts of electronic devices such as solar sensor and control console are also mounted as well.

Completed tracking-type floating PV generation system in the Hap-Cheon Dam is presented in Fig. 15.



(a) Main frame assembly (b) Floating member install (c) PV panel and foothold installation (d) Lifting (e) Launching (f) Fixing external member (g) Foothold (h) Moving and towing (i) Assemble on water surface (j) Completion

Fig. 14 PV Module Installation Procedure

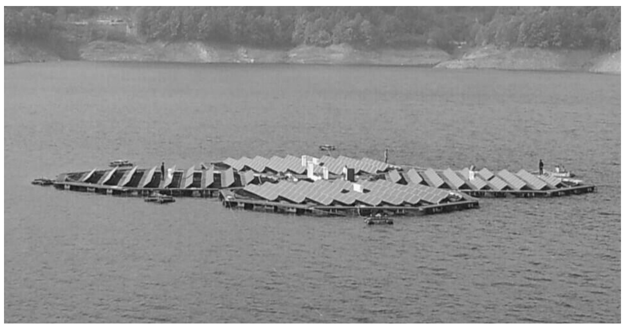


Fig. 15 Tracking-type Floating PV Generation System

5. STRAIN MEASUREMENT IN INSTALLED PV MODULE

Although the FEA can predict the load-displacement behaviors of structures, the results of the FEA may be different from the results of the actual behaviors due to the simplified conditions and assumptions. For this reason, strain measurements are conducted where the maximum stress occurs and the safety of structure is concerned.

Strain gages are installed at 10 points such as beams and vertical members located near the center, footholds, edge of the corner, and center as shown in Fig. 16.

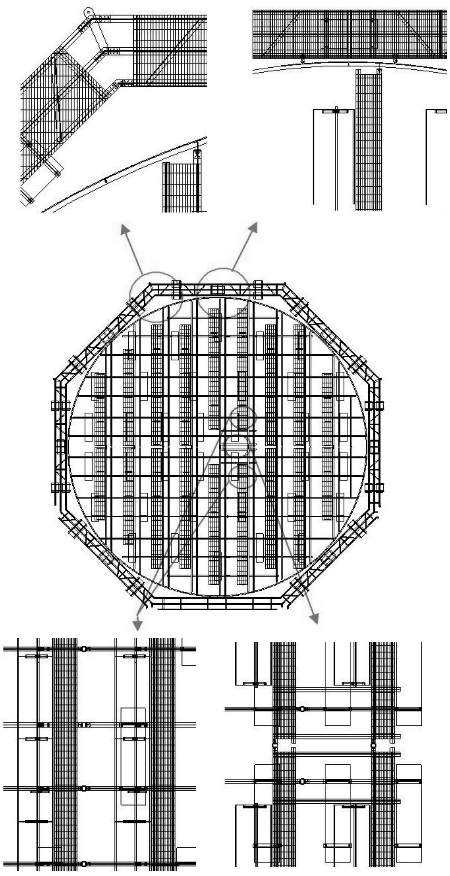
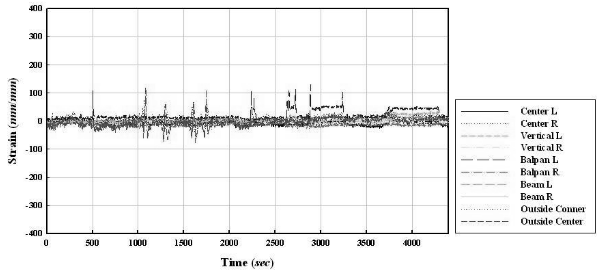


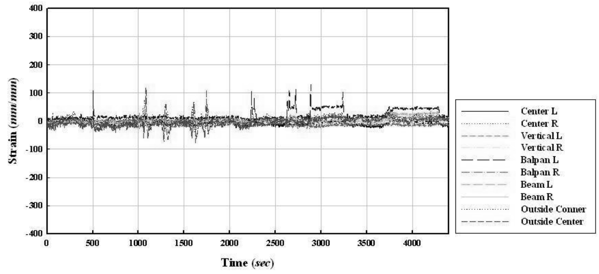
Fig. 16 Location of Strain Gage

Measurements are conducted for 3 days and measurement in each case is carried out more than 3200 seconds with 3 seconds interval.

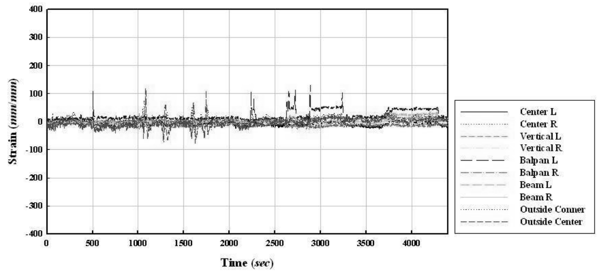
Results of measurements are presented in Fig. 17 and are summarized in Table 8.



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 17 Result of Strain Measurement

Table 8. Results of the Maximum and Minimum Strains

Location	Strain ($\times 10^{-6} mm/mm$)					
	Case 1		Case 2		Case 3	
	Max	Min	Max	Min	Max	Min
Center-L	119.4	-65.4	121.3	-4.7	17.1	-25.6
Center-R	51.2	-91.9	216.1	-115.6	6.6	-29.4
Vertical-L	21.8	-31.3	10.4	-31.3	25.6	-9.45
Vertical-R	12.3	-11.4	10.4	-19.9	0.0	-14.2
Foot-L	124.2	-43.6	121.3	-48.3	129.9	-15.2
Foot-R	110.0	-13.3	116.6	-10.4	0.0	-25.6
Beam-L	29.4	-22.7	37.9	-46.4	34.1	-19.0
Beam-R	53.1	-19.9	35.1	-24.6	13.3	-13.3
Out-Conner	70.1	-108.1	95.7	-162.1	76.8	-41.7
Out-Center	278.7	-173.5	784.8	-171.6	119.4	-71.2

Using the measurement results, the maximum and minimum stresses of structure for each case are obtained. By comparison with the allowable stress, the minimum safety factors of 6.9, which is highly sufficient, are confirmed as shown in Table 9.

Table 9. Comparison with Allowable Stress

Cases	Stress from Measurement (σ_M, MPa)		Allowable Stress (σ_A, MPa)	Safety Factor ($\lvert\sigma_M/\sigma_A\rvert$)	
	Max	Min		Max	Min
Case 1	9.54	−5.94	185.40	19.43	31.21
Case 2	26.86	−5.87		6.90	31.58
Case 3	4.45	−2.43		41.66	76.30

6. CONCLUSION

In this paper, we presented and discussed the results of investigations pertaining to the design, fabrication, and installation of tracking-type floating PV energy generation structure system. The materials for the system are pultruded glass fiber reinforced polymer plastic (PFRP) and sheet molding compound (SMC). Structure supporting PV panels is consisted of pultruded FRP (PFRP) and buoy for floating whole structure system including PV panels is made of urethane filled polyethylene (PE).

(1) Structural parts of the system are designed and checked for the safety according to the pre-standard published by the American Society of Civil Engineers (ASCE). It was found that, the system designed in this study, is generating PV energy under stable and safe conditions.

(2) The system developed is installed at the Hap-Cheon Dam and the structural safety in actual circumstance are evaluated by strain measurement of the points which are concerned about occurrence of maximum stress. Consequently, this structure has the highly sufficient safety factors in actual circumstance.

Although we designed, fabricated, and installed on the surface of water and it is working properly we may need further development to obtain more optimized structural system.

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