

# Research and Design of Fixed Photovoltaic Support Structure Based on SAP2000

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**Abstract.** In the solar photovoltaic power station project, PV support is one of the main structures, and fixed photovoltaic PV support is one of the most commonly used stents. For the the actual demand in a Japanese photovoltaic power, SAP2000 finite element analysis software is used in this paper, based on Japanese Industrial Standard (JIS C 8955-2011), describing the system of fixed photovoltaic support structure design and calculation method and process. The results show that: (1) according to the general requirements of 4 rows and 5 columns fixed photovoltaic support, the typical permanent load of the PV support is 4679.4 N, the wind load being 1.05 kN/m<sup>2</sup>, the snow load being 0.89 kN/m<sup>2</sup> and the seismic load is 5877.51 N; (2) by theoretical calculation of the two ends extended beam model, the beam span under the rail is determined 2200 mm; (3) by the way of using the single factor experiment, through the calculation and analysis of SAP2000, the three best supporting points of the support of the W stent are determined; (4) by comprehensive simulation, the optimal parameters for the rail, beam, support and bolt are 60× 60× 1.0, 60× 60× 1.0, 40× 50× 2.0, and M10 respectively.

## 1 Introduction

Solar energy as one of the new energy resources is most widely used currently. In recent years, with the popularization and application of solar photovoltaic support system, the design and development of structure of the photovoltaic support system have also become the focus of attention. At present, the photovoltaic support is mostly steel structure in the market, but the aluminum profile has the characteristics of light weight, beautiful appearance, corrosion resistance and other characteristics, which has attracted the attention of the market [1-4]. Compared with the automatic tracking support, the fixed photovoltaic support has smaller footprint, lower initial investment and less maintenance in the later stage of the support system; In structure, under the same environmental conditions, the stability of the fixed support structure is better than that of the tracking support; In the power generation capacity, the power generation of the tracking support is better than the fixed support, but it needs a longer investment recovery cycle[5-7]. The software SAP2000 has strong functions, such as model (2D, 3D model, etc.), editing function (adding and deleting units, copying and deleting, etc.), analysis function (time history analysis, dynamic analysis), load function (node load, rod load, surface load and temperature load), custom features, and design function etc.

Taking an engineering project in Japan as an example, the SAP2000 software was used in this paper to carry out the analysis and research on the bearing capacity of the fixed photovoltaic support under various load conditions, so as to provide a reference method for the structural design of the fixed photovoltaic support.

## 2 Simulation

### 2.1 The basic parameters of project

A project was located in Kaseda City Jinfeng town of Japan. The degree of the design angle of PV modules was 15, and the PV module specification was 1650mm×991mm×40mm. The single photovoltaic array unit was composed of 20 photovoltaic modules, which were arranged into 4 rows and 5 columns. According to the design requirements of power station, in the photovoltaic support design process, the array structure strength should meet the environmental requirements, such as the wind load 1.05 kN/m<sup>2</sup>, the snow load 0.89 kN/m<sup>2</sup>, and the basic parameters were shown in table 1.

### 2.2 Design of overall scheme

(1) Design of photovoltaic support structure

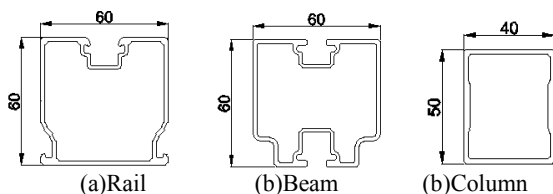
According to the 4 rows and 5 columns PV modules of the fixed photovoltaic support overall requirements, combined with the project development experience, the triple-layer composite of photovoltaic support were rail, beam, and column; The conventional screw pile was used in the foundation part; At the same time, the rail and beam length were determined which were 8390 mm and 4300 mm; There were 5 rails arranged on the upper and lower ends of the PV module; The beam was vertically arranged at the underside of the rail, and the number and span of the beam needed to design and optimize; The type of the pillar arranged below the beam was W, and the 3 contact points of the beam needed to design and optimize.

**Table 1.** Parameters of PV module and design requirements of PV support

Parameter type	Parameter values
Module size	1650 mm×991 mm×40 mm
Module weight	19 kg
Module surface area	1.63515m <sup>2</sup>
Mounting angle of PV support $\alpha$	15°
Module height from the ground	1000 mm

(2) Lightweight design of photovoltaic stent

The commonly used sections of rail, beam, and column were 60×60, 60×60, and 40×50, and various thickness specifications could be selected. The photovoltaic support section could be seen in figure 1. The overall scheme of photovoltaic support structure and the type of section of the main profile were determined, and reducing the amount of aluminum material of the photovoltaic support was the main goal of lightweight design, under the premise of ensuring the structural strength of the photovoltaic support. Using the method of layer by layer design and verification discussed the effects on bearing capacity of the rail and beam with different thickness sections, and provided a basis for the selection of reasonable economic profile.



**Figure 1.** Section of photovoltaic support profiles

**2.3 Method of simulation**

(1) According to the design guide on structures for photovoltaic array (Japanese Industrial Standard, JIS C 8955-2011), combined with the basic parameters of the project, the typical permanent load, wind load, snow load

and seismic load of the photovoltaic support were determined.

(2) According to the two ends of the beam theory, combined with the beam number of designs, the influences of different quantities and span of beam on rail performance were discussed, so as to make sure the number and span of beam.

(3) With the single factor experiment, using SAP2000 software discussed the different support layout effects on the beam performance, so as to make sure the best supporting point position of beam.

(4) When the overall structure scheme was determined, the SAP2000 software was used for further discussion of the effects of different section thickness on the performance of rail and beam. At the same time, the strength of column and bolt was checked, and it provided the basis for the lightweight photovoltaic support structure design.

**3 Analysis and discussion of results**

**3.1 Analysis and determination of PV stent load**

The load of photovoltaic stent consisted of two parts, the permanent load and live load respectively. The permanent load ( $G$ ) included the weight of photovoltaic module ( $G_1$ ), rail weight ( $G_2$ ), beam weight ( $G_3$ ). The live load included wind load ( $W$ ), snow load ( $S$ ), and seismic load ( $K$ ), and the load combination classification was shown in table 2 [8-11].

**Table 2.** Classification of load combinations

Load condition		Distinguishing	
		General area	Snowy area
Long-term	The usual	$G$	$G+0.7S$
Short-term	Snow	$G+S$	$G+S$
	Storm	$G+W$	$G+W$
			$G+0.35S+W$
Earthquake	$G+K$	$G+0.35S+K$	

The permanent load was mainly composed of the weight of PV module, rail and beam and the thickness of each was 2 mm. The total load was set as follow.

$$G=G_1+G_2+G_3 \tag{3-1}$$

Wind load  $W$  was related to wind force coefficient  $C_w$ , design speed pressure  $q_p$  and the area of modules  $A_w$ . In actual situation, the PV modules were divided into two cases: downwind load ( $W_+$ ) and upwind load ( $W_-$ ). By calculation, two kinds of wind load value could be gotten.

$$W_+=C_{w+} \times q_p \times A_w \tag{3-2}$$

$$W_-=C_{w-} \times (-q_p) \times A_w \tag{3-3}$$

Snow load was determined by the average unit load of snow  $P$ , vertical snow cover  $Z_s$ , snow area  $A_s$  and slope coefficient  $C_s$ . The snow load value was as follow .

$$S=C_s \times P \times Z_s \times A_s \quad (3-4)$$

This project belonged to the general area, so the calculated seismic load was as follow.

$$K=k_p \times G \quad (3-5)$$

In which,  $k_p$  was the design of horizontal seismic degree.

After finding out the permanent load, wind load, snow load and seismic load, the maximum load combination could be obtained according to the combination of the general areas in Table 2.

$$P_{max}=G+W=G+|W_+| \times \cos\alpha \quad (3-6)$$

Therefore, the uniformly distributed load on the rail was as follow.

$$q=P_{max}/((n-1) \times L) \quad (3-7)$$

Similarly, the maximum horizontal load combination was as follow.

$$P_x=|W_-| \times \sin\alpha \quad (3-8)$$

The maximum combination of load in vertical direction was as follow.

$$P_z=G+|W_+| \times \cos\alpha \quad (3-9)$$

Among them,  $N$  - rail number,  $L$  - rail length (mm).

In summary, according to the basic parameters provided by the project, combined with the above formula and the design guide on structures for photovoltaic array JIS C 8955-2011, the calculation results were shown in table 3.

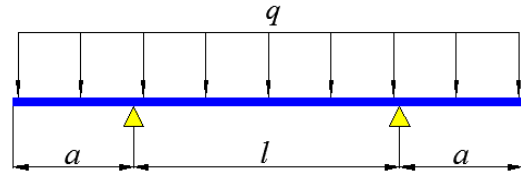
**Table 3.** Key parameters of the photovoltaic stent load

Name	Code	Parameter (N)
Permanent load	$G$	4679.4
Downwind load	$W_+$	30925.5
Upwind load	$W_-$	-37426
Snow load	$S$	27933.6
Earthquake load	$K$	5877.51
Maximum load combination combination	$P_{max}$	36244.8
Maximum load in horizontal direction	$P_x$	9686.5
Maximum load in vertical direction	$P_z$	35749.3

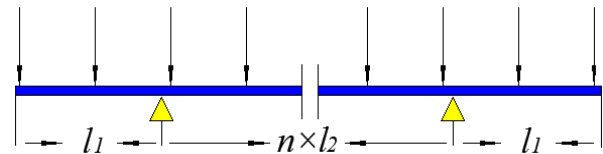
### 3.2 Optimization of beam span

The known PV module specification was  $1650mm \times 991mm \times 40mm$ , and the modules were arranged in 4 rows and 5 columns. Each module had a horizontal distance of 10 mm, and the rail end was 50 mm away from the edge of the module, so the rail length was  $5 \times 1650 + 50 \times 2 + 10 \times 4 = 8390$  mm. According to the two ends extended beam model of material mechanics (Figure

2 (a))[12], the PV support force was simplified into uniform load. The photovoltaic stent could be simplified into a multi fulcrum supporting beam whose ends were extended (Figure 2 (b)). The rail was divided into 2 sections  $l_1$  and  $N$  of  $l_2$ , and the model was symmetrical distribution.



(a) The two ends extended beam model of material mechanics



(b)Simplified model of rail with multi fulcrum supporting

**Figure 2.** Stress model

According to the maximum deflection formula of static perturbation based on the two ends extended beam model[13], if the deformation of the two ends extended beam model was minimum, it could be seen that the relationship between the parameters  $a$  and  $l$  could be obtained just only when the  $W_{max}$  was zero, here  $l \approx 2.19a$ .

$$W_{max} = \frac{q l^4}{384 E I} \left( 5 - 24 \frac{a^2}{l^2} \right) \quad (3-10)$$

Based on the above relationship, when deformation of  $l_1$  was equal to  $l_2$ , the stent deformation tended to be coordinated, and it would not appear a part of the deformation which was too large to avoid increasing the section size or thickness, saving materials and reducing cost. According to the relationship between  $a$  and  $l$  when the deformation was minimum of the two ends of the beam model, the specific parameters of the number of different span beam had been discussed, as shown in table 4.

**Table 4.** The number of the corresponding parameters of different span beam

Number of oblique beam	$l_1$ (mm)	$l_2$ (mm)
2	2002	4385
3	1315	2880
4	979	2144
5	780	1708
6	648	1419

When the number of beam was greater than 4, the span of rail was too small and wasted materials; when the beam number was 3, the length of cantilever was too

large, close to a single block's length; when the number of beam was 1, the span of rail and cantilever were too large. In summary, the number of beam was 4, and the rail span and cantilever were 2200 mm, 895 mm, as shown in figure 3.

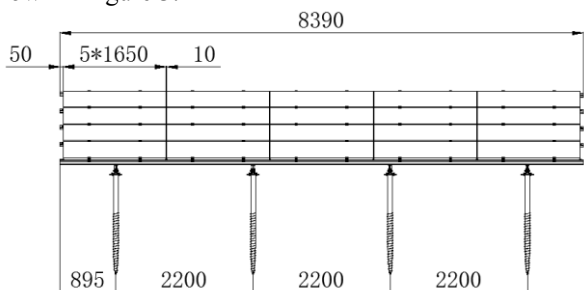


Figure 3. Arrangement of photovoltaic stents

### 3.3 Optimization of the position of connection point between beam and column

The known PV module specification was 1650mm×991mm×40mm, and the modules were arranged in 4 rows and 5 columns. Each module was longitudinally provided with a pressing block with a 23.5 mm distance and with a 50 mm from the end of the beam module edge, so the beam length was  $4 \times 991 + 100 \times 2 + 23.5 \times 3 = 4234.5$  mm. The length was 4300 mm after rounded. The support spacing between beam and pillar was determined by single factor experimental method. With six sets of data, the distance between the support point and the endpoint was 100 mm, 200 mm, 300 mm, 400 mm, 500 mm, 600 mm respectively, using SAP2000 software for simulation, as shown in Figure 4. The structure was symmetrical, so it just needed to monitor two points of contact deformation, and namely the monitoring points were  $P_1$  and  $P_2$ . And the two monitoring characteristic points were end point  $P_3$  and span midpoint  $P_4$  of beam respectively.

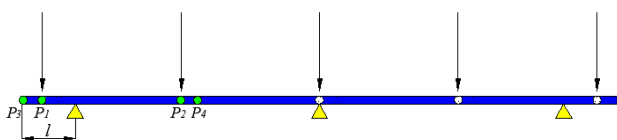


Figure 4. Analysis model of beam

In figure 4, the thickness of beam of the model was 2 mm and the concentrated load of each point was 500 N. According to the data obtained by SAP2000, statistical analysis was carried out. As shown in fig.5, the deformation tendency of the monitoring point was different when the supporting point spacing  $l$  was different. It was shown from the graph that the global average deformation was minimum at  $l = 400$  mm, and the intersection point of deformation track of all monitoring points was between 400-450 mm, so the cantilever support position took 400 mm.

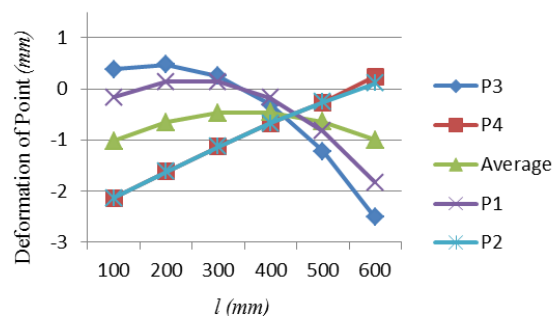


Figure 5. Deformation of monitoring points

### 3.4 Lightweight design of guide rail

On the one hand, the rail should meet the flexibility of the photovoltaic stent specifications ( $l/100$ ,  $l$ -the length of rail's cantilever, 895 mm.), on the other hand, the strength of materials also should meet the requirements. And as known, the yield limit of aluminum profile  $\sigma_s$  was 240 MPa and the safety factor was 1.5, so the  $[\sigma]$  was as follow.

$$[\sigma] = \sigma_s / n = 160 \text{ MPa} \quad (3-11)$$

Among them,  $N$  - rail number,  $L$  - rail length (mm).

According to the engineering experience and the specification of the factory aluminum production, the maximum thickness of the aluminum sections was chosen to carry out the simulation. When the thickness of rail section was 2 mm, the deformation was 4.074 mm and the maximum stress was 44.697 MPa which met the requirements, and there was a large amount of surplus. Combined with the specific profiles of the company produced section, the calculation and analysis of deformation and the maximum stress value of different section thickness were carried out, then the thickness was optimized. The analysis results were shown in table 5.

Table 5. Statistics of deformation of rail with different thickness

Thickness	Deformation (mm)	Stress (Mpa)
1.0mm	5.801	62.595
1.2mm	5.317	57.63
1.4mm	4.93	53.655
1.6mm	4.602	50.244
1.8mm	4.320	47.285
2.0mm	4.074	44.697

From the change rule in table 5, the rail of different section thickness could meet the requirements of the company. From the view of lightweight and material saving, selecting the 1.0 mm thickness of rail was good. The maximum deformation was 5.801 mm < 895/100,

and the stress value was  $62.595 \text{ MPa} < 160 \text{ MPa}$ , which met the requirements.

### 3.5 The lightweight design of beam

Similarly, the beam also needed to meet the specification of the photovoltaic stents allowable deformation value ( $l/200, l = 1750$ ) and material strength ( $[\sigma] = 160 \text{ MPa}$ ) requirements like rail.

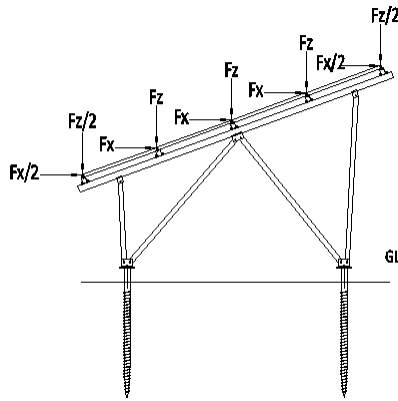
According to the results of section 3.1, and the number of the beam in section 3.2 was 4, with the module horizontally placed, the force on the supporting edge of the rail was half of the middle point. So, it would get the rail and beam contact stress formula (3-13) and (3-14).

$$F_x = P_x / ((n - 1) \times N) = 605.4 \text{ N} \quad (3-13)$$

$$F_z = P_z / ((n - 1) \times N) = 2234.3 \text{ N} \quad (3-14)$$

Among them,  $n$ —the number of rail,  $N$ —the number of beam.

Figure 6 was the force diagram of the beam structure of photovoltaic support.



**Figure 6.** Force diagram of structure

Same as rail, when the thickness of rail section was  $2 \text{ mm}$ , the deformation was  $4.688 \text{ mm}$  and the maximum stress was  $67.287 \text{ MPa}$  which met the requirements, and there was a large amount of surplus. Combined with the production of company with specific section, the calculation and analysis of deformation and the maximum stress value of different section thickness were carried out, then the thickness was optimized. The analysis results were shown in table 6.

From the change rule in table 6, the rail of different section thickness could meet the requirement of the company. From the view of lightweight and material saving, selecting the  $1.0 \text{ mm}$  thickness of rail was good. The maximum deformation was  $6.822 \text{ mm} < 1750/200$ , and the stress value was  $98.416 \text{ MPa} < 160 \text{ MPa}$ , which met the requirements.

### 3.6 Strength inspection of column

Rail and beam specifications had been determined, and the column specification was  $40 \times 50 \times 2$ . In the structural model, each column was equivalent to two-force members, and only the axial force was required and checked. According to the force analysis results of the

known model in SAP2000, the axial force of each column was shown in table 7.

**Table 6.** Statistics of beam deformation with different thickness

Thickness	Deformation (mm)	Stress (Mpa)
1.0mm	6.822	98.416
1.2mm	6.247	89.976
1.4mm	5.815	83.886
1.6mm	5.455	78.781
1.8mm	4.941	70.982
2.0mm	4.688	67.287

**Table 7.** Statistics of column axial force

Name	Axial force (N)
Front column 1	2449.63
Front column 2	1864.82
Rear column 1	4380.51
Rear column 2	2650.52

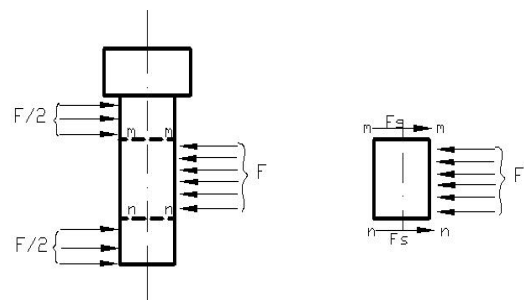
According to table 7, the maximum axial force of column was  $4380.51 \text{ N}$ , and the sectional area of column was  $A = 320.46 \text{ mm}^2$ , so the maximum stress of the column was as follow [13,14].

$$\sigma = 4380.51 / A = 4380.51 / 320.46 \text{ Mpa} = 13.67 \text{ Mpa} < [\sigma] \quad (3-15)$$

Therefore, the strength requirements were met.

### 3.7 Bolt strength check

In the ground fixed support system, the connecting bolts bore the load in the form of shear between column and pile, pillar and beam, pile and beam. The maximum shear force was required to be checked, and it could be seen from table 6 that the value was  $4380.51 \text{ N}$ . The model adopted M10 bolt, whose material was Q235 ordinary carbon structural steel, and the yield limit was  $215 \text{ MPa}$ .



**Figure 7.** Shear model of bolt

The shear model of bolt was shown in figure 7, and F was the shear force of the bolt. The strength condition was as follow [15,16].

$$\frac{4F}{\pi d^2 m} \leq [\tau] \quad (3-16)$$

In which, d was diameter of shear surface of bolt; m was number of bolt shear planes;  $[\tau]$  was allowable shear stress of bolt, and the safety factor was 2.5. The shear stress on a single section was as follow.

$$\frac{4F}{\pi d^2 m} = \frac{4 \times 4380.51}{\pi \times (10 \times 10^{-3})^2 \times 4} = 13.94 \text{ Mpa} < [\tau] \quad (3-17)$$

Therefore, the strength requirements were met.

## 4 Conclusion

In this paper, the load calculation, structural design and optimization, and the strength calculation of the connection parts of the fixed photovoltaic support system are carried out through the actual project case design, which are as follows:

(1) According to the general requirements of the 4 rows and 5 columns fixed photovoltaic stent, the length of the rail is 8390 mm. The initial support profiles thickness is 2 mm, and the typical permanent load of the photovoltaic support is 4679.4N, the wind load 1.05 kN/m<sup>2</sup>, the snow load 0.89 kN/m<sup>2</sup> and the seismic load 5877.51N.

(2) By the two ends of the beam model of theoretical calculation, comparing the span of the rail and the length of the cantilever when the number of the beam is different, the beam number and rail span are ultimately determined 4 and 2200 mm.

(3) By using the single factor experiment method, through the calculation and analysis of SAP2000, the three best supporting positions of the W strut are determined.

(4) By the simulation, and the photovoltaic support design requirements, the optimal parameters are for the rail 60×60×1.0, beam 60×60×1.0, column 40×50×2, bolt M10.

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