Taiwan is located in a subtropical region with common climates that include strong northeast winter monsoon, hot summer, and frequent typhoons and heavy rains. Furthermore, with recent strong global climate changes, strong winds and heavy rainstorms have become a continuous challenge faced by the region’s crop cultivation.

The protected cultivation will provide a stable environment with wind-proof, rain-proof, pest-proof, birds-proof function which can secure the yields and improve the quality of produce.
Preface

- This study introduces the design principle, method and tools of greenhouse resistance to environmental loads.
- The design of greenhouse must consider the required mode of operation of crops, demanded space, operating line, and temperature and humidity control to complete the overall design and planning of the greenhouse.

<table>
<thead>
<tr>
<th>Greenhouse engineering</th>
<th>cultivation</th>
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</thead>
<tbody>
<tr>
<td>Ventilation (Open - roof)</td>
<td>Heat – resist variety</td>
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<tr>
<td>Structure</td>
<td>Polliation of flower</td>
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<tr>
<td>Plastic film</td>
<td>Fertilization managements</td>
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<tr>
<td>Root temperature control</td>
<td>IPM strategy</td>
</tr>
</tbody>
</table>

Basic consideration

- The usage of greenhouse in crop cultivation is to build a closed and controlled environment for planting high quality, year round or off-season crop. In the tropics and sub-tropics, the challenges of greenhouse cultivation are:
- How to reduce the temperature: in summer time, the internal temperature exceeds 40℃, crops cannot grow and farmers cannot work in this situation.
- How to reduce the humidity: induces the severe insect and pathogen problem and also decrease the evapotranspiration of crops.
- How to design a low-cost greenhouse

Cases of destruction due to typhoon

- After the Meranti and Megi typhoon struck Taiwan last year, we found many pipe-framed greenhouses with roughly the same structure design and construction methods, have poor connecting parts and reinforced design.
- The beams and tubes were severely deformed under strong lateral wind forces.

For the greenhouses with foundations and H beams or square tubes as pillars are stronger facilities.
- The wrong direction of the H beams (flange and web) or using a weak steel base plate or poor welding can cause the pillars bent over. The cracked concrete foundations or the heavily rusted reinforced bars were the cause of the structure damage.

Development and approach

1. Many scholars in Europe have conducted greenhouse design research, and with the European Standardization Technical Committee developed greenhouse structure and design standards.
2. Japan Horticultural Association published the safety structural standards of horticultural facilities, the wind pressures and seismic forces of the facilities are calculated in accordance to the Japanese Building Standards.

Taiwan formulated 6+3 greenhouse standard designs
The principles of Greenhouse design

1. The main purpose of the greenhouse function is based on the cultivation of crops. The environmental loads for the greenhouse will need to be carefully considered the design and analysis to meet the safety, cost and life considerations.
2. The greenhouse faced on structural load include its own gravity loads and the natural of the environmental loads. These load patterns also include the intensity loads, variable loads, shock loads and repeated loads.

Considerations for Greenhouse design

1. Geography:
The position, direction, terrain, geomorphology of greenhouse will affect the wind field, resulting in local strong wind and high wind pressures on the greenhouse.

2. Climate:
Greenhouse wind tolerance levels need to enhance for the high probability of Typhoon pathway regions. The drainage design of the greenhouse for rainfall should consider the displacement and structural strength, especially for multi-span greenhouse.

3. Structural:
Greenhouse material structure and the based design of the strength need to consider the deformation, stress bearing, bending strength, and other comprehensive considerations. The connectors play a role for accurate grasp and implementation.

4. Corrosion resistance:
The important work for greenhouse material surface treatment for the anti-corrosion treatment includes chemical, physical, electrochemical corrosion which will cause structural materials corrosion, so that structural strength weakened and cannot sustain large wind pressures.

Greenhouse Intensification and Lightweight Design

1. High strength design for materials:
Improve the performance of the material can improve the structural optimization of the greenhouse. The material of alloy to strengthen, heat treatment of grain refinement, and the application of plastic deformation of the hardening, which can promote the structure of the material to strengthen and lightweight.

strength increase 30%, cost-down 15%,
Greenhouse Intensification and Lightweight Design

2. Optimal design of high coefficient material profile:
The structural optimization of the structural material is a new advantage material design that can be improved without changing the quality of material.

3. Design of high corrosion resistance material:
Corrosion treatment of material structure is the key to improve the life expectancy.

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Beaufort Wind Force Scale

<table>
<thead>
<tr>
<th>Beaufort No</th>
<th>Description</th>
<th>Wind speed (m/s)</th>
<th>Beaufort No</th>
<th>Description</th>
<th>Wind speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calm</td>
<td>0.0 - 0.2</td>
<td>10</td>
<td>Storm</td>
<td>24.5 - 28.4</td>
</tr>
<tr>
<td>2</td>
<td>Light air</td>
<td>0.3 - 1.5</td>
<td>11</td>
<td>Violent storm</td>
<td>28.5 - 32.6</td>
</tr>
<tr>
<td>3</td>
<td>Light breeze</td>
<td>1.6 - 3.3</td>
<td>12</td>
<td>Hurricane</td>
<td>32.7 - 36.9</td>
</tr>
<tr>
<td>4</td>
<td>Gentle breeze</td>
<td>3.4 - 5.4</td>
<td>13</td>
<td>Storm</td>
<td>37.0 - 41.4</td>
</tr>
<tr>
<td>5</td>
<td>Moderate breeze</td>
<td>5.5 - 7.9</td>
<td>14</td>
<td>Hurricane</td>
<td>41.5 - 46.1</td>
</tr>
<tr>
<td>6</td>
<td>Fresh breeze</td>
<td>8.0 - 10.7</td>
<td>15</td>
<td>Storm</td>
<td>46.2 - 50.9</td>
</tr>
<tr>
<td>7</td>
<td>Strong breeze</td>
<td>10.8 - 13.8</td>
<td>16</td>
<td>Strong storm</td>
<td>51.0 - 56.0</td>
</tr>
<tr>
<td>8</td>
<td>Near gale</td>
<td>13.9 - 17.1</td>
<td>17</td>
<td>Gale</td>
<td>56.1 - 61.2</td>
</tr>
<tr>
<td>9</td>
<td>Gale</td>
<td>17.2 - 20.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Greenhouse reinforcement design

1. Strengthening of structural combination:
To improve the greenhouse reliability and service life expectancy is to use the scientific design and analysis methods on greenhouse.

   a. The selection of appropriate component material
   b. The correct link and construction methods.
   c. The connector with combination of structural strength and vibration resistance.

The above items can make the greenhouse structural strength to withstand wind pressure of Beaufort no. 11. (28.5 – 32.6 m/s)

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Greenhouse reinforcement design

2. Strengthening of Internal and external:
The existing and future greenhouse construction should be designed to strengthen the anti-typhoon, increase the internal and external strengthening structures, strengthen the beam of the dome structures, and increase the support pillars in the outside can enhance the greenhouse withstand wind pressures of Beaufort no. from 11 to 12. (~36.9 m/s)

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Windbreak net test in the field

3. Strengthening the windbreak:
The greenhouse located at extremely high risk of typhoon pathway regions, should increase the greenhouse wall or windbreak net strengthening structure can enhance the greenhouse withstand wind pressures of Beaufort no. 12 to 13.
Methods of analysis for greenhouse structure

General engineering analysis

1. The probability analysis for the typhoon pathway at the greenhouse area.
2. Conducted the calculation and analysis of the wind pressures distribution on the side and front of the greenhouse.

Analysis of the wind pressures on the front of the greenhouse

3. Conducted the computer-aided engineering analysis of the increase level of the greenhouse structure.
4. Analysis of structural stress, strain diagram, and safety factor of each components.
5. Conducted the enhanced design with low safety factor and lightweight design for high safety factor components.

Computer-aided engineering analysis of the structural

6. Conducted the computer-aided engineering analysis of the structure of the wind by level up one level.
7. Begin enhance design of the strengthen of the internal strengthening and external strengthening after internal structure has been raised.
8. Level up one level of wind magnitude in order to conduct of the computer-aided engineering analysis of the enhance design of the greenhouse structure.
9. After the internal strengthening and external strengthening design is completed, and then level up a level of wind magnitude for engineering analysis.
10. Control of the windbreak strengthening design for the windbreak density in order to conduct a level up magnitude of anti-typhoon strengthening design.

Design flow chart of anti-typhoon greenhouse

CAE structure simulation used in Greenhouse anti-typhoon design
Computational Fluid Dynamic (CFD) models can be used to simulate the internal and external greenhouse flow field. The simulation of the external flow field aims at the wind pressure of strong wind on the greenhouse walls. The wall of the greenhouse is influenced by the external wind pressure and using one-way fluid-coupled interface FSI (fluid structure interaction) to calculate the pressure exerted on each wall surface and transforms all wall surface pressure into the pressure on each pillar and beam. Then we can calculate the stress, strain and deformation on the structure to examine and optimize the design.

### Geometry > Mesh > Setup > Solution > Results

- The windward side, the greatest pressure
- Roof, high airflow pressure is low or negative
- Leeward side, because the vortex produces negative pressure

#### Top view above the ground 1.8m
- The momentum from the wind is converted to pressure
- Greenhouse wall withstand the wind pressure
- Negative pressure is caused by air separation

### Total Deformation : 9 cm

Greenhouse structure deformed because of the wind pressure against the wall of GH. If the deformation is too large, the structure collapses. In this case, the maximum amount of deformation is at the windward roof (Deformation size enlarged 6.5 times for illustration).
Numerical simulation and wind tunnel experiment

Length 30 m, Width 3.0 m, Height 2.1 m
Maximum wind speed 20 m/s

Wind Tunnel Experiment

半圓形屋頂溫室之縮尺模型，Scale ratio: 1:20

Schematic Diagram of the Experimental Setup

Numerical Simulation of External and Internal Wind by CFD
Comparison of Wall Pressure on the Greenhouse

Comparison of Roof Pressure on the Greenhouse

Comparison of Velocity inside the Greenhouse

Pipe-Framed Greenhouse under Wind Load

Wind speed 33 m/s

Well structured

Bad structured

Structure vibration

Structure collapse

Conclusion

1. The existing problems of greenhouse cultivation under the extreme climate pattern in current situation need to be solved. We can work together to integrate the greenhouse engineering and cultivation methods to design/setup the greenhouse commercialized production system.

2. Greenhouse engineering include enhancing the structure, selected cladding material, root temperature control, and to increase the ventilation rate of greenhouse, and cultivation methods include breeding the heat resist varieties, fertilization managements and IPM strategy.

3. In the greenhouse structural materials, put forward the three technologies which are material strengthening, shape optimization, high corrosion treatment, have estimated improved structure of the structural strength more than 30%, cost-savings of more than 15%, and high corrosion resistance and life expectancy of more than 50%. 

2017/9/29
Conclusion

4. It also proposed the internal strengthening, external strengthening and wind break strengthening of the anti-typhoon strain model of the greenhouse built on the high cost efficiency.

5. In addition, CFD simulation validated by wind tunnel experiment and FSI (fluid-structure interaction) numerical simulation methods can be used to enhance the design efficiency and quality.

Design of Greenhouses for the Tropics and Sub-tropics

Thank you for your attention!