EXPERIMENTAL STUDY ON SEISMIC AND POWER GENERATION PERFORMANCE OF THE SHEAR WALL INTEGRATED WITH PHOTOVOLTAIC BY FASTENING-GROOVE CONNECTORS

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ABSTRACT

Buildings integrated with photovoltaic are now widely applied in high-rise buildings. And the high-rise buildings attached with photovoltaic on facades have great engineering potential because there are huge façade for application of photovoltaic module to transit solar energy to electronic power. But the current investigation of high-rise buildings with photovoltaic facade indicates that the seismic safety is seldom studied on both simulation and experiment. The seismic performance of the new applied form is still remained vague. This research is mainly aimed on the seismic performance of the high-rise buildings with photovoltaic attached on the facades. Based on the research aim, a kind of reinforced concrete shear wall integrated with photovoltaic module is proposed. The fastening-groove connector of the photovoltaic and concrete shear walls was designed in this research. To investigate the seismic performance, the low cyclic reversed test of the reinforced concrete shear wall attached with photovoltaic on facades by fastening-groove connectors was conducted. The construction procedure was simulated during the experiment, and the deformation capacity and the lateral bearing capacity are tested. At the same time, the power generation performance of the PV model was monitored during the whole test. Three main results are achieved through the experiment: (1) The fastening-groove connector provides reliable drift capacity for the compatibility of the PV module to the shear wall during the whole cyclic test; (2) the power generation capacity is stable during the seismic simulation test; (3) considering the redundant drift capacity and the slant bolt, more optimal connectors should be designed based on current connection method. On the other hand, convenience of installation should also be considered.

Keywords: PV panel, building integrated photovoltaic (BIPV), low cyclic loading test, electronic generation capacity

1. INTRODUCTION

City development promotes lots of high-rise buildings become larger and higher, especially in the east and south of China. The electronic consumption of high-rise buildings causes heavy pressure to big cities. Energy consumption of buildings is about 30% of worldwide total energy consumption and is still rising (Zhao, 2001). The proportion in Hong Kong of China is higher and account for 50% (Yang et al., 2006, 2009). Solar energy is a kind of renewable energy sources. Compared to traditional fossil energy which will be used up in several decades, solar energy is clear and unlimited (China Research Network, 2014). Building with solar photovoltaic panel is a newly-developing architectural form which can generate electricity from solar energy. Due to this situation, a series of research programs are launched interiorly and overseas, including “Million Photovoltaic Rooftop Project” in America, “Hundred Thousand Solar Roofs Project” in German. Shanghai in China also launched “Hundred Thousand Solar Roofs Project” (Sina Network, 2007). BIPV has become a significant way...
Actually, the photovoltaic system applied on building facades has appeared in engineering and research. Hong Kong PolyU has been constructing BIPV since 90s, but efficiency of BIPV increases by only 10% (Yang et al, 2006). In recent years many BIPV are constructed worldwide, e.g. Baoding Jinjiang International Hotel and Zhujiang New Town in China (Lu et al, 2017), Brundtland Center in Denmark (DeoPrasad, 2006) etc. Hongxing Yang and Jingqin Peng of Hong Kong PolyU have conducted study on thermal performance of a photovoltaic wall mounted on a multi-layer facade in Hong Kong (Peng et al, 2013). Lau, G.E. (2011) established a numerical model and carried out experiments to analyze the temperature effect of BIPV in natural convection. T.T. Chow et al. (2009) studied the energy consumption of BIPV.

However, researches carried out at home and abroad are less concerned with the safety performance of BIPV. Particularly there is few research on failure mode, deformation performance and synergistic performance of photovoltaic panels, when they are largely used in high-rise or super high-rise buildings. Researches on BIPV only stay on energy conversion efficiency and are less concerned with their seismic performance. The photovoltaic components of the high-rise or super high-rise buildings may become potential safety hazard and induce secondary disaster in the earthquake (Zhang, 2014). In China’s “Applicable Technical Specification of Civil Buildings with Solar Photovoltaic System” there are some rules for design of photovoltaic system including structural measures, installation, routine maintenance and replacement of PV components and it stipulates that the designers should consider earthquake effect in earthquake areas. But safety of connection between shear wall structure and photovoltaic panels need experimental verification. In this study, a shear wall integrated with photovoltaic by fastening-groove connectors and synergetic performance of photovoltaic-connector-shear wall are tested and analyzed.

2 EXPERIENMENT

At present, photovoltaic components are mostly installed on the roof but rarely on the building façade. This study mainly focus on application of PV panels on facades of high-rise buildings. Typically, a shear wall is chosen as the main structure. A kind of fastening-groove connector which is used to connecting photovoltaic panel and shear walls is manufactured referring to traditional connections between photovoltaic panels and buildings. The quasi-static test is done based on the preliminary calculation in order to examine deformation, failure mode and synergetic performance of photovoltaic panels, connectors and shear walls. In general, the performance of the structure can be tested through structural dynamic tests and static tests. As a dynamic test of overall structure is very expensive and its scale effect influence a lot, typical components are manufactured for low cycle test. Anti-seismic performance of shear wall, reliability of connections and seismic effect on power generation performance of photovoltaic panels are studied in this research.

2.1 Design of Specimen

The main structure is traditional reinforced concrete shear wall. Due to limitation of experimental conditions, section of shear wall is designed as 1000mm×2000mm×125mm, aspect ratio is 2.0, and concrete intensity grade is C40, length of edge constraint area is 200mm, intensity grade of reinforcing steel bar is HPB300 and HRB335, top of shear wall is free and the reinforcement of shear wall is shown in Fig. 1 and 2. Embedded parts are put in the four feet of the shear wall according to “Code for Design of Reinforced Concrete Structure”(GB50010-2010) and “Code for Design of Steel Structure”(GB50017-2003). Embedded parts are connected to photovoltaic components through photovoltaic connectors.

2.2 Design of Connectors

China’s “Civil Construction Solar Photovoltaic System Application Technical Specifications” provides: connection and anchoring between photovoltaic panels and main structure must be tight and reliable. The carrying capacity of main structure must be verified through calculations or practicality
experiments. At the same time, it must be able to transmit force from photovoltaic panels and have residual capability to prevent accidental damage. The types of connections between photovoltaic components and structural facades include: direct connection between embedded parts and bolts (Fig.3(a)); subframe compact block connection (Fig.3(b)). Subframe compact block connections are always used on roof while the direct connections are always used on structural façades. Based on those connections mentioned above and considering the convenience of installation, a shear wall integrated with photovoltaic by fastening-groove connectors is manufactured. The structure and size of fastening-groove connectors are shown in Fig.4 and the size and layout of embedded parts are shown in Fig.3 and Fig.4. Stress of all components is within their material elastic range through checking gravity and static wind load. Capsizing, falling and large deformation of photovoltaic components can be prevented by fastening and groove, which helps photovoltaic components conveniently installed on site. Besides it allows the relative deformation of photovoltaic panels and main structure and prevents uneven stress on connection points of components. The upper and lower fastening is made of hard aluminum and groove is made of stainless steel.

Fig.1 Schematic diagram of the reinforcement of RC shear wall with PV panel (unit: mm)

Fig.2 Layout of the embedded parts (unit: mm)

(a) direct connection

(b) compact block connection

Fig.3 connection between photovoltaic panels and structural facades

Fig.4 Schematic diagram of the connection
2.3 Mechanical Properties of Material

According to the concrete material experimental method [14], the designed strength of concrete of shear wall is C40; average elastic modulus is $3.38 \times 10^4 \text{ N/mm}^2$; prismatic compressive strength is $28.3 \text{ N/mm}^2$; compressive strength is $38.6 \text{ N/mm}^2$; intensity grade of embedded anchor plate is Q235; grade of welded steel is B10. The size of embedded parts are shown in Fig.4 and the average values of mechanical properties of steel bars and steel plates which are measured by ourselves are shown in Tab.1 [15]; the mechanical properties of the rubber block are tested according to "Standard Test Method for Compressive Deformation at High Temperatures and Low Temperatures of Vulcanized Rubber or Thermoplastic Rubber". HS65 natural rubber block with a geometric size of $35\text{mm} \times 50\text{mm} \times 50\text{mm}$ is chosen and its stiffness, deformation and damage are tested. The test process is: firstly the rubber surface was coated with lubricating oil, then 6mm steel plates were put on the top and bottom of rubber, finally axial force was exerted on the rubber plate through the steel plate. Devices like extensometer which can measure the deformation are put between the two steel plates or vertically 50mm over rubber block to record force-displacement curve. Especially the measured values and average values of force and deformation are recorded when the amount of deformation is 10%, 20%, 25% and 50%, which is shown in Tab.2.

<table>
<thead>
<tr>
<th>Kind of steel</th>
<th>$E_Y (\text{N/mm}^2)$</th>
<th>$f_{y} (\text{N/mm}^2)$</th>
<th>$f_{c} (\text{N/mm}^2)$</th>
<th>$f_{m} (\text{N/mm}^2)$</th>
<th>$\varepsilon_1 (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6</td>
<td>200442.95</td>
<td>333.56</td>
<td>451.95</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>B10</td>
<td>149516.04</td>
<td>477.94</td>
<td>569.54</td>
<td>20.5</td>
<td></td>
</tr>
<tr>
<td>Steel plate</td>
<td>181469.48</td>
<td>425.53</td>
<td>440.62</td>
<td>24.9</td>
<td></td>
</tr>
</tbody>
</table>

2.4 Experimental Facilities and Loading Process

Loading device which conducts low-cycle repeated test on shear wall specimen with photovoltaic panel is the same as that in the document [17]. One end of horizontal actuator is fixed to reaction wall, and another end is connected to the load beam through a steel plate. In addition, a horizontal limit device is added to out of plane of the top beam to ensure that only in-plane displacement of the test piece occurs and the out-of-plane buckling failure is prevented during loading. According to "Code of Construction Seismic Test Method", a displacement load control method is used in loading procedure. The initial lateral displacement of specimen is 1mm. Before yielding the displacement is increased by 1mm, and loading procedure circulates once at every step. After yielding the displacement of each specimen is increased by 2mm, and the specimen is reciprocally loaded thrice at every step. Loading process is shown in Fig. 5. The yield displacement is determinate based on the inflection point of force-displacement curve of the shear wall. The loading is ended when one of the following situations is first reached: (1) the load drops to 85% of the maximum load; (2) the main reinforcement at the corner of the wall is snapped; and (3) the inter-story drift angle of the floor exceeds 4%.

2.5 Arrangement of Testing Points

Strain Gauge Arrangement: the strain gauge at the bottom of the shear wall is used to measure the strain of the bottom of the shear wall. Two columns of strain gauges along the height direction are used to monitor the development of the plastic zone of the shear wall and the rest are used to measure...
Displacement Transducer Arrangement: in order to study the deformation of photovoltaic panels and connectors, horizontal displacement transducers are put at four corners of photovoltaic panel and connectors respectively. In addition, three horizontal displacement transducers are installed on the shear wall to monitor displacement of the shear wall.

3 RESULTS AND ANALYSIS OF EXPERIMENT

3.1 The Process and Mode of Failure of Specimens

The loading is ended up when the lateral displacement reaches to 40mm, and the failure mode of the shear wall is shown in Fig.6. When displacement is 3mm, the cracks began to appear on both sides of the shear wall. New cracks appeared from the bottom to the top when displacement increased from 5mm to 13mm, upon displacement reached to 15mm, cracks extend to shear diagonal crack. When displacement increased from 17mm to 19mm, new cracks basically no longer appeared, and diagonal cracks widen and deepen. Vertical cracks appear near the corner, and gradually develop to coalesce with the rest of cracks until the corner of the wall was snapped. Until displacement reached to 21mm, the concrete of the corner surface of the wall begins to sporadically fall off. When displacement reached to 25mm, the concrete of the corner surface largely fell off and the reinforced bars were exposed. Upon reaching to 33mm, there is the continuous fracture sound of the bars, and exposed bars bent. During the process from 35mm to 40mm, loud noise continued to appear from the wall. At the end of loading, obvious damage phenomenon did not appear on embedded parts, and no obvious cracks can be found on photovoltaic panels as well.

![Fig.5 Schematic diagram of loading system](image1)

![Fig.6 Failure form of the specimen](image2)

3.2 The Hysteretic Curve of Shear Wall

The characteristics of deformation, stiffness degradation and energy dissipation of the structure under repeated loading can be reflected in restoring force curve, which is the basis for the nonlinear seismic response analysis. The hysteretic curve (No. 1 displacement meter and load sensor) and the skeleton curve of the shear wall which were obtained from the low-cycle repeated loading experiment are shown in Fig.7.

3.3 Bearing Capacity and Displacement Ductility Factor

Measured values of the Crack load, yield load and peak load of the shear wall are shown in Tab.3, where \( F_c \) represents the cracking load, which can take positive and negative values; \( F_y \) represents the yield load, which different scholars put forward different methods of definitions of yield points based on different theories as the skeleton curve has no obvious yield point. This paper defines yield point is 75% of the peak load based on secant stiffness of the actual component. \( F_{max} \) is the peak load of the specimen, \( \mu_{cm} \) is ratio of the cracking load to the ultimate load and \( \mu_{ym} \) is the ratio of yield load to
ultimate load.

Table 3 Test results of bearing capacity of RC shear wall

<table>
<thead>
<tr>
<th>Fc/kN</th>
<th>Fy/kN</th>
<th>Fmax/kN</th>
<th>Average μsx</th>
<th>Average μsy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push</td>
<td>Pull</td>
<td>Push</td>
<td>Pull</td>
<td></td>
</tr>
<tr>
<td>35.19</td>
<td>106.85</td>
<td>-95.00</td>
<td>118.88</td>
<td>-111.36</td>
</tr>
</tbody>
</table>

Displacement ductility factor is defined as \( \mu = \frac{\Delta_y}{\Delta_u} \). \( \Delta_y \) is yield displacement of the specimen and \( \Delta_u \) is ultimate displacement of the specimen, which is the displacement when bearing load decreases to 85% of ultimate load. \( \Delta_c \) is crack displacement. Ultimate displacement ductility factor of the shear wall is shown in Tab.4.

Table 4 Ultimate displacement ductility coefficient of RC shear wall

<table>
<thead>
<tr>
<th>Δc/mm</th>
<th>Δy/mm</th>
<th>Δu/mm</th>
<th>μ</th>
<th>Δc/Δy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push</td>
<td>Pull</td>
<td>Push</td>
<td>Pull</td>
<td></td>
</tr>
<tr>
<td>0.94</td>
<td>8.94</td>
<td>-6.75</td>
<td>25.25</td>
<td>-25.26</td>
</tr>
</tbody>
</table>

3.4 Deformation of Photovoltaic Panels

As non-structural components photovoltaic panels are connected to the shear wall through the connectors. During the process of the low-cycle repeated loading, the photovoltaic panels deform which depend on deformation of the shear wall. According to the data collected from the displacement transducers which are mounted at the four foot points of the photovoltaic panel, the average displacement of the upper two points is taken to subtract the average of the two lower points to obtain the time history of the inter-story drift angle curve of the photovoltaic panel which is shown in Fig.8. As the main material of the photovoltaic panels is tempered glass and their deformation is mainly rigid, the inter-story drift angle is rigid. As is shown in Fig.8, the rotation angle of photovoltaic panels starts from 0. The inflexion appears and the angle increases little later when the angle increases to 1/200. During the process of increasing from 1/200 to 1/100, the angle is still steadily increasing slowly. However, the angle does not deviate and irregularly change until the angle is more than 1/100.

When the inter-story drift angle of the main structure (the shear wall) increases from 0 to 1/50, the drift angle of the photovoltaic panels increases from 0 to 1/80. During the process, no crack appears on panels and no obvious damage appears on embedded parts and connectors. The damage of the specimen is shown in Fig.9 and the connector is shown in Fig.10.
3.5 Electricity Generation Performance of Photovoltaic Panels

In order to adequately study the influence of the deformation of the main structure (the shear wall) on the working performance of photovoltaic panels, the current-voltage-lateral displacement curve of the photovoltaic panels (shown in Fig.11) and maximum power generation-lateral displacement curve (shown in Fig.12) are plotted simultaneously during loading. The results show that there are only some occasional fluctuations but no obvious decrease of output indexes such as voltage, current and power which represent power generation performance for photovoltaic panels during loading in the main structure. The accidental fluctuations in those indexes may be the result of some accidental factors, such as the fluctuation of the output power of the light source and the adjustment of the position of the lamps, etc. In addition, the efficiency of the power generation of the photovoltaic panels will also fluctuate due to the increase of temperature. If the current-voltage curves of photovoltaic panels under each cycle of loading can be plotted on a graph, the shapes of the curves are almost the same. Furthermore, the efficiency of the power generation of the photovoltaic panels remains basically stable during the whole process, which is between 48.7W and 55.5W.

4 DISCUSSION

4.1 The Failure Mode and Bearing Capacity of the Shear wall

As non-structural members photovoltaic panels have no effect on the mechanical properties of the shear wall. The failure process is: at the beginning, transverse cracks occurred at the bottom of the wall during repeatedly loading and the shear wall was regarded to yield according to the above definition of yield point, which is followed by a large number of lateral cracks which have a tendency of upward shift. Subsequently, the transverse cracks expanded steadily while oblique cracks appeared in the front of the wall and extended diagonally to the central section which finally become cross oblique cracks. During the above process no
new crack appears. When the displacement is about 1.5 times longer than average peak displacement, the concrete at the bottom of the shear wall starts to crush. Upon the displacement is about 2 times longer, the corner concrete began to fall off. According to the definition the displacement of the shear wall has reached to limit. After that, the phenomenon of the test becomes more obvious, when the displacement is about 1.5 times longer than the ultimate displacement, cracking sound of steel bars can be heard and the concrete of the bottom of the wall drops. At the same time, the bearing capacity of the shear wall drops sharply. The average peak displacement of the shear wall in both of positive and negative directions is 12 mm, of which the corresponding average peak load is 115 kN; The average ultimate displacement in both positive and negative directions of the shear wall is 25 mm, which the corresponding average ultimate load is 99 kN. The failure characteristics of the above shear wall is consistent with that of normal shear walls. The description of failure characteristics of shear wall under similar loading is described in document (Lu et al, 2007).

4.2 Performance of the Connectors

In this test, the material of pre-buried anchor plate which is abreast with the shear wall and do not damage is Q235 and the grade of welded steel is B10 in the shear wall. The strength grade of steel fastening is also Q235 and its size mainly depends on convenience of installation and bearing capacity under the PV panel gravity and static wind load to ensure that the steel components in such conditions can maintain elastic, and to ensure the PV components lighter under the premise of the quality. The aluminum alloy groove is designed in the upper and lower ends of the PV panel where rubber mats are paved so that the following conditions can be realized: (1) PV panels have sufficient deformation space; (2) PV panels can support their own weight in the building facades; (3) PV panels do not overturn and jump out under certain load to cause secondary disasters. In the test process no damage occurs in aluminum alloy groove. The design of connectors is reliable as obvious cracks or other damage does not appear during the loading process. The performance of the connectors in the quasi-static test can meet the requirements, but the cooperation performance between the photovoltaic panels and the main structural components still needs to be tested and verified in the dynamic test. In engineering application, installability, replaceability, cost and anti-corrosion measures are mainly taken into consideration. As connectors are designed without considering working gap, the material of panels is more than needed, and the optimization of the design based on the boundary conditions can be carried out in further research.

Through the analysis of the voltage-current curve and the power generation efficiency curve of photovoltaic panels, no obvious fluctuations are observed in the power generation indexes of the photovoltaic panels during the test, which indicates that the performance of this connection form is good.

5 CONCLUSIONS

In this study, a low-cycle test was conducted to test the performance of connection between photovoltaic panels and the shear wall in which the ultimate bearing capacity, hysteresis, ductility and failure mode of the shear wall integrated with photovoltaic panels were studied. It was focused on whether the connection between the shear wall and the photovoltaic panels under reciprocating load was reliable and how it influenced the photovoltaic power generation performance. The results of research show that under the condition of large lateral displacement and large deformation of the shear wall the connection did not damage and performance well. No physical damage can be observed in photovoltaic panels and its power generation performance is not significantly affected. China's "Technical Specifications for Application of Solar PV System in Civil Buildings" stipulates that when PV modules are installed on the surface of the wall in areas of low latitudes, the PV modules installed on the wall or directly constituting building envelopes can properly incline to accept more sunlight due to the small solar elevation angle. At the same time, the structural design of the photovoltaic system should be distinguished whether the building is in earthquake-proof areas. In addition to consider the self-weight of the system, wind load and snow load, the earthquake effect should be considered in earthquake-proof areas as earthquake is a dynamic effect, which can influence the connection a lot. Therefore, in order to further research on the seismic performance of BIPV, the
The deformability of the photovoltaic panels and its effect on the power generation performance need further to be studied. More problems are dynamic test of the whole structure integrated with multiple photovoltaic panels, optimization of connections between the main structure and photovoltaic panels, seismic design method of high / super high-rise structure integrated with photovoltaic panels.

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7. REFERENCES


