Design, fabrication, and construction of a freeform GFRP facade

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ABSTRACT
This paper demonstrates the application method of GFRP (glass fibre reinforced polymer) on freeform facades, including the design, fabrication, and construction based on an architectural oddment in Fuzhou. This architectural oddment, which covers a sunken plaza, is a sculptural-shaped structure inspired by three-morning glories, and its freeform facade is made up of 4 mm-thick GFRP panels. It is the first all-GFRP structure in China. Based on the construction plan adopted in this project, the final architectural aesthetics satisfy the original expectations of the design, indicating that GFRP panels can perform well as facade components. On the other hand, certain defects highlight problems for further investigation. The benefits and limitations of GFRP when applied on the facade are discussed at the end of the paper, providing a reference for similar architectures.

1. Introduction
In recent years, the pursuit of architectural art has grown rapidly worldwide, and as a result, various special-shaped buildings have emerged as symbols or landmarks. Traditional building materials are increasingly being subjected to curved surface construction, especially for freeform surface, testing their limitations. However, it is difficult to achieve complex architectural shapes with traditional materials, often resulting in significant construction time and costs. Therefore, researchers and engineers are in constant search for new materials and technologies for the construction of complex geometries.

GFRP (glass fibre reinforced polymer), a typical FRP (fibre reinforced polymer), has been applied in many structural areas more than ever in the past few years, including facades and load-bearing members. This paper presents solutions to two main challenges when applying GFRP as freeform facade panels, which are material design and processing design. A case study is explained in detail, including the entire process (as shown in Figure 1) from the design to the construction of a GFRP freeform facade structure built in Fuzhou, China, called “Fuyun”. The reasons for employing GFRP as a facade material are elaborated, as well as the application methods, including panel design, calculation, panel production, and construction. The purlin is another important component to ensure the accuracy of the facade, of which the design and manufacturing are also introduced. In addition, the connection between the purlins and the GFRP panels and the virtual pre-assembly technology that ensures accuracy are introduced in this paper. Finally, the benefits and limitations of the GFRP when applied in a freeform facade are summarized and discussed, providing a reference for similar structures in the future.

2. Related work
GFRP was first applied in civil engineering when the Second World War was over. The reconstruction after the war and short of construction material at that time indeed promoted its development (Iyer and Sen 1991). Due to its lightweight and high strength, the structural performance of GFRP satisfied structural demands, and GFRP was considered as a future material. However, its lack of durability posed a limitation in regard to long-term performance under the prevailing conditions. Also, in the 1970s, the oil crisis significantly increased the costs of FRP, resulting in a reduction in the number of all-GFRP-structure construction. In a very long time since then, the major GFRP applications in civil engineering were limited to reinforcement, bridge material, and decoration areas.

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Scientists and engineers of composite materials area first tried to utilize the high-strength characteristics of FRP to reinforcement in the 1980s. Saadatmanesh and Ehsani (1991a, 1991b) conducted a series of early experiments on GFRP-sheet strengthened RC (reinforced concrete) beams, and the result showed that the bending strength and stiffness of RC beams were significantly improved. Also, Hollaway et al. (Quantrill, Hollaway, and Thorne et al. 1995; Hollaway 1999) drew similar conclusions in their researches. Arduini and Nanni (1997) studied the behaviour of precracked CFRP (carbon fibre reinforced polymer) strengthened RC beams, and the result showed that the effect of CFRP strengthening was considerable. Current researches are more in quantity and detailed in quality. Islam, Mansur, and Maalej (2005) and Zomorodian et al. (2018) worked on the shear strength of FRP strengthened RC beams, Zhang et al. (2017) studied FRP-reinforced masonry walls through numerical methods. Moreover, corresponding codes have been published to guide FRP reinforcement applications (Council NR 2007; 2010; Maruyama and Ueda; Zureick, Ellingwood, and Nowak et al. 2010). Therefore, FRP reinforcement applications are already relatively mature and standardized.

Regarding bridge construction, numerous GFRP bridges, including all-GFRP bridges and bridges with GFRP deck panels, have been built until now and lightweight plays a key role in the construction process, and actually, most of the current structures with GFRP-load bearing components are bridges. In 1983, an all-GFRP honeycomb box girder highway bridge was built in Beijing (D. TG, Y. T, Z. FG. 1995), which proved that GFRP could perform well as a highway bridge material. Nevertheless, most GFRP bridges are pedestrian bridges, of which technology is relatively mature and industrialized. The pedestrian bridge in Nørre Aaby (Crumbling concrete bridge replaced by GRP composite Denmark: Fiberline Composites A/S 2017) is an example. The bridge was constructed to replace the original corroded concrete bridge, the 6-tons GFRP bridge utilized the existing foundations of 120-tons original concrete bridge, and it only took 2 hours to finish the site construction. The pedestrian bridge built in Reinbek (Municipality installs revolutionary bridge with maintenance-free GRP deck Denmark: Fiberline Composites A/S 2017) applied GFRP bridge deck, of which GFRP parts were manufactured in the factory and installed on the completed foundations on site. Similarly, Delft Infra Composites B.V. built a pedestrian bridge in Harderwijk (‘Bronlibel’ voetgangersbrug in Harderwijk Netherlands: Delft Infra Composites B.V. 2013) to connect two new regions. Based on these applications, researches on GFRP deck panels such as Holden, Pantelides, and Reaveley (2014) and Kim et al. (2009) were well conduct.

In addition to the characteristics of lightweight and strength, the unique processing methods of GFRP are also remarkable, which are commendable for manufacturing curved panels. Although the application of curved GFRP structures was restrained in the 1970s by factors such as oil crisis, it was still proved to be an excellent alternative material to traditional building materials when applied to curved facade through early attempts. In 1956, Maison en Plastique (Quarmby 1974) was designed and constructed for the Salon des Arts in Paris, which was inspired on the shell of a snail, and it was regarded as the first FRP elements load-bearing building. In the same year, the famous Monsanto House of the Future (Meikle 1995) was established in Disneyland, Orlando. Its GFRP C-shaped surface was an attraction in “Tomorrowland” at that time, but it was also criticized for the design intention and cost. In 1968 (Taanila 2004), Futuro was designed and then built worldwide, and its GFRP saucer-shape became the prototype of many following GFRP structures.

With the accumulation of experiences and developments of technologies, there are some applications of composite materials in facades that achieved excellent visual effects nowadays, such as The New Stedelijk Museum Amsterdam (Crouwel 2014) and Mobile Art Pavilion for CHANEL (Hadid 2010). However, GFRP applications are still rare in number and GFRP has always been considered as a “new” material. This is mainly because common designers and engineers are unfamiliar with the application methods of this materials and its cost is still relatively high.
3. Methodology

To better apply GFRP to civil engineering, the two most significant challenges have to be solved, its complicated design method and high processing cost. In general, the design of composite members or structures includes three aspects: structural design, material design, and processing design. These three tasks are equally important and feedback each other during the design phases and thus they have to be carried out simultaneously. Figure 2 shows a simple relationship between the three tasks. For civil engineering designers, structural design is relatively easy to understand, but it seldom involves materials form and processing. So, in the following of this section, the strategies applied to solve the two problems are briefly described, which involve simplifying the GFRP material properties and optimizing the freeform panel processing methods. The detailed application methods are described in the following case study.

3.1. Material design

Material design request designers to consider the applied material form, such as unidirectional reinforced or orthotropic panel, including the mechanic properties of each direction. The material form might influence the processing methods of composite material, but it will definitely influence the material calculation model and material properties during structure design and analysis stage. For multidirectional load bearing members, such as panels, orthotropic symmetrical GFRP laminates are mostly applied due to their relatively low cost, ease of processing, and stable properties. Figure 3 shows a laminate model which is used...
to simulate GFRP panels in ABAQUS, and the model is much more complicated than common building material. Even if designers are familiar with GFRP, it is still difficult to analyze GFRP structures directly using composite material properties due to the large amount of computation and possible convergence problem. Therefore, adopting a convenient and efficient free-form GFRP panel calculation method is the most important task of material design.

To solve this problem, based on the classical laminate theory, this research studied the theoretical calculation method of orthotropic composite materials, and tried to summarize a simple, feasible and relatively accurate calculation method. Thus, a simplified material solution for orthotropic symmetrical GFRP laminates was proposed (Zhao et al. 2019).

The aim is to simplify orthotropic symmetrical laminates into an isotropic material, which needs to work on both stiffness and strength aspects. For stiffness, the analysis of the panel (as shown in Figure 4) can be assumed as plane stress problems.

According to the classical laminate theory:

\[
\begin{align*}
\begin{bmatrix} 
\varepsilon_x \\ 
\varepsilon_y \\ 
\gamma_{xy} 
\end{bmatrix} &=
\begin{bmatrix}
\frac{1}{E_1} & -\frac{v_1}{E_2} & 0 \\
-\frac{v_1}{E_2} & \frac{1}{E_2} & 0 \\
0 & 0 & \frac{1}{G_{12}}
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix}
\end{align*}
\]

where: \(E_1\): elastic modulus of 1-axis \\
\(E_2\): elastic modulus of 2-axis \\
\(v_1\): Poisson ratio of 1-axis \\
\(v_2\): Poisson ratio of 2-axis \\
\(G_{12}\): shear modulus in 1–2

\[
m = \cos \theta \ n = \sin \theta
\]

For orthotropic symmetrical laminates, \(E_1 = E_2\), therefore:

\[
\frac{d}{d\theta} \left( \frac{1}{E_1} \right) = -\frac{4}{E_1} \sin \theta \cos^3 \theta + 2 \sin \theta \cos \theta \left( \frac{1}{G_{12}} - \frac{2v_1}{E_1} \right) \left( \cos^2 \theta - \sin^2 \theta \right)
\]

\[
+ \frac{4}{E_1} \sin^3 \theta \cos \theta = \left( \frac{1}{2G_{12}} - \frac{v_1 + 1}{E_1} \right) \sin 4\theta
\]

when

\[
\theta = \frac{mn}{4}, n = 0, 1, 2, 3 \ldots
\]

or

\[
E_1 = 2G(v_1 + 1)
\]

\(E_x\) is at the extremum. For orthotropic symmetrical laminates, \(E_x\) is minimum and is given by:

\[
\frac{4E_G_{12}}{E_1 + 2G_{12}(1 - v_1)}
\]

and \(E_x\) is taken as the elastic modulus of the simplified isotropic material.

**Figure 4.** Material axis.
For strength, the Tsai-Hill criterion is applied as the failure criterion of GFRP laminate. The general form of the formula is given in Equation (6):

$$F(\sigma_2 - \sigma_3)^2 + G(\sigma_3 - \sigma_1)^2 + H(\sigma_1 - \sigma_2)^2 + 2L\tau_{23}^2 + 2M\tau_{31}^2 + 2N\tau_{12}^2 = 1$$  \hspace{1cm} (6)

For orthotropic symmetrical GFRP laminates, the fibers are distributed equally in the 1 and 2 directions, therefore, Equation (6) can be expressed as Equation (7):

$$\frac{\sigma_1^2}{X^2} + \frac{\sigma_2^2}{Z^2} - \frac{2\alpha_1\sigma_2}{X^2} + \frac{\sigma_1\sigma_2}{Z^2} + \frac{\tau_{12}^2}{S^2} = 1$$  \hspace{1cm} (7)

where: X: strengths in longitudinal and transverse directions
Z: strength in thickness direction
S: shear strength in 1–2

When the laminates are subjected to unidirectional load, the $\sigma_1$, $\sigma_2$ and $\tau_{12}$ can be transformed into $\sigma_x$ (stress in off-axis) as Equation (8):

$$\sigma_1 = \sigma_x\cos^2\theta$$  
$$\sigma_2 = \sigma_x\sin^2\theta$$  
$$\tau_{12} = -\sigma_x\sin\theta\cos\theta$$  \hspace{1cm} (8)

The derivation of $\frac{1}{\sigma}$ is shown in Equation (9):

$$\frac{d\left(\frac{1}{\sigma}\right)}{d\theta} = -\frac{4}{X^2}\cos 2\theta\sin 2\theta + \left(\frac{1}{Z^2} + \frac{1}{S^2}\right)\sin 2\theta\cos 2\theta$$

Therefore, $\sigma_x$ is minimum $\frac{2SZ}{\sqrt{S^2 + Z^2}}$, and this strength is taken as the strength of the simplified isotropic material.

In summary, the principles of the simplified solution are shown in Table 1. The calculation process can be greatly simplified and the efficiency can be greatly improved when applying this simplified method. For deformation, the calculation result of the simplified solution is very close but a little larger than that of original material properties. For strength, the calculation result of the simplified solution is conservative and relatively safe. The failure strength of the simplified solution is far less than that of the actual composite material but is high enough for panels. Overall, the simplified solution is efficient and safe.

### 3.2. Processing design

The processing design should consider the selection of the raw materials, the processing methods, the processing period and cost of the material. When processing freeform GFRP panels, actually most of the cost results from the manufacturing of the curved surface molds but not from the panels themselves, since each freeform panel needs a totally different mold. The hand lay-up process is widely used for curved GFRP panels processing, and it is also the most feasible processing method. However, this process is criticized for its instability, labour intensity and low productivity. Members applied in civil engineering usually require to be produced efficiently, thus, hand lay-up process would result in high labour costs or an unacceptable

![Figure 5](image_url)  
**Figure 5.** Manufacturing steps.

![Figure 6](image_url)  
**Figure 6.** Mold processing steps.
Figure 7. The sectional view of the mold and materials.

Figure 8. Panel processing steps.

production period. Therefore, finding a convenient and efficient freeform GFRP panel processing method was the main task of processing design.

To solve this problem, through investigations and experiments of existing commercial composite material processing technologies, this research focused on solving the problems of the processing method of freeform surface molds and GFRP freeform surface panels, and their high processing cost. An optimized manufacturing method for freeform GFRP panels for architecture facades was proposed (Zhang, Zhao, and Jiang 2019, 2020). The main steps of this method are shown in Figure 5, of which the most important steps are mold processing and GFRP panel processing.

There are two problems with common molds: the expense of mold materials and the long mold processing period. Regarding the expense of mold materials, the simplest solution is applying cheap mold materials, such as Expanded Polystyrene (EPS) foam, and using CAD/CAM technology and engraving machine to manufacture a mold for a huge, curved panel within several hours. The main steps of mold processing are shown in Figure 6. This mold processing method possesses the advantages of having a low material cost, low labour cost, and high processing efficiency.

However, GFRP panels cannot be manufactured directly on EPS foam mold by any processing method, since the resin will flow into the tiny gaps in the foam, which will cause a significant decrease in panel quality. To solve this problem, the processing method, which is based on vacuum-assisted resin transfer molding (VARTM), was optimized for EPS foam molds: another layer of vacuum film was laid on the surface of the molds. The major steps of the panel processing method are shown in Figures 7 and 8.

This processing method greatly reduced the cost and improved the processing efficiency of the freeform GFRP panels; however, the adjustments and measures taken during this process had a certain impact on the panels’ accuracy. Fortunately, the accuracy impact was acceptable since structure dimensions were relatively large.

4. Case study

The case study involves two identical freeform covering structures located in a sunken plaza of a shopping mall in Fuzhou, China. The architecture concept was creating a sculptural-shaped structure representing three-morning glories; an extremely freeform surface with strong visual impact. The architectural design is shown in Figure 9(a,b). Three disconnected flower-shaped structures are located close to each other, whose height is 9.8 m, and the entire surface area is about 1460 m². Viewed from the top, the structure has a circular shape with a diameter of 43 m, covering the round sunken plaza with a diameter of 25 m, as shown in Figure 9(c).

The extremely freeform shape challenged the structure and facade design of this case study. The architectural aesthetic was expected to be seamless and entirely smooth on the surface without any adjustment to the architectural design. Membrane was proposed as the form-finding material in the initial structural design phase, but it was finally abandoned since
membrane had to be welded and connected together to form the expected freeform shape, and that could not satisfy the seamless demand. Also, the colour of membrane would change after aging. Similarly, other traditional materials did not satisfy the architectural requirements without resulting in significant costs and construction time either, and the construction schedule was already tight at the time. Considering these obstacles, GFRP presented a feasible solution. This structure was a small-area oddment, suitable for verifying whether GFRP was truly qualified for surface material as curved façade panels, investigating the problems that might be encountered during design, processing, and construction phases, as well as providing further solutions.

The original architecture model was adopted directly to structural design, which means the panel manufacturing had been not submitted to any optimization and thus, every panel was a freeform surface. Therefore, to realize the architecture, panels and pur- lins had to be manufactured and constructed accurately enough. Besides, this project also had to consider other three requirements:

1. Large wind loads: the oddment is completely outdoor and exposed to the air, covering the whole sunken plaza and carrying the rain. Due to the fact that Fuzhou is located near the coast and affected by Pacific typhoons in summer, the basic wind load is relatively

![Figure 9. Architectural model of the Fuyun. (a). Concept design; (b). Facade model; (c). Top view.](image-url)
large. As an open structure, the wind load must consider both wind suction and pressure, adding further complexity to the structural design.

(2) High humidity and salinity: as mentioned in the last point, the oddment is located near the coast and is completely outdoor. Therefore, the humidity and salinity in the air is relatively high. However, GFRP’s durability against humidity and salinity is naturally high compared to traditional material considering its high chemical stability. This characteristic has caused this material to be widely applied in coastal cities like Fuzhou, namely in GFRP bars as replacement of steel bars to avoid rust and reduce maintenance.

(3) Tight schedule: the architectural design was finalized on July 10th, 2017, and the owner requested that the construction had to be completed before October 1st, 2017 (China National Day), which proved impossible to achieve. The construction was eventually completed by the end of November. It took only 5 months to finish the freeform structure design, façade panel manufacture and all the construction. The whole process indicated that GFRP performs well in terms of the processing cycle and construction convenience.

5. Structural design

The structural design can be divided into two parts: the GFRP facade and internal supporting structure. Processing and construction required extremely high accuracy due to the freeform facade of the structure. Therefore, difficulties in the final processing and construction should be considered during the structural design in order to improve the convenience of processing and construction, while ensuring the final architectural aesthetic.

5.1. Facade design

During the facade design phase, the first main task was to divide the entire facade into individual parts, which was done by using the software Rhinoceros and the plug-in: RhinoScript. To guarantee the convenience of panel processing and construction, two principles must be followed when dividing the facade:

(1) Purlin arrangement: steel purlins were arranged in the gap between panels to support and connect the GFRP surface. Therefore, the panel division was basically determined by the purlin arrangement. Since the façade was a freeform surface, the shape of purlins had to be twisted to fit the surface. Therefore, the facade was divided at the flat areas where the curvature was small in order to reduce the difficulty of purlins processing and construction.

(2) Panels maximum size: there were several factors that influenced the panel size such as process, transportation, and installation. If the panel size was too small, the process would be convenient but might result in a large number of panels and purlins, which would result in complex stacking and construction management on site.

Figure 10. The curvature of the freeform façade. (a). Minimum radius nephogram; (b). Legend of Figure 4(a); (c): Segmentation lines of the façade.
However, if the panel size was too large, the panel had to be thicker to reduce the deformation, which would increase their overall cost and the difficulty of their processing, and complicate the transportation. Thus, considering the processing ability and construction and stacking scheme, the size of the panels was finally determined to not exceed 2 m × 2 m.

Based on the two principles, the panels were divided as follows: first, the architecture model was imported to the software Rhinoceros 5 to calculate the minimum radius of the facade surface. The nephogram of the calculation is shown in Figure 10(a) and a corresponding legend is shown in Figure 10(b). The red area indicates the spots with minimum radius larger than 3000 mm, which means the flat areas; and the blue area indicates the spots with minimum radiuses smaller than 80 mm, which means the curved part of the surface. Therefore, the facade segmentation lines should be arranged in the red area and avoid the blue areas so as to reduce the distortion of purlins. Through overall division, the facade segmentation lines are shown in Figure 10(c).

After the division, a script program was executed in the RhinoScript to number all the panels, as shown in Figure 11. The three flowers were divided into 838 curved panels in total. The numbering of the panels was of great importance since it was the only way to distinguish the 838 pieces of similar but completely different panels. The construction benefited from an appropriate numbering rule which could provide an approximate spatial position of where the panels should be installed. In fact, the management work was even more significant for Fuyun, and an essential task laid in locating the corresponding panels and purlins.

The GFRP in this project took epoxy resin as matrix and glass fibre was arranged in ±45° as reinforcement. The material properties of every layer are shown in Table 2.

Since every panel was different, all panels had to be calculated to evaluate their strength and deformation, which further determined the thickness of panels. The calculation amount and complexity would be huge if the material properties of GFRP applied the original laminate material properties during calculation. Actually, after trials, the calculation could not proceed at all since convergence problems occurred all the time.

The simplified material solution for GFRP was applied in this case (Table 1), according to which all the parameters could be obtained from the ±45° bending test of GFRP as shown in Table 3.

The calculation process became much more convenient through application of the simplified material solution. Although the failure strength of GFRP is only 60MPa, which is much less than its longitudinal failure strength, it is still high enough, being the low stiffness the dominant factor during design phase. Therefore, the main factor influencing the thickness of GFRP panels was their deformation. As mentioned before, due to the influence of the Pacific typhoon, the wind load in Fuzhou is relatively high and, according to the Load Code for the Design of Building Structures (China MoHaURDotPSRo), the basic wind pressure of Fuzhou is 0.7 kN/m². Since there is no stipulation for the maximum deformation of the composite panel in the Technical Code for Building Curtain Wall (Construction SU, and Communication Commission, 2012), we referred to the stipulations of glass: the maximum deformation is limited to 1/60 of the short side length, which is about 33 mm in this case. For a 2 m × 2 m GFRP panel, a thickness of 4 mm could satisfy the deformation requirements.

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### Table 2. Material properties of GFRP layer.

| Property       | Value (MPa) |
|----------------|-------------|
| Density         | 2000        |
| $E_1$          | 16,000      |
| $G_{12}$       | 3000        |
| $\nu_{12}$     | 0.14        |

* $E_1$: longitudinal elastic modulus
* $G_{12}$: transverse elastic modulus
* $\nu_{12}$: Poisson ratio
5.2. Supporting structure design

Each purlin supported and connected two curved panels and transferred loads from the panels to the main steel frame inside. In this case, the purlins material was steel and they were arranged along the segmentation lines as mentioned before and shown in Figure 10(c). The purlins were welded to each other into a whole steel frame and connected to the main steel structure by braces on horizontal and vertical joints, and the GFRP panels connected to the purlins on the flange.

Cold-twisted square steel tubes were initially considered to manufacture purlins, which presented the most convenient and steel-efficient plan, but it proved to be difficult to satisfy the precision requirements in experiments. There were two main problems:

1. The twisting processes of the square steel, including similar cross-sections, proved to be a complicated process of spatial twisted components, which would induce relatively large errors or even failure. Besides, some local buckling phenomenon might be fatal since they would destroy the flange surface and the purlin could no longer provide a useful surface to connect panels.

2. There would be an uncertain elastic recovery after the cold machining of square steel, which was difficult to control in the actual operation.

![Processing diagram of a purlin.](image12.png)

![An overview of purlins.](image13.png)
Finally, a T-shape was adopted for the cross-section of the purlins due to the fact that twisted T-shape steel components were convenient to manufacture precisely. Regarding the welded T-shape cross-section, the flanges and the webs of twisted T-shape members were manufactured respectively and then welded into whole components since the tolerance in flattening the thin strips were generally small. We modelled the T-purlins in Rhinoceros 5 and then imported them into 3ds to export processing blueprints of steel members. The basic steps of creating processing blueprints are shown in Figure 12. The processing blueprints were basically the spatial coordinates of control points. Thus, the processing of purlins could be described as follows: first, we cut the flattened shapes on plane steel; then, we bended and twisted the plane shape steel according to the spatial coordinates of control points; finally, we assembled the deformed web and flange through welding. The welding of web and flange could also provide a constraint to each other to maintain the twisting deformation, further ensuring processing accuracy, while reducing deformation recovery.

An overview of purlins is shown in Figure 13. The dimensions of the steel T-purlin were calculated in 3ds and according to the Technical Code for Building Curtain Wall (Construction SU, and Communication Commission), a 6 mm-thick flange and 8 mm-thick web T-purlin were found to achieve the strength and deformation requirements. Horizontal purlins were disconnected at the joints and welded to the vertical purlins. Adjacent vertical purlins were welded 10 cm below the joints of the horizontal and vertical purlins. A total of 869 horizontal and 459 vertical purlins, which were numbered, processed at the factory and installed on site.

The main steel frame (as shown in Figure 14) is composed of different steel tubes. One or two steel tubes column standed in the centre, and steel trusses were arranged on the top close to the façade, providing the supporting position for purlins. Trusses of “three flowers” were connected on the top, which also strengthened the structural integrity. The upper purlins were connected to the steel trusses and the lower purlins were connected to the steel tubes column directly.

6. Facade panels processing

The large number of completely different free-from panels greatly challenged the manufacture and processing of the GFRP panels. To produce the $838 \times 2 = 1676$ freeform panels in total, traditional process methods would prove to be unproductive. During the design phase, the exploration of processing method was conducted simultaneously and an optimized manufacturing method was proposed to manufacture the GFRP panels, which was continuously adjusted during processing phase. Eventually, it took about 100 days to produce all the panels.

The production procedure of GFRP panels can be divided into three main phases: mold processing, the preparation of auxiliary materials and the processing of panels. Normally, steel, wood and other conventional materials are employed as GFRP panel mold materials, but they are suitable for the mass production of a unique shape. Also, conventional mold processing methods generally have a relatively high cost and take a long time to process a mold. Therefore, they were not suitable to produce plenty of freeform panels since only two pieces were needed for each of 838 distinct shapes. It was therefore important to develop an economical and efficient mold processing method. In this case, EPS (Expanded Polystyrene) foam was applied as mold material and the engraving machine was employed as mold processing equipment (as shown in Figure 15(c)). The advantage of EPS foam lied in its softness, allowing it to be rapidly engraved into the desired shape through an engraving machine. Also, the EPS foam is lightweight, therefore no lifting equipment was required and EPS foam molds could be transported by manpower easily, which further increased the production efficiency.

![Figure 14. Main steel frame.](image-url)
Programs were executed in RhinoScript to automatically output the mold image file and the foam blank dimension simultaneously. The mold image files (Figure 15(a)) were transferred to the software in the engraving machine to generated the tool path according to the corresponding configuration (Figure 15(b)), which then the cutter would follow to engrave the foam mold. The surface smoothness was

![Figure 15. Mold processing diagrams. (a). Mold file in Rhinoceros 5; (b). Tool path for engraving machine; (c). Engraving machine; (d). Engraved foam molds.](image)

**Figure 16.** Fiberglass fabric preparation. (a). Enlarged outer contours; (b). Fabric cutting machine.
determined by the overlap ratio of the cutter. The higher the overlap ratio, the smoother the mold would be, but the longer time it would take. Through trials and adjustment, a 30% overlap ratio was found appropriate, taking about 90 minutes to engrave a small GFRP panel mold (Figure 15(c,d)) and about 3 hours for a large one. The entire engraving process was automated; thus, multiple machines could be manipulated simultaneously by one skilled operator, which saved labour costs and greatly improved mold processing efficiency.

Auxiliary material preparations included cutting of fiberglass fabric, resin distribution medium, peel ply, and vacuum films. Resin distribution medium, peel ply, and vacuum films were prepared in several fixed sizes to simplify the cutting process. However, a fixed-sized fiberglass fabric would result in great wastage due to its large quantity and high price. The fabric cutting machine was employed to cut the fiberglass fabric in the desired shape. Programs were executed in RhinoScript to approximately flatten all panels onto the plane and duplicate their contours. The contours were the expected toolpath of the fabric cutting machine, however they had to be enlarged to guarantee they covered the original curved surfaces, as shown in Figure 16(a), since there were inevitable systematic errors when flattening surfaces. Through trials, a 15–20% enlarging ratio was found appropriate to guarantee that the original surface was completely covered, and excessive waste was avoided. Then we output the enlarged outer contours, imported them into the fabric cutting machine and cut the fiberglass fabrics as shown in Figure 16(a,b).

The GFRP panel processing method also required adjustment to correspond to the previous mold and auxiliary material preparations. As mentioned before, hand lay-up had advantages in processing curved panels, but a low processing efficiency and unstable material properties made it difficult to fulfill the requirements. Resin Transfer Molding (RTM), with high efficiency and uniform quality, was adapted as basic processing method to process panels. However, since the mold was made of EPS foam, another layer of vacuum film had to be arranged at the bottom, which constituted a vacuum film “bag” as shown in Figures 7 and 17. This vacuum film “bag” had a great influence on the panel quality, since the panels were not adsorbed on the mold by atmospheric pressure but placed on it, which certainly reduced the panel smoothness. Therefore, during their processing, the fiberglass fabrics had to be carefully laid to fit the mold closely without obvious folds on the surface. During the curing stage, the position of the panels was firmly fixed. The panel smoothness was apparently reduced, but it could still achieve engineering requirements.

Figure 17. Modified RTM with vacuum film “bag”.
7. GFRP panels and purlins connection

GFRP connection methods can be divided into mechanical connection and bonding. Mechanical connections were difficult to apply in this case since bolts would be visually obvious and the facade had to be visually seamless as a whole surface. Therefore, structural adhesive bonding was more advisable for this structure. The structural adhesive needed to satisfy the connection strength, as well as be able to fill the gap between panels. Scientific researches on structural adhesive connections are ongoing, and various structural adhesives are already available on the market (Mays and Hutchinson 1988; Dillingham et al. 2014; Kumar, Patnaik, and Chaudhary 2017). For the actual projects, product maturity and construction convenience were also significant factors and thus, a commercially-available structural adhesive with a practical construction plan was required. It was necessary to ensure that the panels, the structural adhesive, and the steel purlins were tightly fixed during the curing process of structural adhesive. Thus, the connection shown in Figure 18 was adopted.

Table 4. Material properties of CBSR-A/B.

| Property                     | Value                                      |
|-------------------------------|--------------------------------------------|
| Tension strength              | >30MPa                                     |
| Elastic modulus               | >3.5GPa                                    |
| Elongation                    | >1.2%                                      |
| Compression strength          | >65MPa                                     |
| Bending strength              | >45MPa                                     |
| Steel-Steel shear strength    | standard >15MPa                            |
| Steel-Steel tension strength  | value >17MPa                               |
| Steel-C45 tension strength    | >2.5MPa, Failed                            |
|                     | since concrete tension                      |

*C45 means concrete with a 45MPa compression strength average value.

Figure 18. Diagram of connection between GFRP and purlin.

Figure 19. Connection experiment. (a). Specimen diagram; (b). Tensile testing machine; (c). Failed specimen.
Countersunk rivets were applied to fix purlins, structural adhesive and GFRP panels tightly during the curing process, and the strengths of rivets were neglected when calculating this joint strength. The structural adhesive CBSR-A/B of Carbon Composites (Tianjin) Co., Ltd. was adopted to adhesive steel components, and the tensile strength of more than 15MPa could be guaranteed according to the product instructions when applied between steel members. Its main ingredient is modified epoxy resin, which is similar to the GFRP matrix. The official material properties of CBSR-A/B are list in Table 4:

According to the instruction of CBSR-A/B and Table 4, the ingredients and properties are similar to the adhesive BUFA-BONDING PASTE 740–0110 applied in our previous researches on FRP-to-steel joint (Jiang, Kolstein, and Bijlaard 2013, 2014; Jiang et al. 2015a, 2015b), which properties have been already studied. In China, CBSR-A/B is massively available in the market, however, there was no related adhesive parameter when it was applied between GFRP and steel, and the manufacturer of CBSR-A/B could not provide them, either. Therefore, tests were conducted to verify its tensile strength and further evaluate if its properties were similar to BUFA-BONDING PASTE 740–0110 when applied to adhesive GFRP and steel. The test specimens and the experiment device were prepared as shown in Figure 19(a,b): The upper and lower parts were two T-section steels, the middle piece was a piece of 4 mm-thick GFRP panel, and structural adhesive was painted between the steel flange and the GFRP panel. Six test specimens (specimen 1 to 6 in Table 5) were prepared according to the actual construction conditions: the steel flange surfaces were simply polished; structural adhesive was applied on the two sides of the GFRP panel and sandwiched between two steel flanges; adhesives flew out of the edges of the specimen to guarantee the adhesive quantity was enough; and fully squeezed the specimens for 24 hours until the structural adhesive was cured. Another two specimens (specimen 7 and 8 in Table 5) were prepared as a control group, and the difference was that specimen 7 and 8 were carefully polished on the steel flange surface since this action might influence the adhesive strength. Finally, the experiments were conducted and the tensile strength was obtained, as shown in Table 5.

For specimen 1–6, the failures were mainly located on the steel surface (Figure 19(c)), but for carefully polished specimen 7 and 8, the failures were partly between the structural adhesive and GFRP sections. The minimum strength was more than 5MPa (as listed in Table 5), and the strengths of specimen 7 and 8 indicated that a careful treatment on flange might improve the strength. In this structure, GFRP panels were supported on four sides by purlins, and the width of adhesive connections was at least 2.5 cm. Therefore, 5MPa tensile strength could guarantee the connection strength.

8. Virtual pre-assembly

Virtual pre-assembly is a common method in current steel structure engineering which is highly recommended for precision control. In order to satisfy the freeform seamless architecture effect, the panels and purlins had to be precise enough and assembled accurately. Virtual pre-assembly could provide correction and modification information, so as to assist in achieving the accuracy requirements. A brief description of virtual pre-assembly applied in this structure is listed below, and please refer to our previous article (Liu et al. 2018) for more details.

Three-dimensional laser scanning was performed on panels and purlins to obtain scanning models. Then we contrasted the scanning models to the design models through a program that automatically analysed the differences. Spatial geometric errors were obtained as shown in Figure 15. When scanning panels, it was necessary to pay more attention to the fact that the panels in the model were in 0 stress state without any deformation. Since the panels were only 4 mm thick, their deformation would be obvious if they were constrained or supported improperly, even under their own weight. So, scannings were conducted when GFRP panels were in a state of no deformation, otherwise, the scanning models would be valueless. According to the contrasts result as shown in Figure 20(a), the manufacturing errors of GFRP panels were relatively small, but the twisted purlins were indeed inaccurate with a maximum error of 30 mm (Figure 20(b,c)), which was unacceptable. Components with large errors had to be modified, and after the single purlin’s error satisfied the tolerances, a batch of purlins was virtually assembled to calculate the errors for double-checking (Figure 20(d)).

9. Construction of the freeform structure

Building plenty of completely different components on site presented great challenges for engineers. The following measures were adopted to assist construction scheduling and structural integrity. The purlins of the “three flowers” were divided into the top and bottom
parts, and the top parts were further divided into several batches. After welding and assembling the purlins of one top batch on the ground (Figure 21(a)), the workers raised the batch to the designed height and connected it to the main steel structure, and then installed the GFRP panels on the top purlins on the lift trucks in the air to release the ground space of construction site, so that other purlins could be assembled continuously. After all the top purlin batches were connected to the main steel structure, workers welded the purlins between the batches which connected the top batches into a whole (Figure 21(b)). At last, workers installed the bottom purlins pieces and the entire purlin construction was completed.

As mentioned before, GFRP panels were installed in the air to release the ground construction space (Figure 21(c)). During installation, workers on site selected the corresponding panels and purlins according to the blueprints, polished the surface of the purlins to remove the rust layer, mixed the structural adhesive and coated the edges of the panels, aligned the panels with purlins, drilled holes on the edges and
fixed the panels with an average of six countersunk rivets on each side. After all the panels were installed, workers filled in the gaps between panels and the holes of countersunk rivets with structural adhesive to form the seamless facade. Finally, painters polished the surface of the GFRP panels, then painted primer and putty, and finally completed the overall surface painting as shown in Figure 21(d). The construction was accomplished as shown in Figure 21(e,f).

10. Result

Through applying GFRP panels as freeform façade in an actual structure, four main results can be obtained as follows.

(1) Compared with traditional building material, the application of freeform GFRP panels is more complicated. There were many problems that had to be solved, such as inaccurate purlins, which eventually influenced the smoothness of the entire surface due to insufficient preparation, and the gaps between panels were difficult to be fully concealed. In addition, the GFRP panels were translucent since they were only 4 mm-thick. Therefore, they did not achieve complete light-proof after the final painting of the facade. The shadows of purlins, putty and some smudges can be observed through sunlight during the daytime, although the appearance was much better when lit at night. Some of these problems were caused by the freeform shape, but the main reasons lied in the immature application methods of GFRP.

(2) The simplified material solution is effective. As mention before, the calculation could not proceed at all when applying laminate material properties since various errors occurred all the time. Although the failure strength of GFRP is limited to only 60MPa, which seems to be much smaller than the ultimate strength of the GFRP, it is still sufficient for members like panels.

(3) The production period can meet tight deadlines. In this case, a total of 1676 freeform panels were manufactured in 100 days. Also, by applying the
optimized processing method, freeform GFRP facade systems are feasible and even had a significant price advantage over traditional facade systems, which at last generated economic benefits.

(4) GFRP is a suitable alternative panel material for façades. The final architectural aesthetics of this project case satisfied the original expectations of the design and gained highly praised from the owners and architects.

11. Conclusion

This paper introduces the application method of GFRP panels as a freeform material and focuses on the simplification of anisotropic material properties and the optimized processing method on freeform GFRP panels. Then, a case study which applied GFRP as freeform façade was described in detail including the computer-aided design, processing, and final construction.

In the end, GFRP proved to be a good alternative material for freeform or complex-shaped façades, being more cost-effective compared to traditional building materials. Also, the characteristics of GFRP, including high strength, lightweight, and convenient processing and installation, are especially valuable for complex-shaped façades. Nevertheless, when applied to regular-shape structures, GFRP materials are not that cost effective, which means that GFRP is more suitable for freeform or complex-shaped surfaces than regular-shape structures.

Although a simplified solution of GFRP material properties and an optimized processing method was applied in this case, more effort must be paid on composite material design and processing methods. These two aspects would cause a complicated design process and a relatively high cost of GFRP, which limit the application of GFRP in civil engineering. Meanwhile, since many designers are not familiar with GFRP or composite material, more and better publicity is necessary to promote their application and development. It is believed that, with continuous efforts and improvement, more GFRP structures will soon be unveiled all around the world.

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