DOI: 10.5075/epfl-ICSS12-2018-191-193

# STRUCTURAL DESIGN AND OPTIMIZATION OF FRP CURVED SANDWICH PANELS USED AS THE ENCLOSURE STRUCTURE OF A LARGE BRIDGE

Xinmiao Meng[1,2] and Peng Feng[3]
[1] Department of Civil Engineering, Beijing Forestry University, Beijing, China. mengxinmiao@bjfu.edu.cn
[2] Department of Civil Engineering, Tsinghua University, Beijing, China.
[3] Department of Civil Engineering, Tsinghua University, Beijing, China. fengpeng@tsinghua.edu.cn

## 1. INTRODUCTION

Non-linear architecture releases the imagination and creation of architects when designing the buildings and infrastructures [1]. However, when constructing the freeform appearance, the traditional construction techniques especially using concrete, face high construction cost and slow construction speed. FRP curved sandwich panels, composed of FRP (fibre-reinforced polymer) face sheets and PUR (Polyurethane) foam core, provide a better solution to the above issues. Such panels have the advantages of low density, high strength, convenient construction and excellent designability, and are suitable to construct non-linear architecture fast and economically. So it has been pioneered to build several non-linear architectures and infrastructure [2-3], such as the roof of the Yitzhak Rabin center in Israel [4], Novartis main gate building in Switzerland [5] and Wuhan factory gate building (China) [6].

This paper also presents a practical engineering application, a 9028.5 m$^2$ enclosure structure of a large bridge in Beijing, designed and manufactured with such panels [7]. The structural design and optimization process will be displayed here to give a reference to the similar projects.

## 2. PROJECT INFORMATION

The bridge with the 210-m length and five spans, located in Beijing, China, is composed of steel main structure and exterior enclosure structure. The appearance of the enclosure structure with 9028.5-m$^2$ area is highly non-linear, but impressive, as shown in Fig. 1. The main structure is made of steel arch and the enclosure structure is made of FRP curved sandwich panels with PUR foam core. To connect the enclosure structure and the steel arch, the steel brace system has to be designed. The enclosure structure is grouped into several parts according to each location, including bottom part, water platform and sidewalk parts as Fig. 2 shows. Each part is further divided into small components, from 3.5 m to 5.5 m, along the longitudinal direction. The total enclosure structure is divided into 968 panels. Each panel is unique and has to be designed individually. The main loads, includes 5.5-m water pressure at most, 2-kN/m$^2$ fundamental wind pressure, and 0.4-kN/m$^2$ fundamental snow pressure.

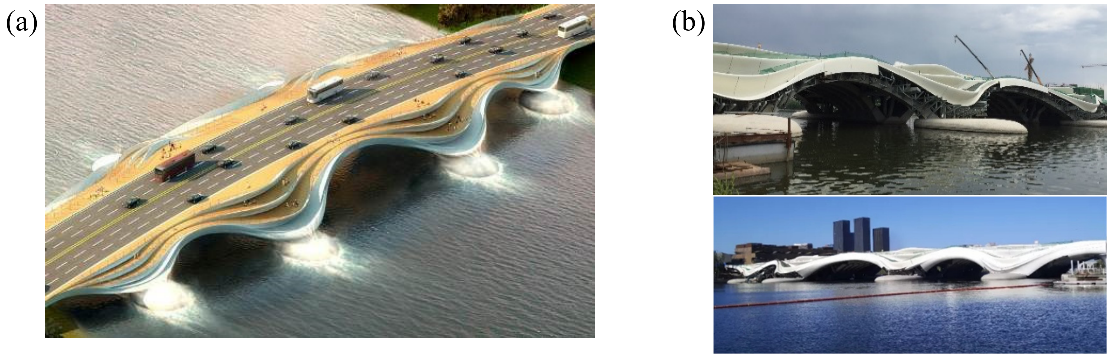


*Fig. 1: Enclosure structure of FRP curved sandwich panels: (a) rendering; (b) partial installation.*

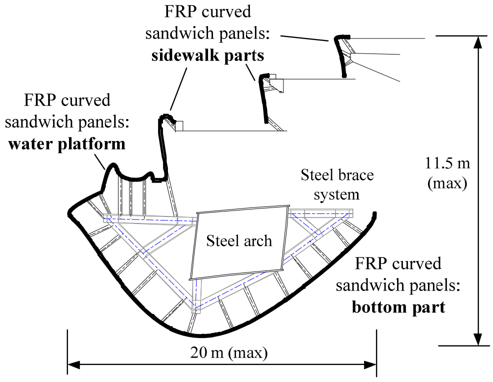


*Fig. 2: The composition of the enclosure structure.*

## 3. MATERIAL PROPERTIES

The FRP curved sandwich panel is composited of GFRP (glass fibre-reinforced polymer) laminate face sheets and PUR foam core. The GFRP laminate is designed as transverse isotropic and the PUR foam core is designed as isotropic. The material properties are listed in Table 1.

***Table 1: Material properties of GFRP laminate and PUR foam core.***

| Materials | $E_1$ (GPa) | $E_2$ (GPa) | $E_3$ (GPa) | $G_{12}$ (GPa) | $G_{23}$ (GPa) | $G_{13}$ (GPa) | $\nu_{12}$ | $\nu_{23}$ | $\nu_{13}$ |
|---|---|---|---|---|---|---|---|---|---|
| GFRP laminate | 20 | 20 | 3.2 | 3 | 3 | 3 | 0.30 | 0.30 | 0.30 |
| PUR foam core | $E$=20×10$^{-3}$ | | | $G$=7.8×10$^{-3}$ | | | $\nu$=0.15 | | |

## 4. STRUCTURAL DESIGN

### Design of sandwich panel

The sandwich panels have highly non-linear appearance, as shown in Fig. 3(a), making it impossible to design with theoretical method [8]. FEA (finite element analysis) provides an efficient approach to assist the structural design. In the enclosure system, most of the bottom part is submerged into the water when the water depth comes to 5.5 m. So it is chosen here to show the structural design process. The digital model of bottom part in Rhinoceros is saved as ACIS documents (.sat format). Shell 99 element is selected to simulate FRP curved sandwich panels in ANSYS, the shell is defined into three layers, including two layers of FRP face sheets and one layer of PUR foam core. The element size is about 0.4 m, and the total element number is 15903. Each panel is usually supported by 5 steel brace trusses through support joints. Adjacent panels are connected with assembly joints. The boundary conditions are defined by constraining the degrees of freedom at corresponding nodes. The water load is applied perpendicular to each element according to each location. The dead weight is also considered. The FEA is based on elastic analysis. The safety factor of strength is set as 3. The displacement of FEA results for bottom part is shown in Fig. 3(b). Based on the FEA results, the thicknesses of FRP face sheets and the foam core are adjusted to optimize the structural design. Final the thickness of FRP face sheets changes from 6 to 12 mm, the thickness of foam core changes from 40 to 100 mm according to the load conditions.

***Fig. 3: FRP curved sandwich panels: (a) the groups and divisions; (b) the displacement of FEA results of bottom part.***

### Design of connection joints

The connection joints include support joints and assembly joints, as shown in Fig. 4(a). The support joints are embedded in the sandwich panels. To reduce the stress concentration, the support joint is designed as Fig. 4(b), in which the FRP ribs have the K-shape end. The assembly joint is designed to connect adjacent panels but let the water leak out at the same time. The load is transferred from the panels to the steel brace system through the support joints. The structural design is conducted with FEA in ANSYS. The safety factor of strength is set as 4. In the FEA, the FRP is simulated by solid 46, and the foam core is simulated by solid 45. The thickness and length of the components are optimized through analyzing the FEA results.

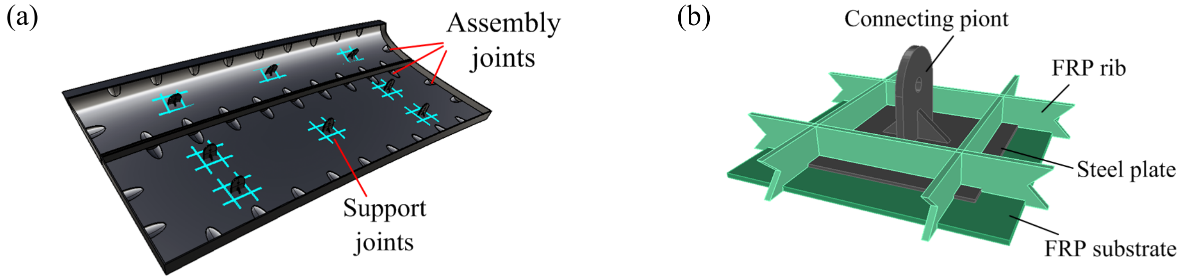


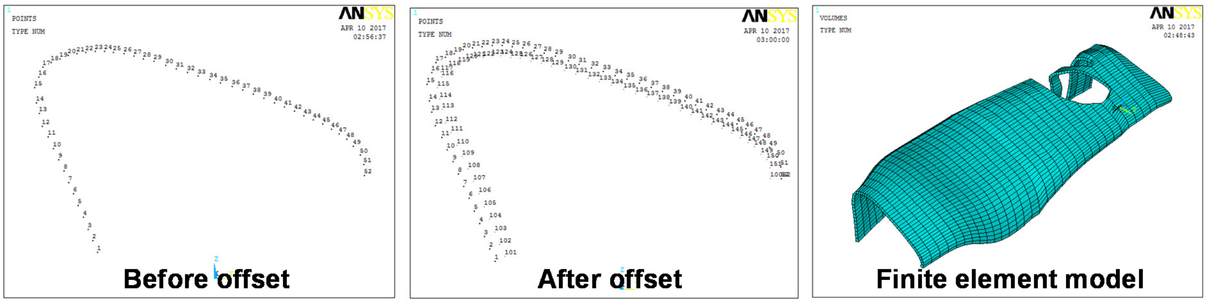
***Fig. 4: Connection joints: (a) the sketch; (b) the details of support joints.***

## 5. STRUCTURAL OPTIMIZATION AND MANUFACTURING

In this project, the 3D digital model built in Rhinoceros contains only the facade of the enclosure system, but not the thickness of the panel, which can be calculated and determined through FEA. Generally, the thickness of the panel is design to be uniform for a single panel in the current FEA process. However, the thickness can be further optimized to reduce the use of the materials as soon as possible. A parametric offset method is put forward here to realize the above objective. In this method, the offset is along the angular bisector direction, and the offset distance $R$ is controlled with a function $f(j)$ as shown in Eq. 1, where the $f(j)$ is the function of the optimization variables defined in ANSYS.

$$R = f(j) + R_0 \tag{1}$$

The mismatch correction method is provided in the parametric offset process to ensure the finite element model built successfully for the facade with large curvature. The parametric offset and modeling process is shown in Fig.5. The nodes on the outer appearance were first chosen in Rhino and then were input into ANSYS. Then the nodes were offset one by one according to the distance function $R$. Finally, the finite element model was built up based on the solid model directly generated from the nodes as shown in Fig.5.



Before offset

After offset

Finite element model

*Fig. 5: Parametric offset and modeling using ANSYS.*

The results of structural optimization are used to guide the manufacturing. To reduce the cost, two kinds of manufacturing processes are applied. For the overwater panels, the hand-lay-up technique is chosen because of the low level of loads. However, for the underwater panels, the VARTM (Vacuum Assisted Resin Transfer Molding) is chosen to provide high quality. In the process of hand-lay-up technique, the mold could be constructed with wood to further reduce the cost.

## 6. CONCLUSION

The following conclusions can be drawn from this study:

(1) The structural design and optimization are conducted through the design of FRP curved sandwich panels, connection joints.

(2) The FRP ribs and K-end are designed to reduce the stress concentration at the support joints.

(3) The variable thickness optimization for FRP curved sandwich panels is realized through parametric offset.

## ACKNOWLEDGMENTS

The authors acknowledge funding supported by the Fundamental Research Funds for the Central Universities of China (No. BLX201706), and supported by the National Natural Science Foundation of China (No. 51278276 and No. 51522807).

## REFERENCES

[1] N. Hu et al., “Structural art: Past, present and future”, *Eng. Struct.*, 2014;79:407-416.

[2] T. Keller, “FRP sandwich structures in bridge and building construction”, *CICE 2016*: 2016, 23-28.

[3] A. Manalo et al., “State-of-the-art review on FRP sandwich systems for lightweight civil infrastructure”, *J. Comps. Const.*, 2016;21:04016068.

[4] F.G. Roosenboom, “Building the future with FRP composites”. *Reinf. Plast.*, 2014;51:26-9.

[5] T. Keller et al., “Structural concept, design, and experimental verification of a glass fiber-reinforced polymer sandwich roof structure”, *J. Comps. Const.*, 2008;12:454-68.

[6] W. Xu, “Structural envelope”, *Archit. J.*, 2014:1-5.

[7] X. Meng et al., “The application to bridge enclosure structure of FRP curved sandwich panels with foam core”, *APFIS2017*: 2017,.

[8] Y. Frostig, “Bending of curved sandwich panels with a transversely flexible core-closed-form high-order theory”, *J. Sandw. Struct. Mater.*, 1999;1:4-41.