Structural behavior and realization of a monumental ice structure in China for IASS/APCS2022

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Abstract

This paper will focus on the design and construction of a sculpture designed by American contemporary artist KAWS in collaboration with AllRightsReserved. The sculpture consists of two monumental characters. The inner structure is made with a steel frame. The steel frame was covered with a fiber reinforced polyester (FRP) composite. The surface has a layer of 5 cm reinforced ice and was realized in the winter of 2021-2022. The surface of the FRP was covered with a fabric to ensure a solid connection between the reinforced ice and the FRP. The sculpture is unique with regard to the application of ice composites in combination with FRP. In this paper there will be a special focus on the structural behavior of the sculpture. Ice can be reinforced by adding (cellulose) fibers such as wood and paper. These fibers make the ice up to three times stronger and increase the ductility, thus creating a reliable building material. This sustainable, fully recyclable building material might be a solution for temporary constructions in cold areas, ice events, the Olympic Winter Games or possibly even Mars missions. In this paper the latest developments will be described. The technique used might also be interesting for more architectural and sculptural structures.

Keywords: Ice shell, pykrete, FRP mold, ice composite, renewable, bio based, steel frame

1. Introduction

After years of experience with geometric ice structures, we are challenging ourselves to build a more complex and delicate ice sculpture in 2022. We have been able to realize this sculpture in collaboration with the American contemporary artist KAWS, AllRightsReserved, Arno Pronk, Qingpeng Li, Elke Mergny, Yilling Zhou and local construction workers.

2. Realization

From august 2021 we had several meetings about the realization of the ice sculpture, we discussed the topics below:

2.1 Design of the sculpture

The design of the sculpture started with one object. We assumed that this was not stable enough. Therefore a smaller object was added to the larger one to ensure the stability of the structure. For the foundation of the structure we considered several options. At the end we chose to realize the sculpture on a platform to spread the load over the frozen soil.

2.2 What kind of mold to work with

We have thought about different options for the construction of this sculpture. Therefore we considered: inflatable mold, mold build out of straw, or mold made of polystyrene. Due to the complexity of the sculpture and the demands of the American contemporary artist KAWS we finally choose to work with an inner model of fiber reinforced polyester (FRP) with a surface thickness of 3 mm. Because 3 mm or FRP was not strong enough we had to add an inner steel frame for the structural reliability.

2.3 How to connect the ice composite to the mold

The surface of the inner model was covered with a layer of 5 cm reinforced ice. To ensure a solid connection between the reinforced ice and the inner model a layer of fabric was applied to the fiber reinforced polyester.

2.4 What kind of reinforcement for the ice composite will be used

To improve the strength and ductility of ice natural fibers like cellulose, wood, cotton of sisal will be added. This makes this material a very sustainable, safe and reliable material to work with. It makes the material 3 times stronger than normal ice and easier to form complex shapes while keeping the structural strength. Regular ice is sensitive for thermal shock and lead to cracks in the ice. The benefit of ice composites is that it the reinforcement of the ice is not sensitive for thermal shock. This discovery could hold solutions for (temporary) constructions in cold area, events or even a Mars mission. In extreme temperature areas in the north of south pole, Siberia, or at the top om mountains it is very hard to bring common building material. Transferring natural fibers like cellulose to these areas would be an easy and sustainable way of constructing reliable structures with ice composites.

2.5 Tools and materials to work with

For the construction of the Ice sculpture the following equipment and material is required: crane, cherry picker, hoses, pumps, mixing devises, mobile container, hot air blower, electricity, cellulose, water, steel frame, foundation platform, frp mold.

2.6 Construction, location and weather conditions.

Qingpeng Li coordinated the realization of the structure. First he did some experiments in a freezer to prove that spraying of wet cellulose on a frp mold would work. There were some problems with 'X X' shape of the head of the sculpture. But after some experiments in order to achieve the iconic 'X X', we discovered a special waxing treatment preventing it to be covered from spraying ice.

The first location was in the north west of China. Later we changes the venue to Changbai Mountain which is close to the north Korean border with an altitude of 2,750 meters. On location it was not allowed to work during the night to avoid nuisance for the people that slept in the hotel close to the building site.

The usual temperature in this time of year at Changbai Mountain is -3C. But this year we experienced unusual warm temperatures of +10 degrees. The snow was melting and the earth was softening. Therefore we faced many problems and challenges. After a couple of weeks the weather chanced for the good and we were able to find a solution to deal with the problems and presented a stunning ice sculpture.

3. engineering

After a half-year research and preparation, Structural Ice made the structural design and calculation of the ice sculpture. Together with AllRightsReserved we discovered a new construction method, to realize the delicate KAWS COMPANION sculpture precisely in ice.

The structure is composed of two monumental objects (See Figure 1). The height of the biggest object is equal to 12 m. The objective of the report is to verify the displacements and the stress level of this structure under dead load and wind load.

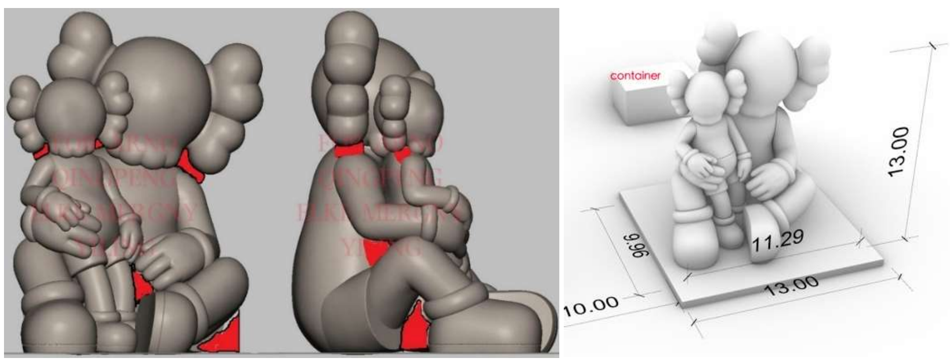


Figure 1 - Ice sculpture

4. Material

Inspired by the statue of liberty, engineered by Alexandre-Gustave Eiffel (born on December 15, 1832 in Dijon, France), our team chose to make a sculpture with an internal steel structure.

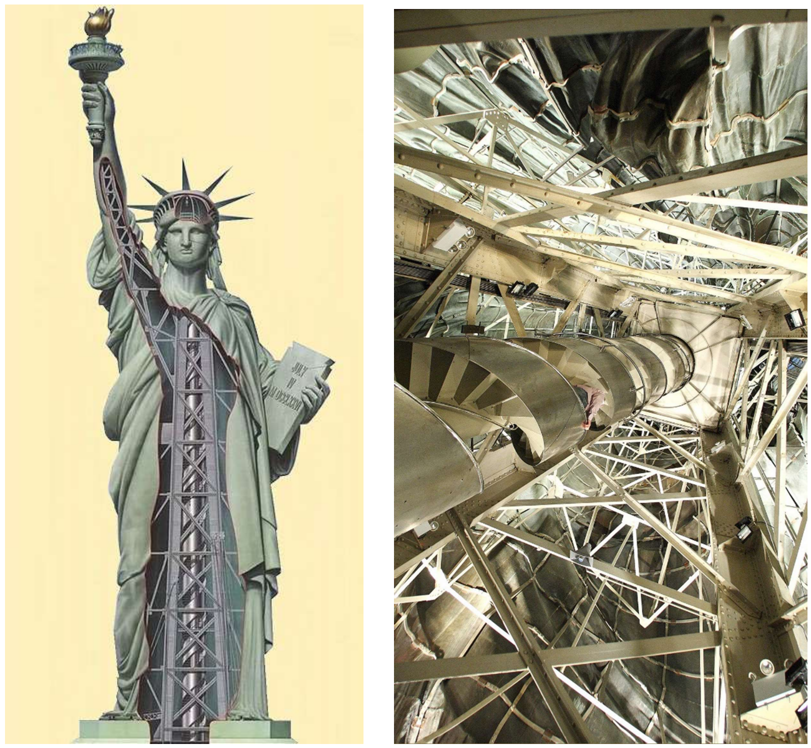


Figure 2 – internal steel structure statue of liberty

The sculpture is made by fiber reinforced polyester (FRP) supported with a steel structure. The FRP has a thickness of 3 mm and will be covered with fabric. This model will be sprayed with a mixture of cellulose and water. This mixture will form a layer of ice with a thickness of 5 cm reinforced ice. The fabric on top of the FRP will ensure the connection between the FRP and reinforced ice. The hereunder table gives the proprieties of the considered material.

Table 1

Mechanical Proprieties	Tensile strength [MPa]	Compressive strength [MPa]	Elastic modulus [GPa]	Density [kg/m³]
FRP	90	-55	3,23	1,35
Cellulose ice	0,3	-1	0,5	0,9
Steel	355	-355	210	7580

4.1 Loads

The following loads are considered:

Self-weight of FRP and steel structure

The gravity acceleration is considered equal to [9.81 m/s²]

Dead Load of the ice

We do not consider the structural role of ice. Ice therefore constitutes a dead load.

Wind Load

The wind load is equal to 0,5 [KN/m²] and acting on the vertical projection. Two cases are considered. In the first case, the wind is applied on the front of the sculpture and in the second case, the wind is applied on the back.

Figure 3 – Wind direction

4.2 Combinations

Based on Chinese Standards [2], one considers the following combinations (D=dead load, W=wind load) :

1.35D + 0.84W

1.2D + 1.4W

The second combination appeared to be the most critical and will be the only one presented in the results of the report.

4.3 Software

The Software that is used for the numerical simulation is ABAQUS FEA (formerly ABAQUS). Abaqus FEA is a software suite for finite element analysis and computer-aided engineering, originally released in 1978. The present version has several modules. The one that is used for this analysis is "Abaqus/Standard", a general-purpose Finite-Element analyzer that employs implicit integration scheme.

4.4 Model

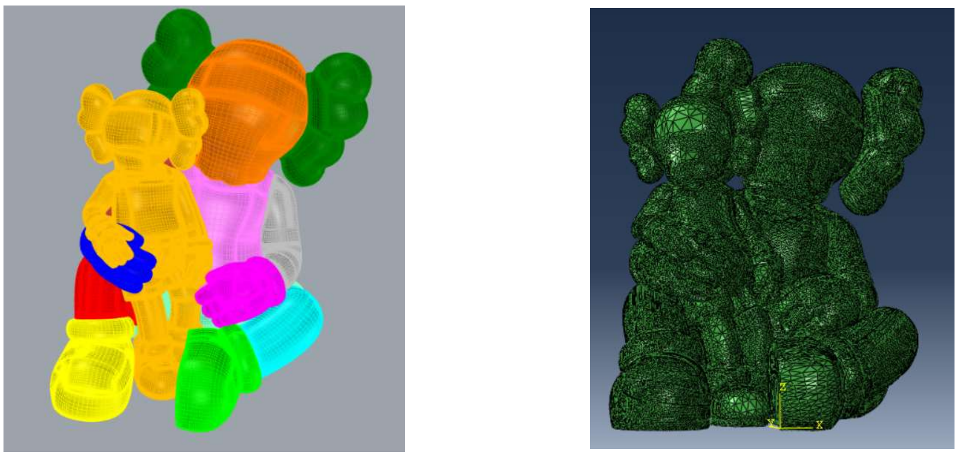
The model of the sculpture in ABAQUS are made based on the model provided by the clients. The model was modified in GiD® to be suitable for conversion into a mesh in ABAQUS (Figure 5). The mesh is made on three-dimensional triangular shell elements with reduced integration (Figure 4 (a)).

The truss was drawn in Rhino (

Figure 6) and converted into a mesh with GiD®. For the truss structure, two-node linear beam elements are used (Figure 4 (b)). The connections between the elements are rigid.

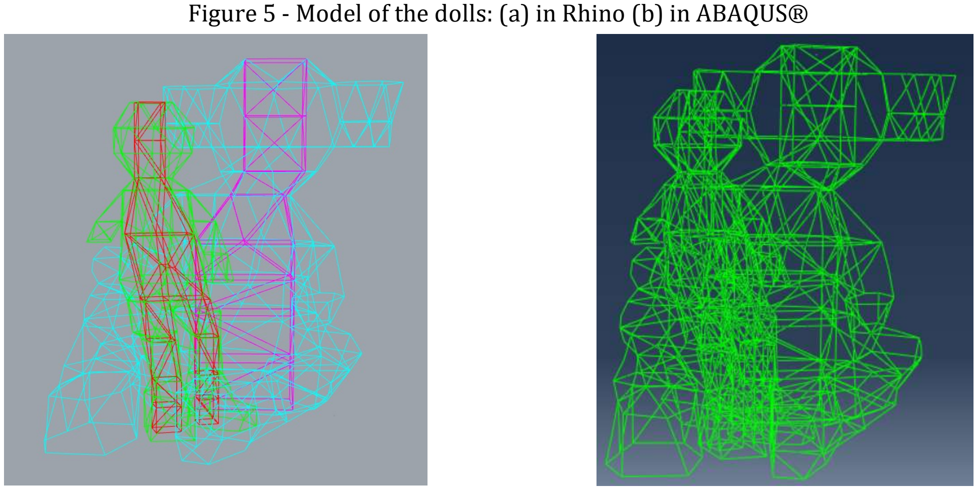
(a) **(b)**

Figure 4 - Elements used in ABAQUS: (a) Triangular shell elements (b) Two-node linear beam



(a) **(b)**

Figure 5 - Model of the dolls: (a) in Rhino (b) in ABAQUS®



(a) **(b)**

Figure 6 - Model of the truss: (a) in Rhino (b) in ABAQUS®

4.5 Frontier conditions

The part of the model in contact with the ground is completely fixed.

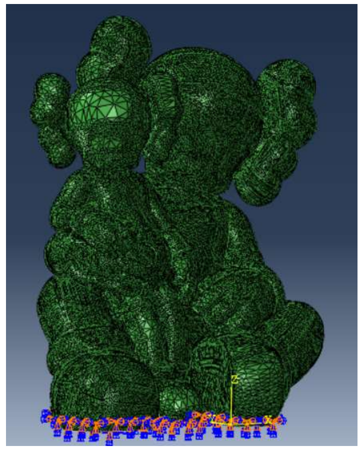


Figure 7 - Frontier conditions

5. Results

Two cases are considered:

- Displacements and stresses for the FRP alone, without any truss for reinforcement.
- Displacements and stresses for the sculpture with a truss.

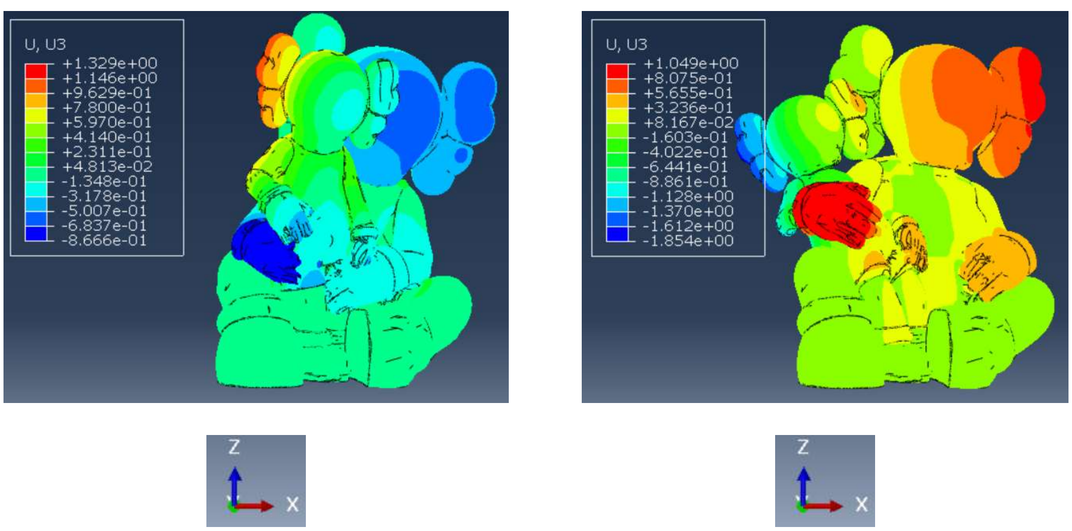
For each cases the results for the "back wind" and "front wind" are presented.

The displacements are given in [m] and the stresses are given in [N/m²] = 1E-6 [MPa]

5.1 Sculpture without truss

1.1.1 Vertical Displacements

The displacements are of the order of a meter in both cases. The FRP is not stiff enough.

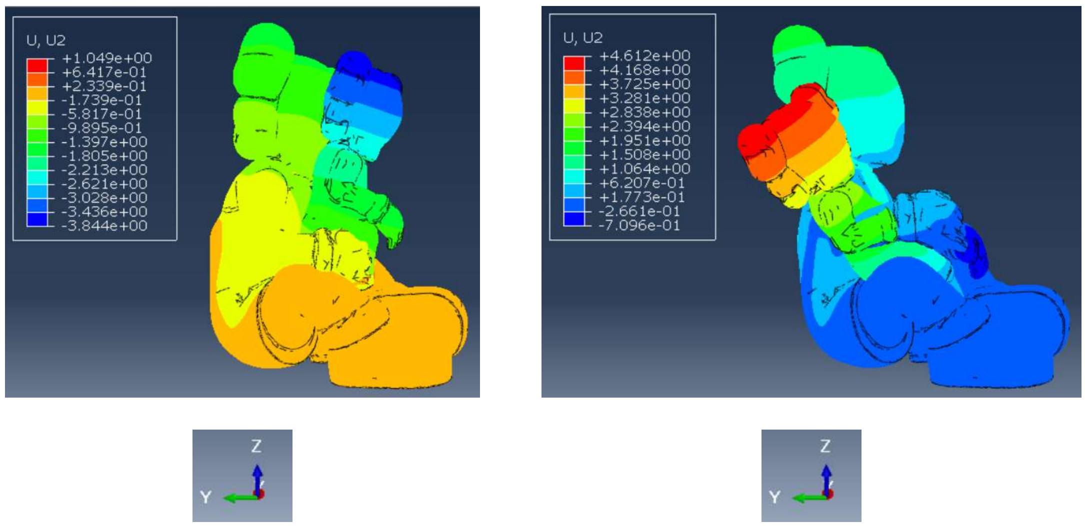


(a) **(b)**

Figure 8 - Vertical displacements [m]: (a) Back wind (b) Front wind

1.1.2 Horizontal displacements (wind direction)

The observation is the same as before. The displacements are of the order of a meter in both cases. The FRP is not stiff enough.

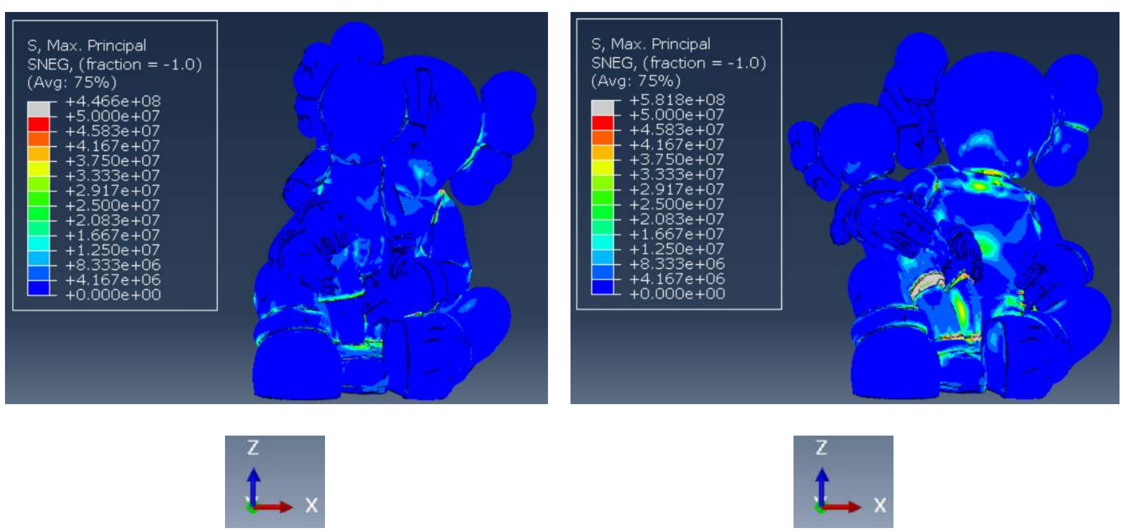


(a) **(b)**

Figure 9 - Horizontal displacements [m]: (a) Back wind (b) Front wind

1.1.3 Stresses in the dolls

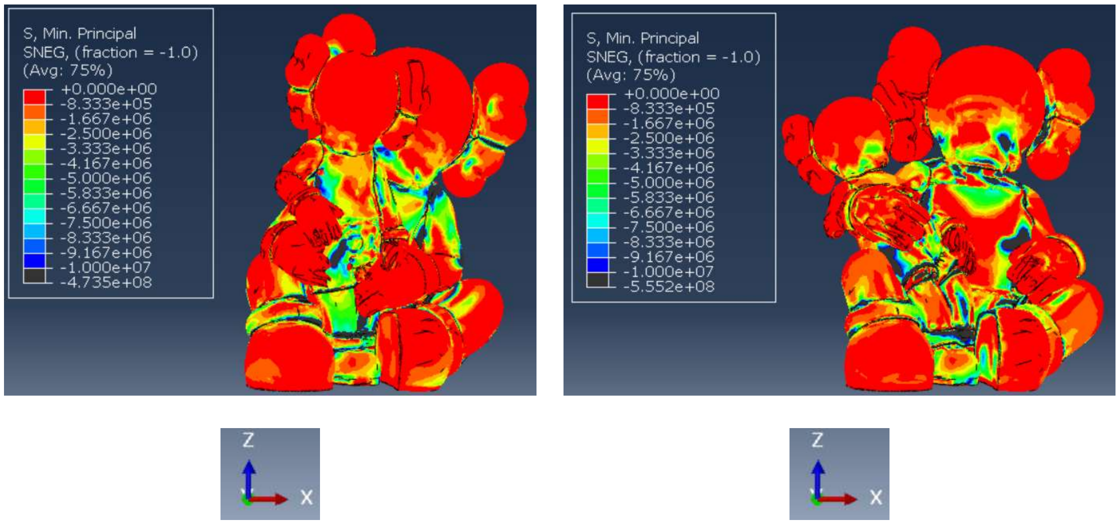
The tensile strength of FRP is equal to 90 [MPa]. Most compressive stresses are less than 50 [MPa]. The maximum stresses for the cases (a) and (b) are respectively equal to 446 [MPa] et 581 [MPa]. These stresses are found at the junctions between the parts.



(a) **(b)**

Figure 10 - Maximum principal stress [N/m^2]: (a) Back wind (b) Front wind

The compressive strength of FRP is equal to -55 [MPa]. Most compressive stresses are below -10 [MPa]. The maximum stresses for the cases (a) and (b) are respectively equal to 473.5 MPa et 555 MPa. The highest stresses are found at the junctions between the parts of the dolls and at the points of contact between the dolls.



(a) **(b)**

Figure 11 - Minimum principal stress [N/m^2]: (a) Back wind (b) Front wind

1.1.4 Conclusion

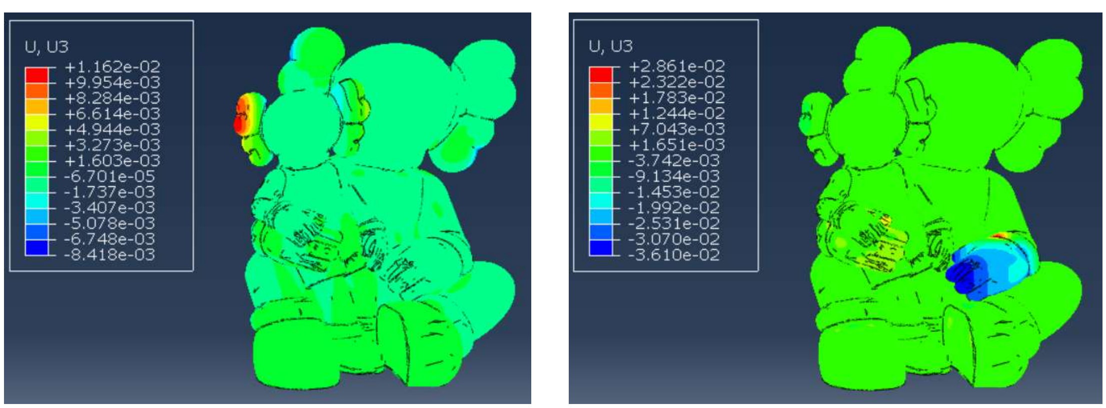
The displacements and the stresses are too high for the FRP alone. It is necessary to add a truss structure.

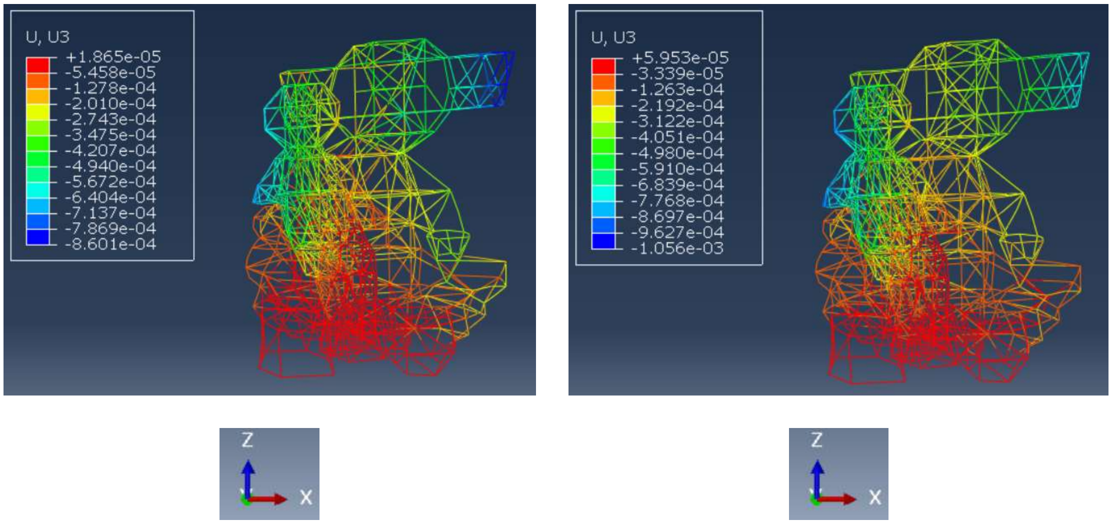
5.2 Sculpture with truss

A steel structure is added. The profile is a hollow square section of 20 cm with an interior thickness of 1 cm. This section was chosen to reduce the vertical displacements under 1cm.

1.1.5 Vertical displacements

The displacements are less than 1 cm in all cases.



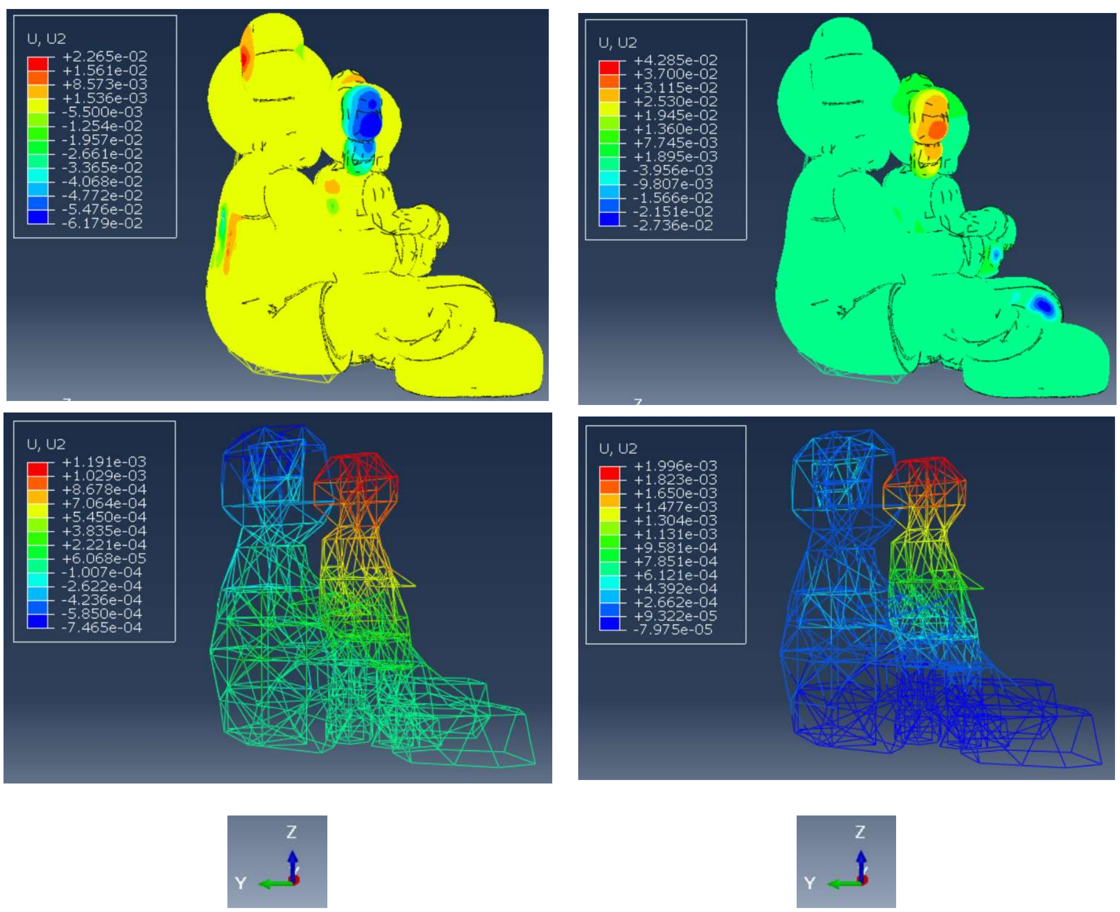


(a) **(b)**

Figure 3 - Vertical displacements [m]: (a) Back wind (b) Front wind

1.1.6 *Horizontal displacements (wind direction)*

The maximum displacement is equal to 6.12 cm in FRP. The displacements are very low in the steel structure and are less than 2 mm.

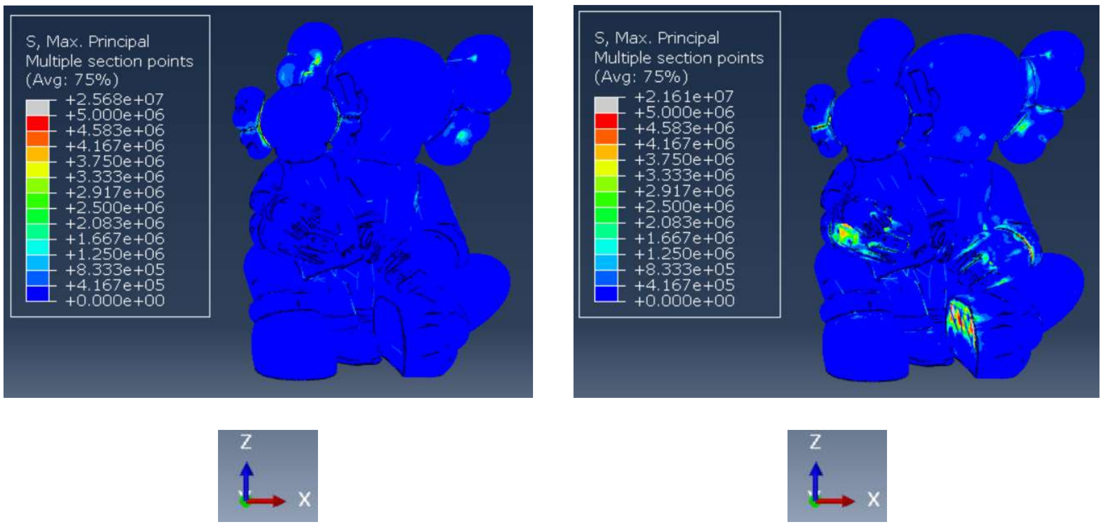


(a) **(b)**

Figure 13 - Horizontal displacements [m]: (a) Back wind (b) Front wind

1.1.7 Stresses in the dolls

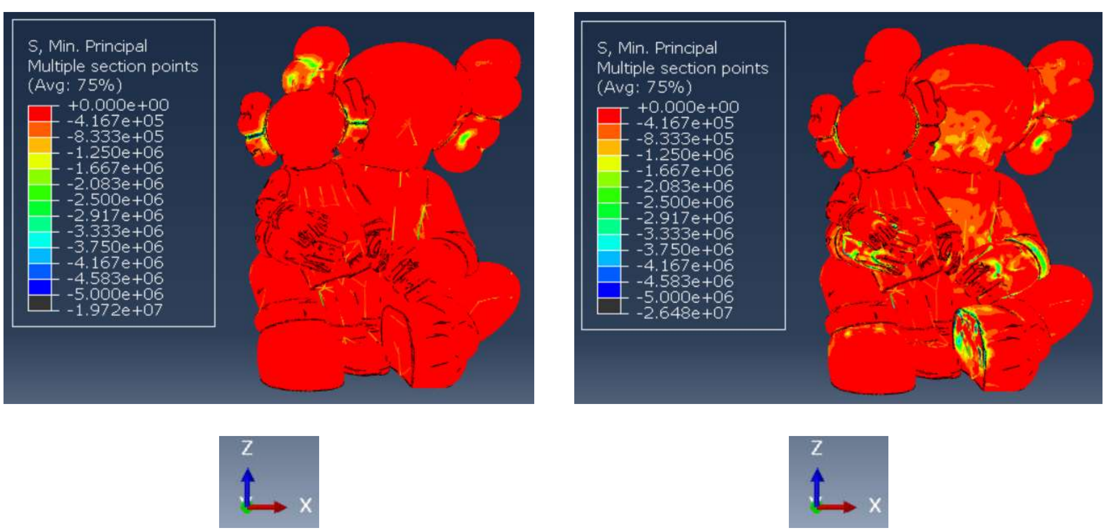
The tensile strength of FRP is equal to 90 [MPa]. Most compressive stresses are less than 5 [MPa]. The maximum stresses for the cases (a) and (b) are respectively equal to 25.7 [MPa] et 21.6 [MPa]. These stresses are found at the junctions between the parts.



(a) **(b)**

Figure 14 - Maximum principal stress [N/m^2]: (a) Back wind (b) Front wind

The compressive strength of FRP is equal to -55 [MPa]. Most compressive stresses are below -5 [MPa]. The maximum stresses for the cases (a) and (b) are respectively equal to -19.72 [MPa] et -26.48 [MPa]. The highest stresses are found at the junctions between the parts of the dolls and at the points of contact between the dolls.



(a) **(b)**

Figure 15 - Minimum principal stress [N/m^2]: (a) Back wind (b) Front wind

1.1.8 Stresses in the truss

The maximum tensile stresses for the cases (a) and (b) are respectively equal to 4.16 [MPa] et 5.25 [MPa]. These stresses are within the limits of steel.

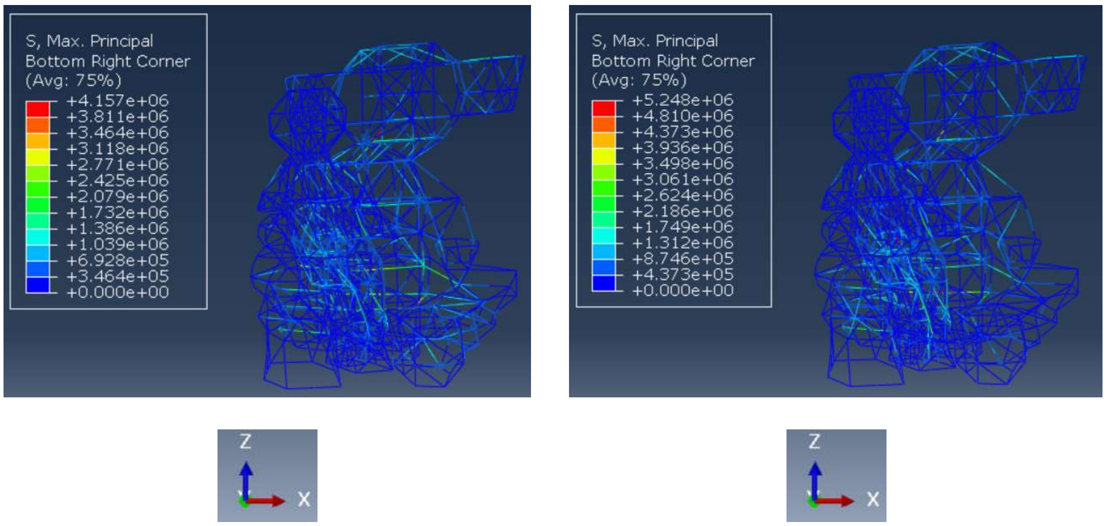
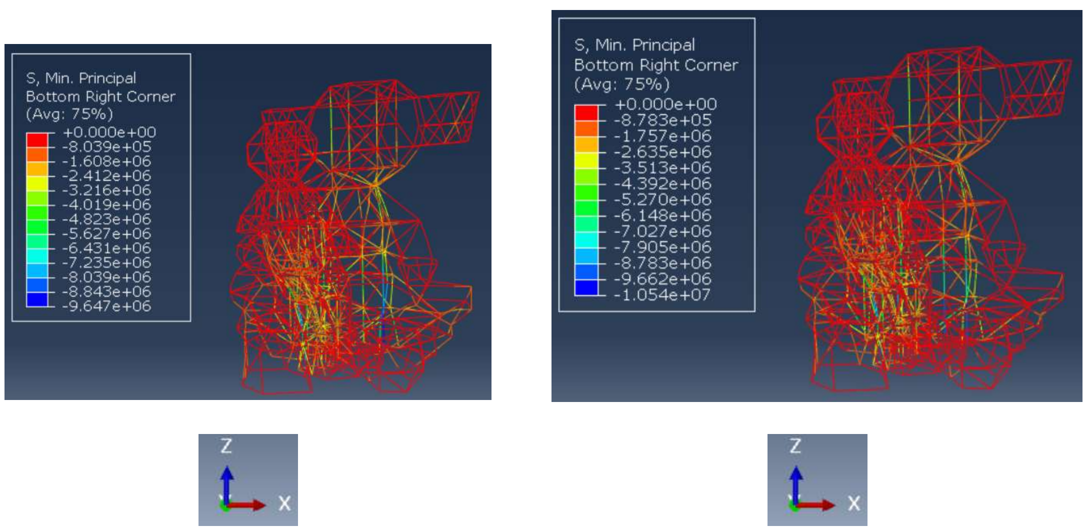


Figure 16 - Minimum principal stress [N/m²]: (a) Back wind (b) Front wind

The maximum compressive stresses for the case (a) and (b) are respectively equal to -9.65 [MPa] et 10.54 [MPa]. These stresses are within the limits of steel.



(a) **(b)**

Figure 17 - Minimum principal stress [N/m²]: (a) Back wind (b) Front wind

FRP alone cannot support the self-weight, wind loads and dead load of ice on its own. A steel structure makes it possible to maintain a satisfactory level of stress and low displacement.

The design of the steel structure is indicative and cannot be considered as a definitive design. Indeed, it will be necessary to optimize the section and to check the buckling of the elements. This design must be carried out by an engineering office.

6. Conclusion

Structural Ice are pursuing all the possibilities of ice structures, from dome to tower, to 3D printed grid shell structures, etc. The last project opens a new door of possibility and meanings to make ice sculptures. With all of the challenges people are facing around the globe, I think it's a very important time to have public art. This sculpture in the Changbai Mountain is such an incredible environment and it's an honor to have the opportunity to show this work on this location. I hope that people take some time to come together, break their usual routine of daily life, and have a meaningful experience with the sculpture and landscape. What are we going to build in the future? Please look forward to new ideas and share your ideas with us!

7. Notification

There were no conflict of interest and we thank all people that were involved in this project for their hard work and contribution.

Figure 18 – 20 FRP sculpture covered with fabric

Photo@by.harper

Figure 21-23 – FRP sculpture covered with ice

Photo @hym.1 Photo@nk7

Figure 24 – Final result of ice sculpture

8. References

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