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Design and construction of SPACEPLATES for underwater habitat

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Abstract

The paper presents an experimental design project in collaboration with N55, a Danish group of artists, and architect Anne Romme to build an underwater habitat using a facetted plate shell structure. The egg-shape structure is constructed with 6mm welded steel plates; three plates meet in all vertices, and structurally this has the consequence that the vertices are not active in the overall load transfer of shell forces. The structure also has wet porch at the base for open access. The finished structure will be inhabited for three months during 2015.

The single-person habitat will be constructed and placed at 2.5m below water at Darling Harbour of Sydney, Australia. The base of the structure is filled with concrete and scrap steels to work as ballast, which will counteract the uplift force from the hydrostatic pressure. Acrylic plates are integrated into some of the steel plates for construction windows. The thickness of the windows are 15mm and 25mm; thicker window is located at the top plate where the pressure difference between internal pressure and hydrostatic pressure is the greatest. The structure will be suspended from nearby pontoon(s) using three stainless steel cables. These tension cables will prevent the structure to drift way by underwater wave, and from other dynamic loads created by the unsynchronized movements between the structure and the pontoons. However, the actual governing design load for the cables has been for lifting the submerged structure out of the water after its service life.

A simplified finite element model has been constructed for the project, and also computational fluid dynamic analysis has been carried out to study the effect of wave loads on the structure.

Keywords: Facetted Shell, Underwater, Design, Construction, Computational Analysis, Spaceplates.

1. Introduction

Shells constructed in continuous Gaussian curvature can have great structural efficiency with appropriately designed form. Facetted shell structures are constructed with plane plate elements [1], yet the discretised form can approximate the efficiency of continuous shell forms. In addition, the flat panel elements are much more practical in means of construction in comparison to double curved surfaces. For an example, in Bristol Greenhouse Project, the facetted shell structure was constructed using prefabricated laser-cut aluminium panels [2]. The panel sizes are adequate for one person to carry. The panels are joined together using simple bolt and nut connection along the edges of the panels, and owning to the geometrical efficiency, the part of the structure gains the necessary stiffness as soon as it is joined with the adjacent panels. Thus, following the adequate sequence the whole structure can be constructed by only one or two people (Figure 1).

Figure 1: Spaceplates Greenhouse Project (Photos by N55 and Anne Romme)

This paper presents the design and construction of a facetted shell structure, which will be suspended 2.5 metres below the sea level at the Darling Harbour, Sydney, Australia. Three stainless steel wire-ropes are used to suspend the structure from nearby pontoons, as they are not permitted to stand on the sea bed. The main stresses in the wire-ropes are induced from the orbital wave motions. When undisturbed by such dynamic forces, the structure will be in the state of equilibrium as the total buoyance force will be balanced by the calculated weight of the structure, and thus there is a minimal contribution to the total tension stresses in the wire-ropes. Preferably, the weight is adjusted to give a slight force resultant acting downwards; to secure a steady environment in the habitat.

The structure is located at a relatively calm location in the harbour with small wave heights (conservatively, 0.62 m from passing by ships and 0.71m from wind waves [4]). Normally measured wave period is 6 to 8 seconds due to the sea breeze in New South Wales coast area [5]. However, in consideration of the site being shielded from the strong sea breeze, the wave period is estimated as in the range from 2.3 to 5.0 seconds which is the value used to calculate the corresponding phase velocity of the wave.

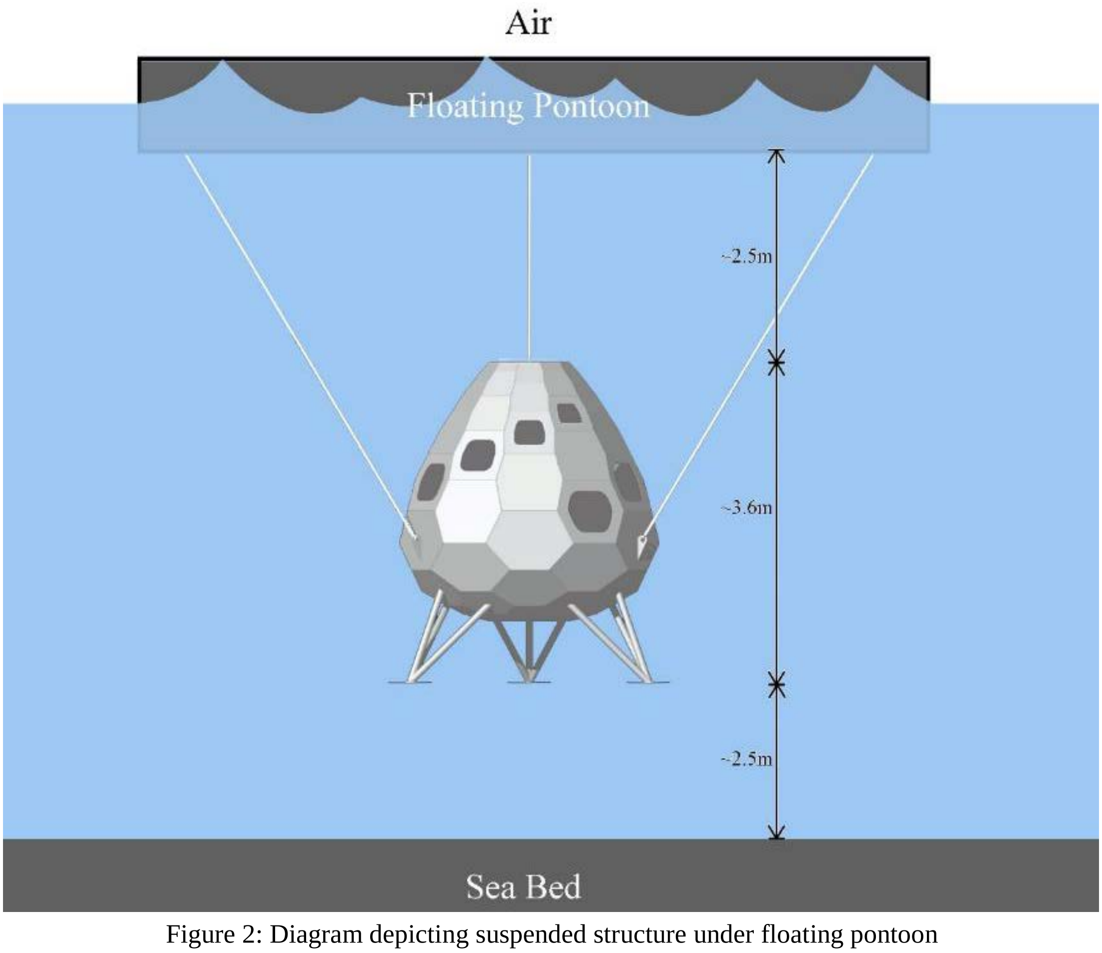

Figure 2: Diagram depicting suspended structure under floating pontoon

2. Loads

The following loads are considered for the design and analysis:

- Hydrostatic Pressure
- Internal Air-Pressure
- Wave Load
- Self-weight of Steel Shell Structure
- Concrete Ballast Load
- Live Load
- Growth Load

2.1 Hydrostatic Pressure and Internal Air-Pressure

Hydrostatic pressure increases linearly with depth, which means the greatest hydrostatic pressure is present at the bottom entrance level of the structure. The internal air pressure must counterbalance the hydrostatic pressure to prevent overflow of water through the wet-porch. Given that the magnitude of air pressure is constant at any point inside the structure, it leaves the greatest pressure difference at the top surface of the structure where the hydrostatic pressure is lowest.

The hydrostatic pressure at the entrance of the structure is 58 kPa; whereas the pressure at the top surface is 29 kPa. Thus the greatest pressure difference, which exists at the top plate becomes 58 – 29 = 29 kPa.

2.2 Wave Load

Linear wave theory has been used for the following calculations. As it is mentioned above, the wave period of the site is estimated at 2.3 ~ 5.0 seconds. An accurate approximation for the wavelength is calculated from the following equation [3]:

$$\lambda = T\,(gd)^{\frac{1}{2}}\left(\frac{f(\omega)}{1+\omega f(\omega))}\right)^{\frac{1}{2}} \qquad (1)$$

Where,

$\boldsymbol{f(\omega)}$ = 1+$\sum_1^4 \boldsymbol{\alpha_n \omega^n}$, $\boldsymbol{\omega = \frac{4\pi^2 d}{gT^2}}$, and $\boldsymbol{\alpha_1 = 0.666}$, $\boldsymbol{\alpha_2 = 0.445, \alpha_3 = -0.105, \alpha_3 = 0.272.}$

The phase velocity has been calculated according to the following equation [3]:

$$c = \sqrt{\frac{g\lambda}{2\pi}\tanh(\frac{2\pi d}{\lambda})} \qquad (2)$$

Based on the above equations the wavelength is calculated as 8.0 ~ 29.4m and the phase velocity is calculated as 3.5 ~ 5.7m/s.

For theoretical wave load calculations, Morrison's Formula and Froude-Krylov Force methods are used [3] which are later compared with the values from computational method. Both methods showed good correlation, for example, for wave period of 2.3 seconds the Morrison's formula gave wave load of 23.0 kN; and 21.0 kN for Froud-Krylov Force method. These theoretical values also showed good correlation with the value from computational analysis at 28.6kN which will be discussed in more detail in section 3.

2.3 Self-weight of Steel Shell Structure and Concrete Ballast Loads

Total vertical force (Buoyancy force) from the hydrostatic pressure is calculated as 132 kN. The self-weight of the steel structure is at 13.6 kN (1.4 tons), and the weight of concrete ballast (filled up to the lower half level of the structure) is 113.50 kN (11.6 tons). In conclusion, there is about theoretical 5.0 kN buoyancy force left still to be balanced. This is of course theoretical value, and there will be discrepancies during the construction, on-site measurements and necessary adjustments will be inevitable.

3. Computational Analysis

3.1 Static Analysis

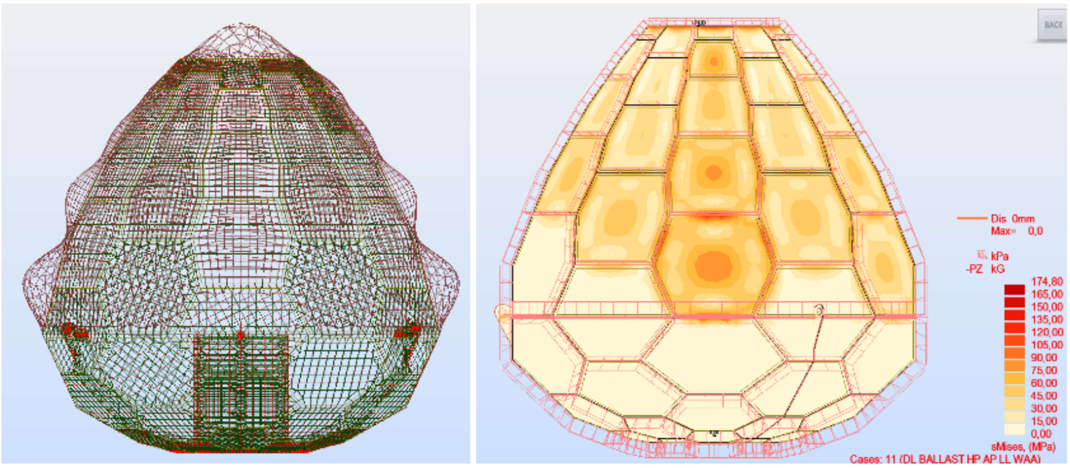

Figure 3: Structure under combination loads: Deformation (Left) and Von Mies Stress Contour (Right)

A finite element model has been created where the loads have been applied in selective combinations. The analysis shows that in general the initially suggested 6mm thickness of the steel plates is more than sufficient for the combined loads. The maximum stress incurred in the plates is 175 MPa, where the allowed maximum stress for the material is 280 MPa/ 1.1 = 255 MPa. However, the critical stress condition incurs at the tension cable connections, when the structure is pulled out of the water. At this state, the structure is under full gravitational act with additional marine growth on the surface. From the computational model, it is calculated that the total reaction force at each anchor point reaches 75kN.

The permissible bearing resistance at the anchor hole is calculated in accordance with Eurocode 3 (EN1993-1-8:2009, Table 3.4) with the consideration of smaller pin size than the hole diameter. The bearing resistance with 10mm plate thickness is calculated as 81kN, which is sufficient for the given load.

3.2 CFD Analysis

The wave load applied to the structure is calculated from simple computational fluid dynamics analysis with the wave phase velocity of 3.5 m/s (min.) and 5.8 m/s (max.). The calculated static pressure on the applied face is 10.1 kPa (min.) and 26.6 kPa (max.); and the negative pressure perpendicular to the wave direction is 8.6 kPa (min.) and 23.0 kPa (max.) respectively. These values are applied as wave loads to the static analysis model shown in section 3.1.

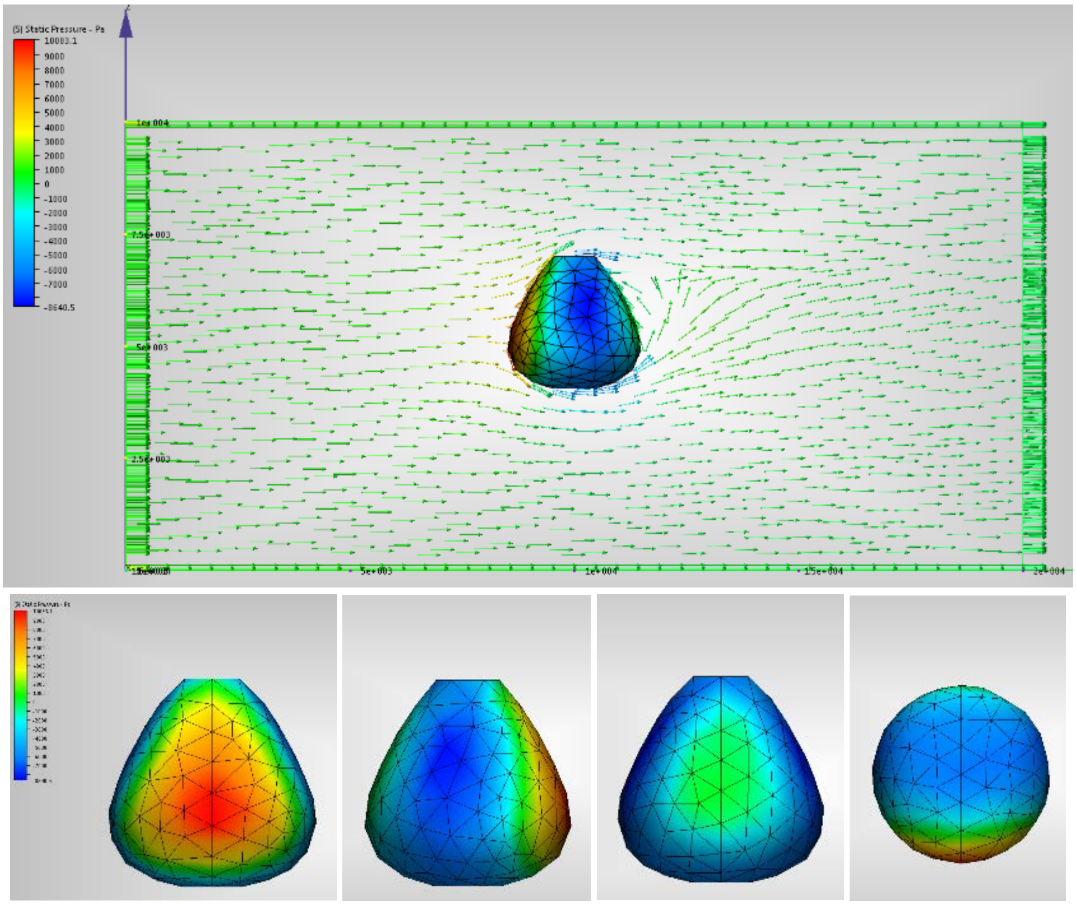

Figure 4: Velocity vector contour (Top),
Static Pressure on Front Face, Side Elevation, Rear Face, Bottom Face
(From Bottom Left to Right)

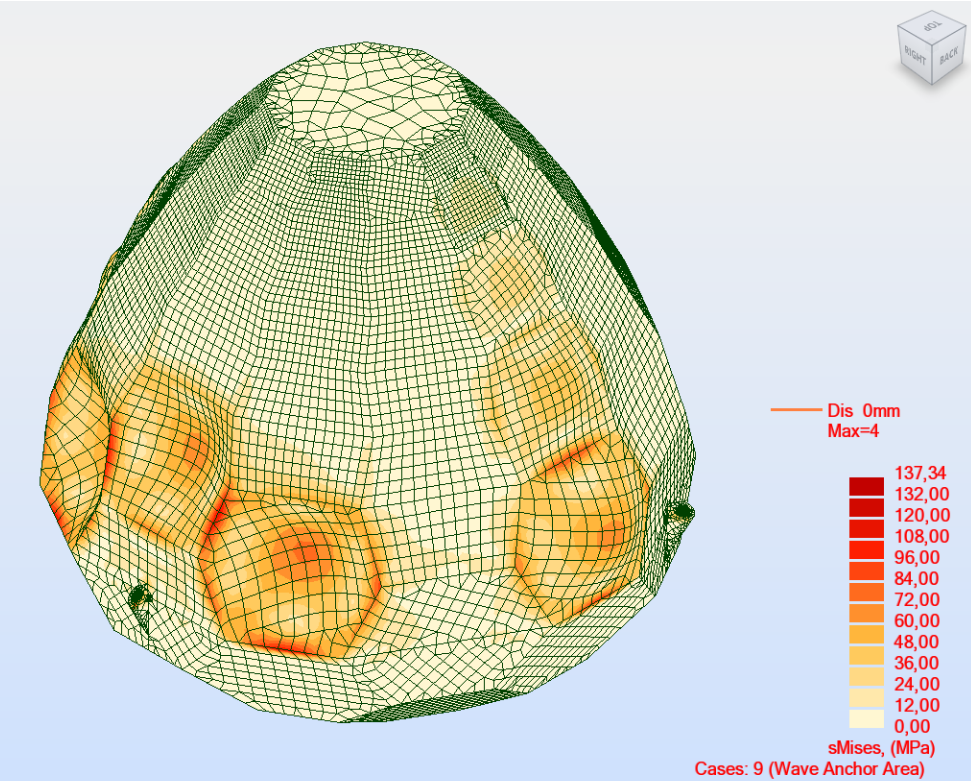

Figure 5: Von Mies Stress Contour for applied wave load

The highest von Mises stress is incurred at anchor connection with the value of 137 MPa, which is below the allowable stress of the steel, 255 MPa.

4. Construction Scheme

The structure is currently in the first phase of construction in Australia at Newman Senior Technical College. The plates are cut into the individual shapes, which are then initially joined together by point welding, which is then followed by full welding. The general construction and site installation scheme is summarized as below:

1. The steel plates are joined together to the complete shell form.
2. The supporting legs are attached to the shell structure.
3. Concrete is then poured into the ballast spaces in the shell structure.
4. Epoxy pain is applied to the structure.
5. Windows are mounted.
6. The structure is weighed.
7. The structure is then transported to the harbour site.

8. Suspension cables are connected.
9. The structure is submerged into the water.

As discussed above, the onsite adjustment for the final ballast load seems to be inevitable. There could be a number of methods to this, however it seems the most straightforward method is to add extra loads onto the structure in steps until the vertical equilibrium is achieved.

Figure 6: First phase construction with Newman Senior Technical College (Photo: Lloyd Godson)

5. Conclusion

The current paper has presented the outline of a project, which has been developed for design and construction of steel facetted shell structure for underwater habitat. In its fully submerged state, the structure is exposed to relatively small stress conditions. The worst stress condition can occur at the tension cable connections when the structure is pulled out of the water at the end of its service life.

The paper does not include discussions about mass movements of the structure under dynamics loads and the consequential comfort level of the occupants. It is part of a further investigation, and at current stage of research it is considered that the inertia of the structure from its mass will prevent any excessive dynamic movements of the structure which will cause significant discomfort of the occupant.

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