Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Iona SkyDome, A Structural Steel Gridshell at the Upper Deck of a Cruise Ship

Kosmas E. MOUPAGITSOGLOU*, Lorenzo SANTELLI

*Eckersley O'Callaghan
236 Gray's Inn Road, WC1X 8HB, London, UK
kosmas@eocengineers.com

Abstract

SkyDome is a structural steel shallow dome with glass infill panels that is located at the top deck of P&O Cruises ship Iona. It was designed by Martin Francis, the Detailed Design was carried out by Eckersley O'Callaghan and the Construction Design and Installation by Frener & Reifer in Meyer Werft shipyard. The base dimension of the dome is approximately 41x29.4 m. The initial design of the roof considered a lightweight ETFE cushions envelope and the supporting hull structure had already been designed to accommodate these loads. Both the designer and the client wanted to alter the design and adopt a more transparent solution. However, any new structure with total mass beyond 130 t would have compromised the stability of the vessel. To ensure that the total weight is within that limit, we developed a Grasshopper script to optimize the dome structurally. One of the main differences with similar land based projects, is that the dome had to be designed to accommodate not only live, thermal, wind and snow loads but also accelerations in all directions due to the ship movement, the deformations of the hull due to hogging and sagging and fatigue. To prevent unpleasant vibrations, the natural frequency of the dome was checked to be outside the frequency spectrum of the sea excitation and the ship's engines. In addition, detailed geometry non-linear analysis models with geometric imperfections were carried out to ensure that snap-through buckling of the shallow dome structure is prevented. To succeed the optimum structural behaviour, increased transparency and reduced glass waste, the selected panelisation was based on a grid with the maximum number of repeated 3m equilateral triangles. Finally, FEA models and performance mock-up tests were carried out to ensure that the glass panels can resist hailstone impact and that in case of breakage the glass panel could stay safely in place until it is replaced. Iona SkyDome is the first of its kind in the historically conservative shipbuilding industry and paved the way for similar innovative designs to be accepted.

Keywords: gridshell, dome, glass, snap-through buckling, marine, cruise ship, parametric design, optimisation

1. Introduction

SkyDome is a structural steel shallow dome with glass infill panels that is located at the top deck of P&O Cruises ship Iona. It was designed by the yacht designer Martin Francis and engineered by Eckersley O'Callaghan (detailed design). The construction design and installation was carried out by the facade contractor Frener & Reifer in Meyer Werft's shipyard in Papenburg, Germany.

The roof was initially designed by others with lightweight ETFE cushions, and the supporting hull structure was already configured to manage these loads. As per the shipyard's instructions, any other design solution for the roof exceeding a total mass of 130 tonnes would compromise the stability of the vessel.

Martin Francis, who was responsible for the architectural design of the dome, proposed to replace the ETFE roof with a glass grid shell construction. In addition, he conceived a grid shell geometry with the maximum number of repeated panels specifically to match the footprint of the ETFE dome.

The glass gridshell roof surpasses ETFE in several aspects, including robustness, transparency, and acoustics (eliminating drumming noise from rain). Moreover, it offers increased flexibility for installing lighting, sprinklers, and entertainment accessories. However, there were concerns regarding the added weight and the potential need for increased ballast due to the dome's position at the upper deck of the vessel (Moupagitsoglou [1]). Eckersley O'Callaghan played a pivotal role in developing the detailed design and persuading the historically conservative shipbuilding and cruise ship industry that a feasible solution could be achieved, one that was robust, lightweight, elegant, energy-efficient, and transparent. A lack of similar precedents in ship design has meant that our extensive expertise in structural, glass and facade engineering has been crucial in convincing the relevant regulatory bodies of the design's code compliance.

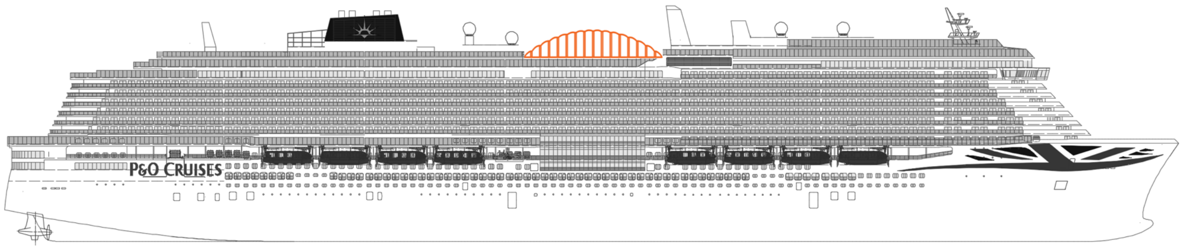

Figure 1: Elevation of the cruise ship showing the dome location.

2. Geometry of structural system

The SkyDome features an elliptical, triangulated structural steel gridshell, incorporating a tension ring and glass infill panels. The equilateral triangular glass panels have a maximum edge length of 3m. With base dimensions approximately measuring 41m by 29.4m, the dome's 4.3m height aligns with the shipbuilding hall's ceiling clearance to accommodate the overhead crane movement. Almost all of the gridshell elements are mild steel S355 RHS 140x80x5 members. The thickness of some of these members has been increased locally to withstand increased stresses from specific load combinations. Similarly, the ring beam, is composed of mild steel S355 RHS 200x300x12. All gridshell members are securely interconnected through welded connections at solid steel nodes and to the ring beam. The triangular glass panels are continuously supported to the gridshell structure for pressure loads whereas for suction loads they are kept in place via discrete patch fittings (4No. per glass panel side).

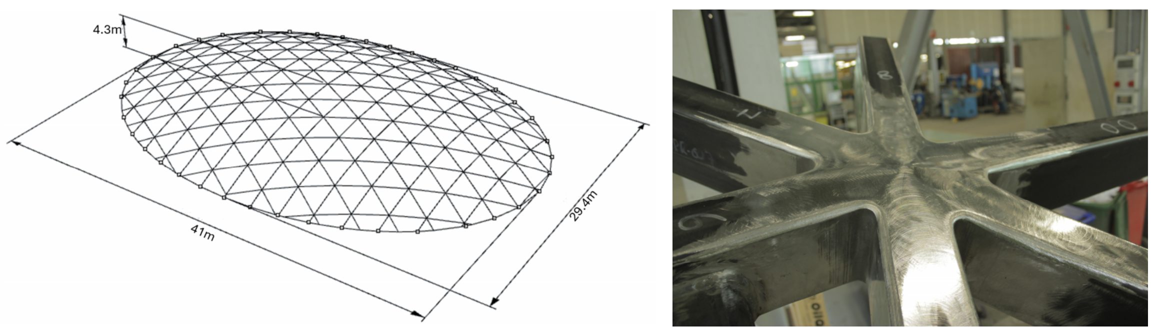

Figure 2: Geometry of structural system and typical connection at node.

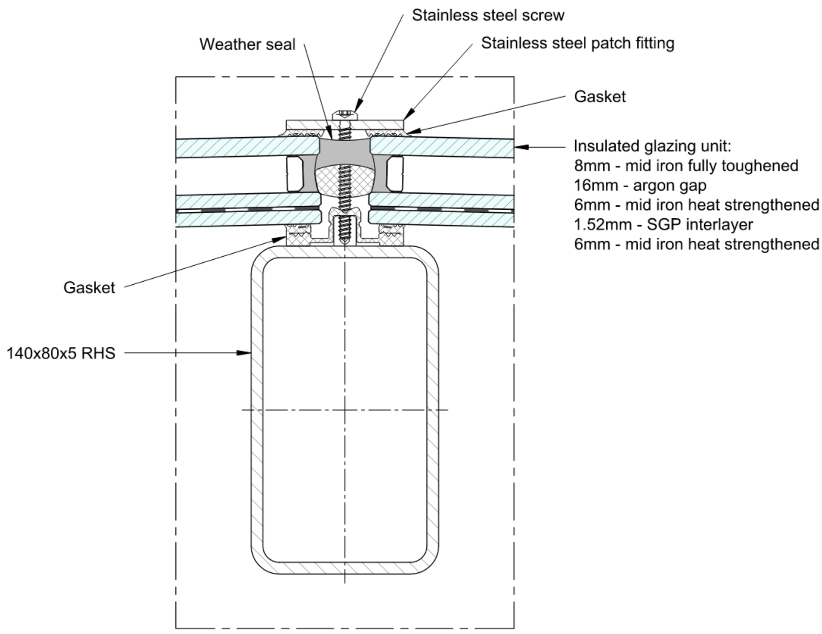

Figure 3: Glass panel to steel gridshell structure connection detail.

3. Load cases

One significant distinction from similar land-based projects is that the dome had to be designed to withstand not only maintenance live (0.60 kN/m^2), thermal, wind, and snow loads but also accelerations in all directions resulting from ship movement and hull deformations due to hogging, sagging, and fatigue. The vessel's classification society is RINA and oversees the development and enforcement of technical standards for ship design, construction, and surveying. In accordance with RINA regulations [2] and considering the dome's location, structural design required the application of a 2.5 kN/m^2 uniformly distributed load in pressure and suction. However, to account for asymmetric loads in our design, assuming maximum uniformly distributed load equal to 2.5kN/m^2, we have also incorporated the wind and snow load distributions based on Eurocodes as separate load cases [3]. The values of the accelerations in all directions due to the movement of the vessel that were used in the design are as follows:

Table 1: Acceleration values due to the movement of the ship.

Longitudinal acceleration, A.X	±0.22G
Lateral acceleration, A.Y	±0.55G
Vertical acceleration, A.Z	±0.55G

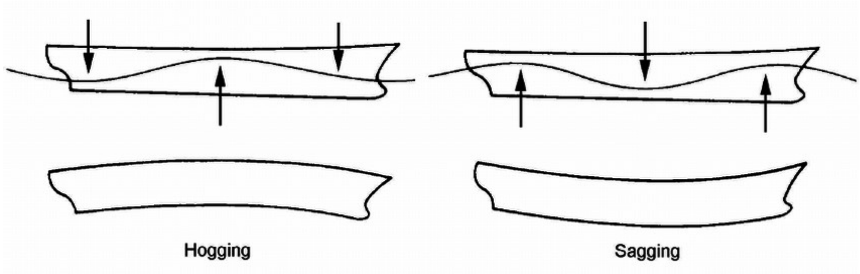

Figure 4: Hogging and Sagging of a vessel.

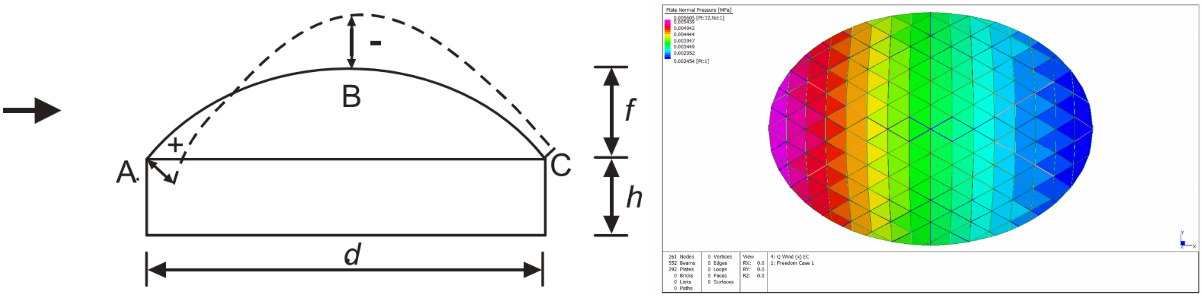

Figure 5: Wind load distribution according to Eurocodes to allow for destabilising loads.

All the load combinations and their load factors were evaluated using the 'RINA Rules for the Classification of the Ships' [2]. The most critical load combinations for stresses and global buckling calculations are the following:

— 1.0*Dead Load + 1.0*Super Imposed Dead Load + 1.0*RINA Pressure UDL + 1.0*Vertical Acceleration (-z) + 1.0*Longitudinal Acceleration (+x) + 1.0*Lateral Acceleration (+y) + 1.0*Differential Temperature Loads + 1.0*Deformations of Hull Structure due to Hogging
— 1.0*Dead Load + 1.0*Super Imposed Dead Load + 1.0*RINA Pressure UDL + 1.0*Vertical Acceleration (-z) + 1.0*Longitudinal Acceleration (-x) + 1.0*Lateral Acceleration (-y) + 1.0*Differential Temperature Loads + 1.0*Deformations of Hull Structure due to Sagging

4. Boundary conditions

The dome is upheld by vertical RHS columns on each side. It is rigidly connected to the hull structure at the front and supported at the rear by sliding bearings, which offer vertical (Z) support and allow lateral movement along the X and Y axes. While the roof structure is designed to be largely independent of the vessel's superstructure, some level of interaction is inevitable. Consequently, we modelled the vertical translational Z stiffness and the lateral rotational stiffnesses about the X and Y axes of the hull superstructure. Additionally, we simulated the induced translational deformations along the X, Y, and Z axes of the hull onto the dome, accounting for hogging and sagging effects that occur during the ship's movement.

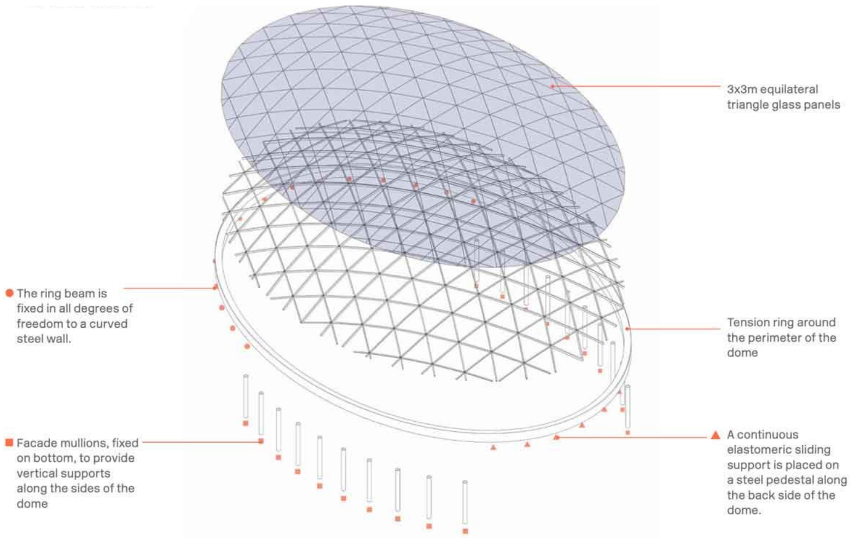

Figure 6: Boundary conditions.

5. Parametric design

Rhinoceros 5, Grasshopper and Strand7 were selected as software to perform the structural analysis. Rhinoceros and Grasshopper gave us the opportunity of generating complex 3D models, while Strand7 provided the right level of detail required by the analysis and design process. A link between the two was missing. Continuously importing models from the CAD environment to the FEM environment proved difficult and time consuming, especially during the optimisation process. The API (Application Programming Interface) gave us the possibility to create a link between the CAD and the FEM environments. This synergy gave us the possibility to optimise the analysis process and evaluate several types of grids in a relatively short amount of time.

To ensure that the total weight is within the 130 t limit, we developed a Grasshopper script to optimize the dome geometry, the cross-sections and the wall thickness of all its members. Through multiple iterations, we determined that the initially proposed gridshell geometry with 3-meter equilateral triangles as the most structurally efficient solution within the fixed parameters. The automated beam sizing script we developed to reduce the steel tonnage isn't innovative in itself, however our novel implementation accounted for the global buckling behaviour and natural frequency checks which are critical for this specific application.

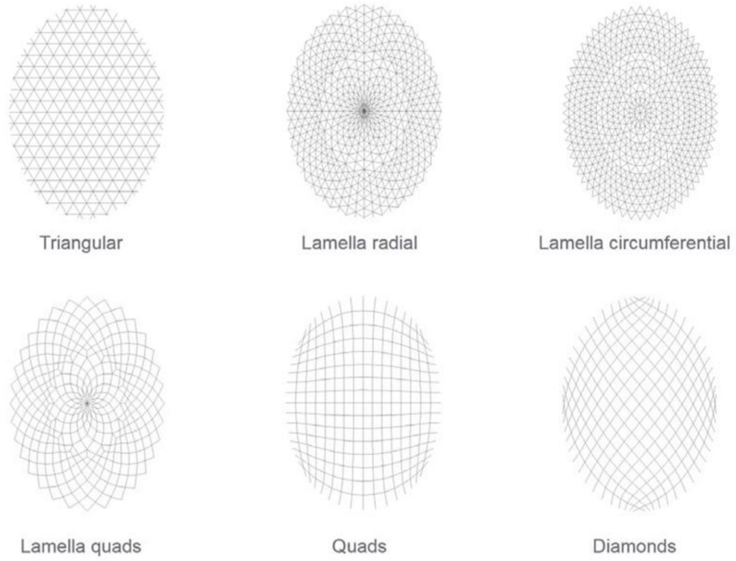

Figure 7: Parametric study of grid geometry options.

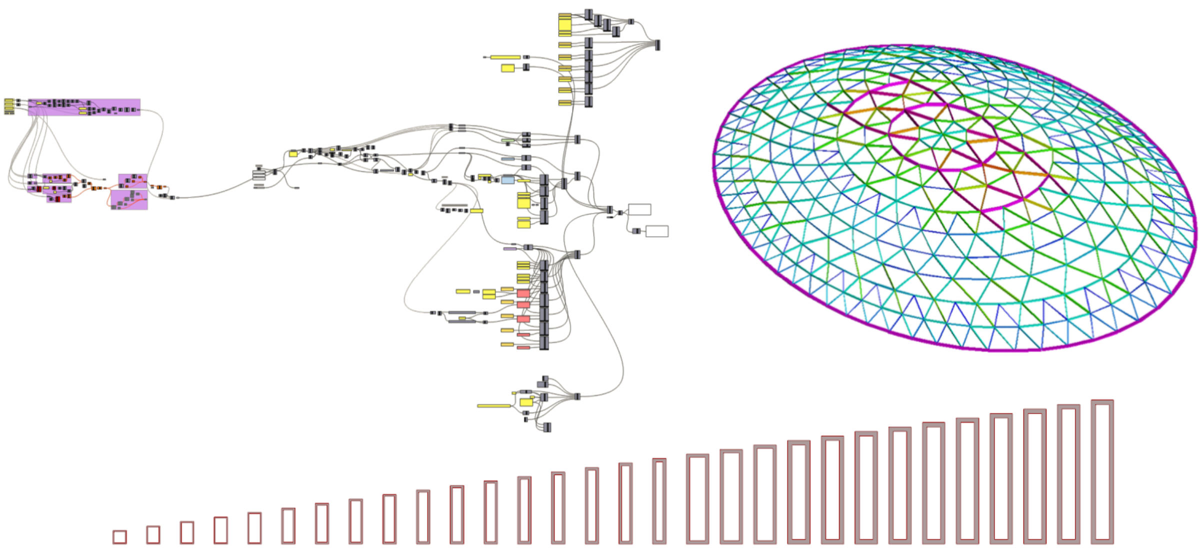

Figure 8: Parametric design for cross-section optimization.

6. Linear static analysis

As a first step, a linear static analysis was carried out to ensure that the maximum stresses of all members and the global deflections were within allowable limits.

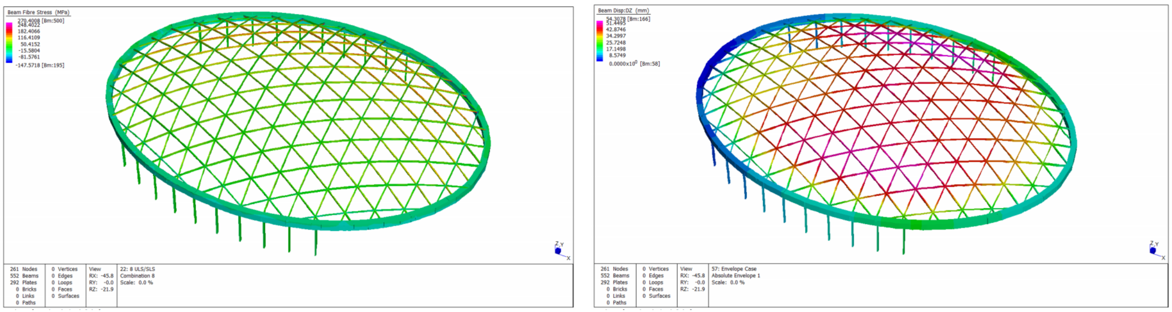

Figure 9: Maximum stresses and deflections using linear static analysis.

During the Construction Documents stage, the contractor conducted thorough structural design checks and calculations. These included detailed considerations for fatigue and comprehensive design of the connections between the grid-shell members and the ring beam.

7. Global buckling and natural frequency check

Extensive analysis and design was carried out to prevent snap-through buckling in the shallow dome. Initially, a linear buckling analysis was conducted to identify the critical load combinations and to estimate the global buckling load factor (BLF=5.4). Subsequently, for the load combinations with the lowest buckling load factors, a non-linear geometry analysis without geometric imperfections was performed (BLF=3.8). Finally, a geometry non-linear analysis with geometric imperfections was carried out (2nd order theory, BLF=2.0). Figure 10 clearly demonstrates a significant reduction in the stiffness of the structure and loss of stability when the load factor exceeds 2.0 (the load factor of 1.0 corresponds to the Ultimate Limit State, ULS load combinations outlined in Section 3). The geometric imperfections added (Span of buckling zone/200 ~ 20mm) were based on the deformed shape of the lowest buckling mode and the deformed shape of the frequency mode with the maximum mass participation. Despite the expected significant reduction in the global buckling factor between the different analysis methods, it can be safely concluded that global buckling is not a critical concern for the design of the structure.

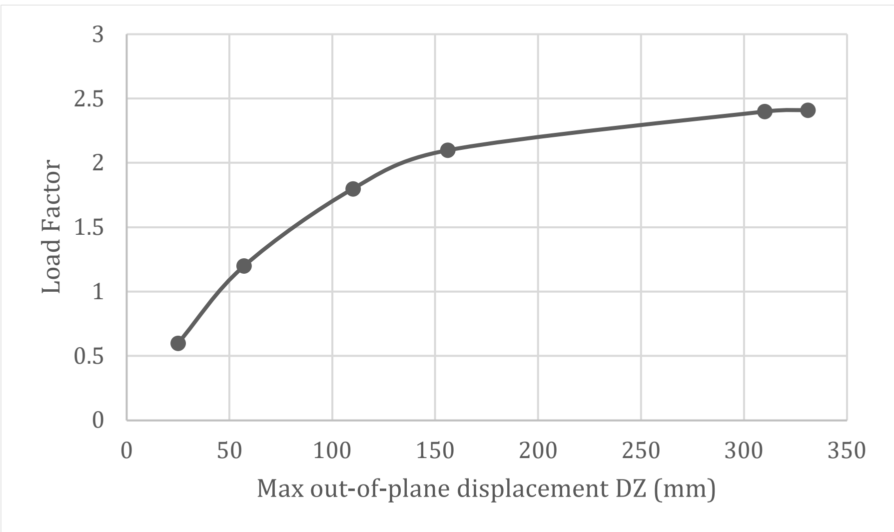

Figure 10: Maximum out-of-plane deformation DZ (mm) vs. load factor to evaluate the global buckling factor of the structure.

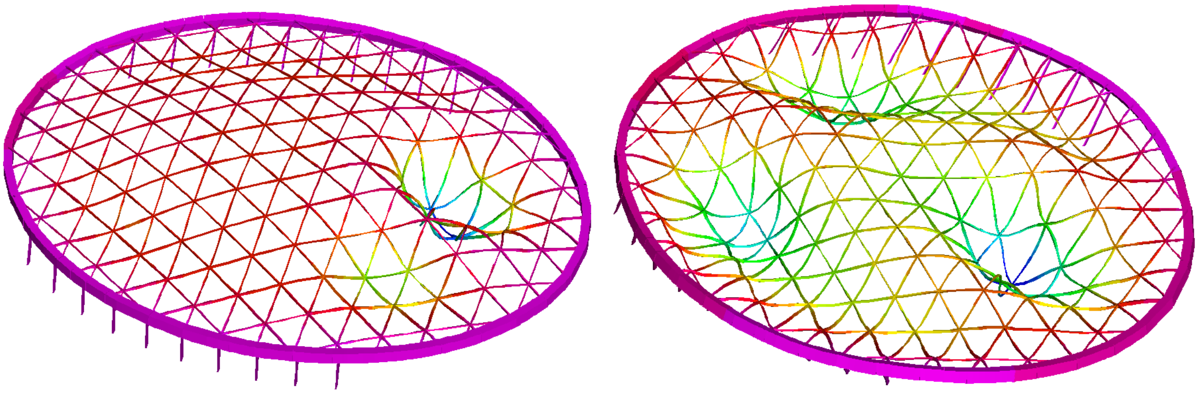

Figure 11: Exaggerated shape of geometric imperfections representing the critical linear global buckling mode (BLF=2.0) and the natural frequency mode with the maximum mass participation (BLF=2.1).

To prevent unpleasant vibrations, the natural frequency of the dome was checked to be outside the frequency spectrum of the sea excitation (0-3.5 Hz) and the ship's engines (6.0-12.9 Hz).

8. Structural glass design

Alongside the steel structure design, we also focused on specifying the glass elements. It's essential to note that while glass panels don't contribute to the structural stiffness, they significantly add to the weight of the system. Any miscalculation in estimating the glass build-up could have led to the cancellation of the glass option.

Out of the total mass of 130 tonnes, 67 t account for the structural steel, 11 t for the superimposed dead load, and 52 t for the mass of the glass panels.

To meet the U-value requirement of 1.8 W/m^2K and to provide a coating offering reduced g-value and high transparency (high light transmission), the glass panel had to be an insulated double glazed unit (DGU). Initially, we faced the challenge of convincing RINA that both the external and internal glass packages of the DGU could withstand external loads. Fortunately, this was easily resolved as it aligns with common practice in the facade industry. The glass build-up we proposed consisted of an 8mm Fully Tempered Heat Soak Tested outer pane and a 2x6mm Heat Strengthened laminated glass inner pane with a 1.52mm SG5000 interlayer.

Additionally, we had to demonstrate that the glass panels could withstand a hailstone impact. As there are no design standards for assessing the effect of a glass panel under hailstone impact, we relied on testing to demonstrate the glass performance. More specifically, we followed the FM 4473 test method [4]. To ensure that the test would be successful, we also conducted a local Finite Element Analysis (FEA) model of the panel to simulate the impact by using an equivalent static force of 6kN (Sun et al. [5]).

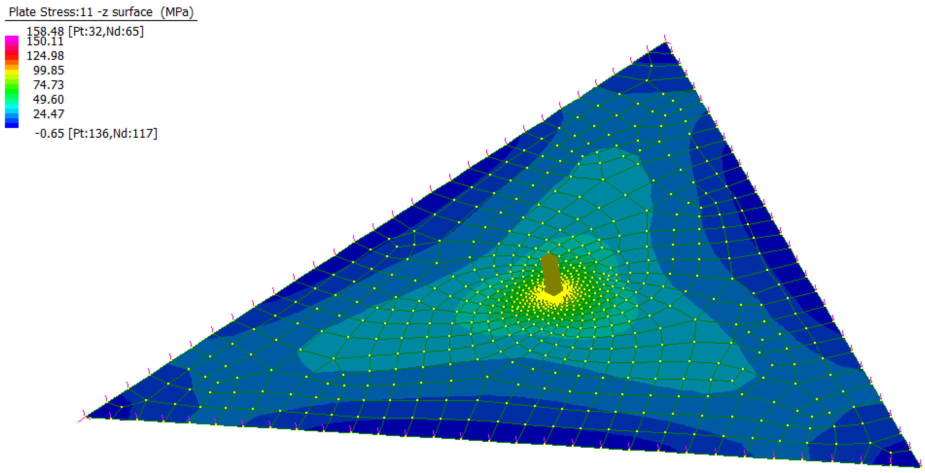

Figure 12: FEA model of hail stone impact using an equivalent static load.

Figure 13: Hail stone impact test according to FM 4473.

Finally, a fragility CWCT test ([6], [7]) was conducted to demonstrate to RINA and the client that, in the event of failure, the glass panel could remain in place until replacement. The CWCT test comprised a static, a hard body impact, and a soft body impact test. The results of the tests convinced the project team of the viability of our proposed specification. The outer Fully Tempered glass, with increased bending strength, effectively withstands various impacts, while the inner laminated Heat Strengthened glass, combined with the stiff SG5000 interlayer, helps the pane remain in place even if it breaks due to the interaction between the large heat strengthened glass fragments and the stiff SG5000 interlayer.

Figure 14: Static load test.

9. Conclusion

Iona SkyDome is the first of its kind in the conservative shipbuilding industry and paved the way for similar innovative designs to be accepted. The domes in Sun Princess (Princess Cruises) and Icon of the Seas (Royal Caribbean Cruises) are two examples that show the significant impact that Iona SkyDome had in the industry.

Figure 15: Interior view of the dome.

Acknowledgements

We would like to acknowledge Martin Francis, the dome designer, Frener & Reifer, the facade contractor and the client P&O Cruises / Carnival Corporation.

References

[1] K. Moupagitsoglou, "Structural Glass in Superyacht Applications: Overcoming Challenges, Design Standards and Analysis Methods," Challenging Glass 7, 2020.

[2] RINA Rules for the Classification of Ships.

[3] Eurocode 1: Actions on Structures - Parts 1-3 & 1-4: General actions – Snow Loads & Wind Actions.

[4] Specification Test Standard for Impact Resistance Testing of Rigid Roofing Materials by Impacting with Freezer Ice Balls, FM Approvals Class Number 4473.

[5] J. Sun, N. Lam, L. Zhang, D. Ruan and E. Gad "Contact Forces Generated by Hailstone Impact," International Journal of Impact Engineering.

[6] CWCT Technical Note 66, Safety and Fragility of Glazed Roofing: Guidance on Specification.

[7] CWCT Technical Note 67, Safety and Fragility of Glazed Roofing: Testing and Assessment.