Challenging Glass 7
Conference on Architectural and Structural Applications of Glass
Belis, Bos & Louter (Eds.), Ghent University, September 2020.

ISBN 978-94-6366-296-3, https://doi.org/10.7480/cgc.7.4609

Structural Glass in Superyacht Applications: Overcoming Challenges, Design Standards and Analysis Methods

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Structural glass has become a popular material in marine applications. It has been used to enhance the transparency not only in luxury yachts (Fig. 1) but also in passenger vessels like cruise-ships (Fig. 2). Yacht designers being inspired by all-glass facades and structural glass pavilions are trying to adopt these achievements and promote the glass design and engineering technology in the shipbuilding industry. However, designing glass elements in a marine environment involves more challenges comparing to civil applications. Glass engineers should not only consider in their calculations the wind loads and the movements of the support structure, but also the significantly higher wave loads and accelerations due to the ship movement. In addition, the watertightness of the windows is particularly important for the integrity of the vessel and the safety of the passengers. Finally, the thickness and weight of the glass can influence significantly not only the cost but also the stability of the whole vessel. The aim of this paper is to describe the typical requirements a glass window in superyacht applications needs to fulfil, possible challenges a glass engineer will meet and methods to overcome these challenges. In addition, we will present the most important design standards and compare them with relevant standards from the building industry. We will then explore the most common analysis methods and their impact on the accuracy of the results and glass build-up optimization. Adhesive connections of the glass elements to the main structure will also be described as these are the main mechanism to accommodate the hogging, sagging and torsional deformations of a hull in case of a stormy sea.

Keywords: Superyacht, Marine glass, Yacht glass, Curved glass

1. Introduction

The use of glass has become an integral part of yacht design. New superyacht concepts push the boundaries of the material beyond limits that have already been reached in civil engineering projects.

Even if the yacht designers were initially inspired by the developments of glass in the architectural industry, yacht-glass is different comparing to architectural glass for the following reasons:

- Marine environment is different to terrestrial. At sea there is no outside space to evacuate people to, no fire brigade that will come to the rescue and no hospitals.
- The glass envelope is not important for the structural integrity of the buildings. Unlike land-based structures, glass in marine applications is responsible for the weather and watertightness of the vessel. In case a glass fails, water might enter in the vessel and cause capsizing or sinking.
- The design pressures of the architectural glass elements are significantly lower comparing to glass in marine applications. In addition, marine glass is constantly subjected to accelerations in all directions due to the ship's movement.
- Clients expectations from the yacht industry are higher in terms of the visual quality of the glass elements.
- At specific locations e.g. at the wheelhouse, the visual quality of the glass is important for the safe navigation of the vessel.
- The nature of the superstructure movements is different in marine applications and are usually of larger magnitude.

The main purpose of windows in superyachts is to provide weather/watertightness and a visually continuous space between the interior of the vessel and the world outside. There is no other material like glass that can connect and separate at the same time.

Typical glass elements in superyachts consist of portholes, windows, windscreens and balustrades. Nowadays, yacht designers and clients are pushing for more challenging glass features such as stairs, pools, skylights, floors and underwater windows!

Fig. 1 Venus is one of the first superyachts in which glass was used extensively. Designer: Philippe Starck | Structural Glass Engineers: Eckersley O'Callaghan | Shipyard: Feadship Aalsmeer.

Fig. 2 P&O glass dome Iona is the first structure of this type in the cruise ship industry. Designer: Martin Francis | Structural Engineers: Eckersley O'Callaghan | Shipyard: Meyer Weft.

2. Design Standards

2.1. Rules and Regulations

According to the regulations of most of the Flag States a Load Line must be assigned to a yacht. Because of this, the design of yachts needs to follow the requirements summarized in the 'Conditions of Assignment' and the 'International Convention on Load Lines (ICLL), 1966'. Particularly the requirement for water tightness is a fundamental part of these regulations. Because the above standards were mainly written for commercial vessels, Flag States have developed national equivalents. One example is the British Red Ensign Group Yacht Code (REG:2019). REG Yacht Code gives general requirements for the weathertight integrity of glazed openings but suggests that the strength and the design pressures need to be evaluated using ISO 11336-1:2012. ISO 11336 was mainly developed to cover the need of Flag States for optimized and safe yacht glass design according to the latest developments in glass science and technology.

2.2. Design Pressures

For yachts up to 12 passengers, 3000 GT and maximum length 90m, ISO 11336-1:2012 can be used for the calculation of the glass build-up. In all other cases, BS MA 25:1973, rules and regulations from the Classification Societies or an equivalent national or internationally recognized standard can be used.

Another important aspect in the design of yacht glass is to consider the impact from floating debris such us shipping containers. Windows and portholes at the lower level of yachts need to be protected by deadlights, which are fitted on the inside of the vessel. Nevertheless, large windows cannot have deadlights that can be installed practically, quickly and easily in the event of glass breakage. In this case, sacrificial layers of glass should be added that we allow to fail in case of impact from a heavy floating object. The number of additional plies can only be determined by laboratory impact tests. The specification of these tests is usually agreed on a case by case basis with the Flag State and the Classification Society.

2.3. Glass Types

Until the release of ISO 11336-1:2012 the main glass type permitted in yacht applications was thermally toughened glass. The main advantage of thermally toughened glass is its high tensile strength and fail-safe mode. However, comparing to the other glass types, it has the worst optical quality due to visual effects such as anisotropy and defects like roller-waves. In addition, in case of failure, the glass breaks into small dice which can block the view outside. Because of its failure mode, thermally toughened glass is not recommended in overhead applications as it has small post-failure stiffness and capacity. ISO 11336-1:2012 allows the use of chemically strengthened glass that has higher characteristic strength and failure mode / optical quality like the annealed glass (it breaks into large pieces). Unfortunately, none of the yacht standards allow the specification of annealed or heat strengthened glass and their use on new projects must be agreed with the Flag State on a case by case basis.

2.4. Glass Strength

Both BS MA 25:1973 and ISO 11336-1:2012 are using Allowable Stress Design (ASD) for the calculation of the windows' thickness. According to ISO 11336-1:2012 the design strength of thermally toughened and chemically strengthened glass is equal to 40 MPa. BS MA 25:1973, only provides formulas for the calculation of the glass thickness but the glass design strength of 40 MPa can be back-calculated using analytical equations. Based on the above, the global factor of safety in case of thermally toughened glass is 3.00 and for chemically strengthened glass 3.75. This is based on characteristic strengths 120 MPa and 150 MPa respectively according to Eurocodes. Even if ISO standard underestimates the design strength of chemically strengthened glass, this conservative approach somehow allows for the reduction of the strength due to the ageing of the material.

3. Laminated Glass Interlayers and Adhesives

3.1. Interlayers

All types of glass interlayers are currently used in the yacht glass industry. Ionomer interlayers like SG 5000 are mainly used due to their robustness against water egress and their ability to activate almost full composite action of the glass laminate. PVB interlayers are used by most of the glass manufacturers because they are easier to apply and available in many colors but have poor stiffness properties and humidity resistance. Structural PVBs like DG41 have better mechanical properties comparing to standard PVB and are also used. EVA and UV-cured cast-in acrylic recin interlayers are almost equivalent to standard PVB but they have much better humidity resistance and can be used in external environments and in wet areas.

Finally, it is important to highlight that laminated glass in yacht applications need to meet the requirements for laminated glass and particularly laminated safety glass as they are described in BS EN ISO 12543-2:2011 (Laminated Safety Glass) and BS EN ISO 12543-4:2011 (Test Methods for Durability). BS EN 14449:2005 and BS EN 12600:2002 need also to be followed.

3.2. Connections to the vessel

Structural glass in building envelope applications is either mechanically restrained or bonded to stainless steel frames and connections using structural silicone. The detailing of these connections is such that over-restraint is prevented by accommodating the building movements.

Yacht glass is mainly bonded to the hull of the vessel either with polyurethane (PU) or with Silyl Modified Polymers (SMP). Glass windows and their connections are subjected to hogging, sagging and torsional deformations due to the ship movement. Since glass panels are stiff in-plane, the main assumption is that the all the movements of the supporting structure are accommodated by the adhesive bond. The material substrate in marine applications is mainly aluminium alloy or carbon steel. Due to silicone contamination on metal substrate bond surfaces, silicone-based adhesives are not permitted by the marine industry. Low molecular-weight silicone oils on bond surfaces can inhibit or preclude the adhesive-to-substrate contact required to achieve strong adhesion. PU and SMP adhesives have similar stiffness but are stronger comparing to silicone products. Their main disadvantage is the fact that they are not UV and temperature stable. The UV-degradation of these materials can be prevented by adequate bond coverage either with ceramic frit or with appropriate primers.

ISO 11336-2 provides all the necessary regulations to design such bonded connections. However, PU and SMP manufacturers have not yet provided all the required information to design accurately and efficiently with their products. In general, reduction factors that allow for temperature, ageing, load duration, dynamic loads (~10000 cycles) and fatigue (>10^7 cycles) need to be applied to the characteristic strengths of the materials.

Apart from the deformations of the vessel and temperature loads that usually define the bond thickness, accelerations due to the ship movement and wind suction loads need to be considered for the design of the adhesive's bite. Design pressures due to wave loads are mainly causing compressive stresses to the bond and are rarely critical for the calculation of the bond size.

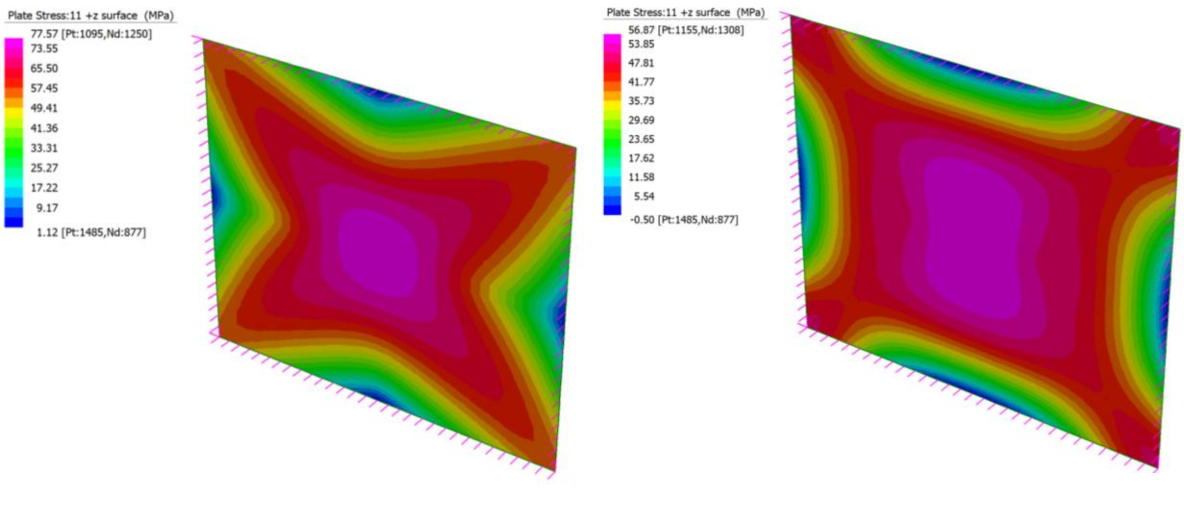
4. Analysis Methods

Both ISO 11336-1:2012 and BS MA 25:1973 provide simplified linear formulas to calculate the glass build-up of flat 4-side supported windows. These equations do not consider the curved shape of the glass and its possible positive or negative impact on the stress and deflection calculations.

As a rule of thumb, non-linear geometry finite element analysis provides more accurate results when the yacht glass is deflected more than half of its thickness. This is usually the case for large span windows at the lower levels of the vessel due to the high design pressures. Linear static analysis using FEA or simplified formulas is adequate for smaller glass panels.

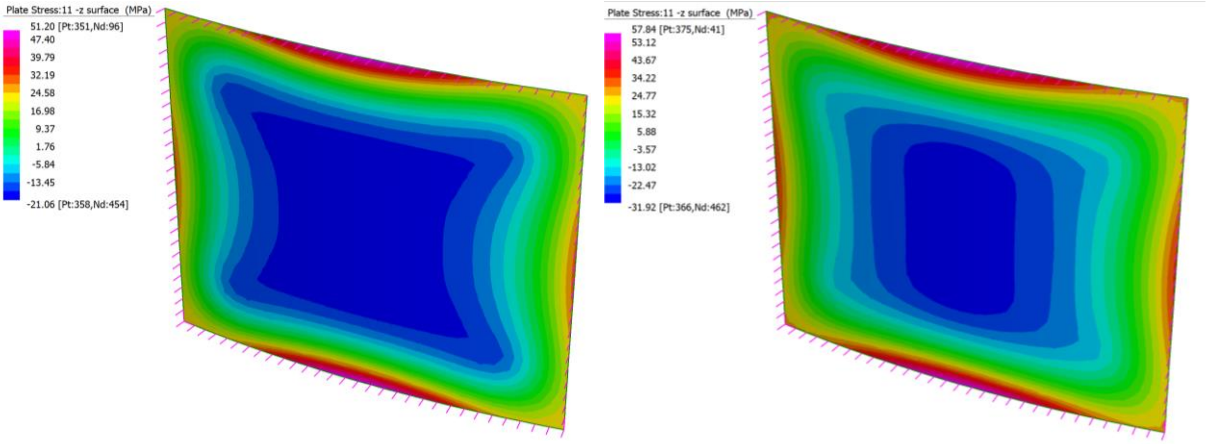
The glass contributes considerable weight to a yacht. Because of this, the yard and naval architects often requires its weight to be reduced. A small increase in the glass build-up might require multiple increase of the ballast weight. This is undesirable because it will reduce the deadweight of the vessel. The simulation of the exact geometry of the panel using FEA and non-linear geometry analysis can significantly reduce the overall glass thickness.

The following example of two chemically strengthened panels, one flat 4-side supported and one cylindrically curved (R=10m) 4-side supported, with dimensions 3000x2500mm, thickness 24mm (2x12mm), subjected to a normal pressure of 20kPa was used to describe the importance of selecting the right analysis method in yacht glass. Nonlinear geometry analysis activates the membrane action of the flat glass and because of this both stresses and deflections are significantly reduced (Fig. 3). The glass engineer can then specify much thinner build-up. In the cylindrically curved glass example, nonlinear geometry analysis gives higher stresses and deflections (Fig. 4). This is because the analysis considers the deformed shape of the panel. Due to the high load and the small curvature of the panel the glass gradually becomes flat and loses its stiffness. This effect cannot be considered by the linear analysis and therefore this method underestimates significantly the actual behavior of the panel.



a) b)

Fig. 3a), b) Maximum principal stresses of the flat panel using linear static analysis (77.57MPa) and nonlinear geometry analysis (56.87MPa).



a) b)

Fig. 4a), b) Maximum principal stresses of the cylindrically curved panel using linear analysis (51.20MPa) and nonlinear geometry analysis (57.84MPa).

5. Design Challenges

5.1. Thermal Performance

In the past, most of the external windows in yachts were made of single laminated units with the outer ply being of tinted glass. This approach was adequate to improve the performance of the glass against solar gain, but the U-value was significantly high, and the glass looked dark. Nowadays, the thermal performance of yachts is more important and therefore insulated glass units are often required to reduce the thermal losses or gains. In addition, yacht designers have started pushing the industry for larger transparent areas. Choosing the right processes so that yacht glass can meet the thermal performance requirements is probably the most challenging task at the early stage of each project. Usually the most complicated glass elements in terms of fabrication will define the visual appearance of the whole vessel.

High performance coatings can be used in the gas cavity of flat insulated glass units. The glass build-ups with these coatings combine low U-value, low g-value and high light transmission. In case of single-curved thermally toughened glass there are some limited coating options but are usually not high performance. Single and double-curved glass panels are typically made of chemically strengthened glass. This is not only to resist the high design pressures but also to avoid having the negative visual effect of anisotropy and roller-waves that are inherent with heat-treating processes. Due to the fabrication procedure of chemically strengthened glass and the thin surface compressive layer (a few tens of microns), coatings cannot be used and therefore coloured PVB interlayers are the only option to reduce the g-value of the glass. PVB interlayers are less stiff and less robust against water egress and particularly in a marine environment the risk of delamination is significant. One solution that is usually proposed is to add a ply of annealed glass, that can be coated, in the compression zone of the window. A thermal shock check is therefore required to ensure that the annealed glass will not fail due to thermal loads.

Finally, it is important to mention that insulated glass units are permitted by the classification societies, but the engineers need to design the glass to be stepped. Additionally, the internal glass package must be non-structural and therefore it should be neglected in the structural calculations. The main reason for the stepped insulated glass unit is the high design pressures. If the internal package had worked structurally, the high design pressures would have caused failure of the spacer bar and the butyl primary sealant.

5.2. Visual Quality

As we have already mentioned, the superyacht industry demands the highest quality when it comes to the visual appearance of glass elements. This is the reason why Hadamar Guidelines and other traditional approaches to assess the visual quality of glass in buildings are not stringent enough for superyacht projects. The most common approach is a bespoke specification to be agreed between the Client, the Yacht Designer, the Yard and the Glass Contractor before the appointment of the glass manufacturer and the fabrication of the glass. Large size visual mock-ups and samples are necessary to ensure that the glass manufacturer can achieve the desired visual quality. After the fabrication of the glass panels and before their installation to the vessel, factory assessment tests (FAT) are organized in order to ensure that each panel meets the visual criteria of the specification.

Low-iron glass is required only in case of transparent glass whereas for dark glass panels with low light transmission the green tint appearance of regular clear glass will not be visible.

5.3. Curved Glass

Large curved glass panels with complex geometries are playing an important role in the aesthetics and aerodynamics of luxury yachts. In most of the projects with curved glass, this is either thermally toughened or chemically strengthened. Below, we have summarized and reviewed from yacht-glass perspective, alternative bending methods that could help designers achieve the desired curved geometry.

In case of land-based facades with small curvatures, the curved shape can be easily achieved through cold-bending (site-bending) using mechanical restraints. Unfortunately, this method can be rarely used in marine applications due to the significant glass thickness and the subsequent bending stresses in the glass that are caused by the induced movement in combination with the low glass strength specified by the design standards.

Another bending method that can be used alternatively is warm-bending (lamination-bending) of the thermally toughened glass using an ionomer interlayer (Fig. 5). This method results in lower bending stresses because each ply is now bent independently. The minimum radius that can be achieved is ~1500*t, where 't' is the thickness of the thicker ply. Careful simulation of the boundary conditions and selection of the analysis method to calculate the total glass stresses due to external loads and lamination bending is required. Depending on the stiffness of the connections to the support structure, the total glass stresses can either be increased or in some cases even reduced. Comparing to curved glass during the thermally toughening process, the optical quality of the glass is better due to fewer distortions and reflections.

Even if annealed glass has low design strength, slumped annealed glass can be used at higher decks where the design pressures are low. Since chemically strengthened glass cannot be coated, in case the structural build-up is made of this glass type, annealed glass can be used as a medium to apply coatings. In this case, it is always recommended the annealed ply to be placed in the compression zone of the cross-section. Finally, the risk of thermal shock needs always to be considered during design.

Thermally toughened double-curved glass is the latest development in the curved glass industry (Fig. 6). The main advantage of this method is the durability / high strength of the material and the fact that many more coating options are now available.

Fig. 5 Thermally toughened warm-bent (lamination-bent) glass fabricated by Sedak. Singapore Jewel Apple Store. Architects: Woods Bagot HK | Structural Engineers: Eckersley O'Callaghan | Contractor: Seele Austria.

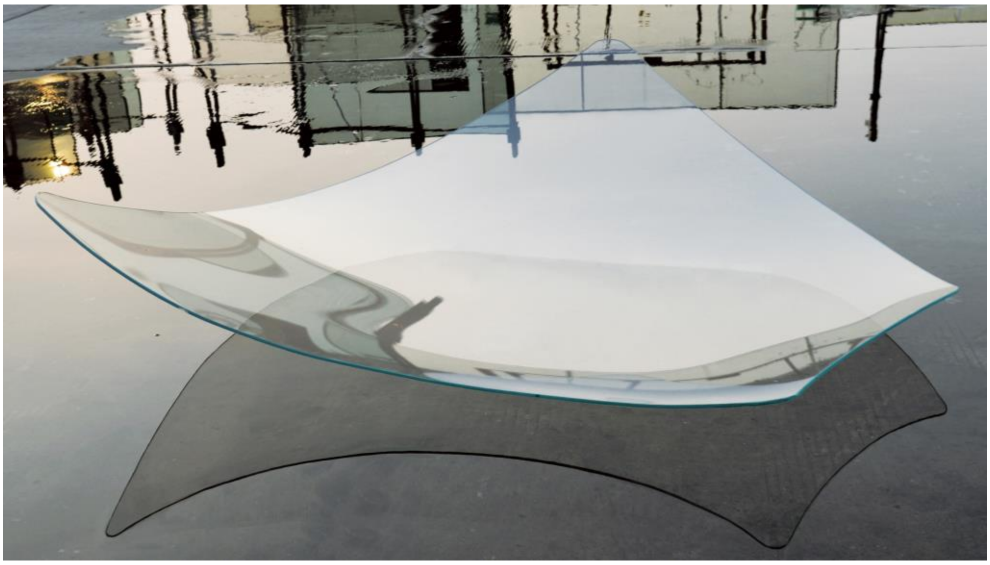


Fig. 6 Thermally toughened double-curved glass fabricated by Tianjin Northglass.

5.4. Underwater Windows and Nemo Lounges

The release of ISO 11336-1:2012 changed the mindset of the yacht industry and provided all the necessary tools to better understand and explore the potentials of this material when used in extreme applications.

Windows below the waterline are nowadays a common request by clients and yacht designers (Fig. 7). Since underwater windows are critical items for the watertightness and robustness of the vessel special attention should be given to their design criteria and design details.

The main design criteria can be summarized as follows:

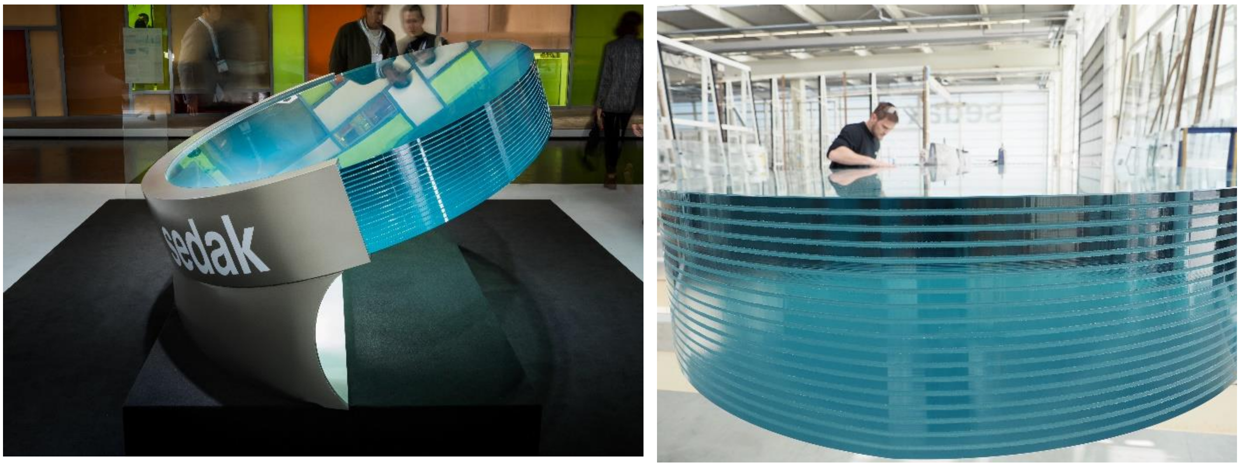
- The floatability of the boat must not be compromised after failure of the glazing (compliance with intact stability criteria after flooding of the compartment is one way to demonstrate this).
- Timely evacuation from the space must be ensured in all cases where there are people inside the compartment.

In general, permanent attached deadlights are required. In case this is not possible due to the size of the opening, the following alternative arrangements of glazing in lieu of deadlights can be acceptable:

- Add one more glass pane with thickness equal to the one required from structural calculations. Each glass pane needs to be supported independently to the hull and the distance between them needs to be such that impact/contact is prevented.
- Double the thickness of glass required from the structural calculations. In this case, the effective thickness is doubled but this arrangement is less robust and not recommended in critical applications because there is only one support back to the hull of the vessel.

Underwater windows are subjected to long-term water pressures and therefore the long-term strength properties of glass and stiffness properties of the interlayer need to be considered. Moreover, these panels are usually small in size, 4-side supported and of significantly thick build-up. Due to the panel's high stiffness, only a small percentage of the full composite action will be activated and therefore detailed calculation of the effective thickness is required.

Pool glass belongs also in the category of 'underwater windows' and in general the same design principles need to be applied. Furthermore, the self-weight of the glass pool including the water needs to be increased to allow the accelerations due to the yacht movement.



a) b)

Fig. 7a), b) 18-ply laminated marine glass with SG 5000 interlayer. Underwater window fabricated by Sedak. (photographer Franzel Drepper).

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ISBN 978-94-6366-296-3, www.challengingglass.com

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