Can glass compete with Acrylics in Large Aquarium Enclosures ?

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Abstract

In the world of aquarium enclosures, acrylic plastics impose their supremacy. The optical qualities of acrylics are unbeatable even for the highest thicknesses. However, aspects such as their low abrasion resistance or their low availability due to the scarcity of certified manufacturers, gives laminated glass the opportunity to overcome it in certain applications.
The design specifications of flat rectangular windows for underwater vision on a new hippopotamus installation at Barcelona Zoo question the use of acrylic. This paper describes a case study in which monolithic PMMA and laminated glass are compared from the perspective of resistance, optical performance, safety, availability, manufacturing, assembling and maintenance costs. Although still in the concept design stage, the study reveals laminated glass to be the preferred option.

Keywords: aquariums, abnormal loads, laminated glass, heat strengthened glass, monolithic PMMA, post-breakage stability.

Theme: structural design - hydrostatic pressure / abnormal loads - laminated glass / monolithic acrylic plastic

1. Introduction

Barcelona Zoo is planning a new installation for hippopotami. To provide a better view of these exotic mammals the installation includes flat rectangular windows for underwater vision which are 7 m width and 3 m high. The windows have their water level at 1.6 m over their sill and will be exposed to indoor conditions on their dry side and to outdoor conditions on their wet side.

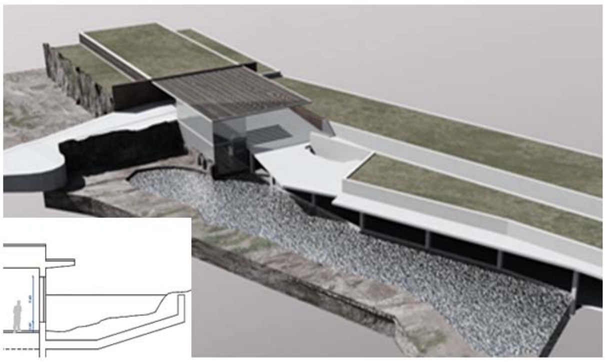

Figure 1: The preliminary design of new facilities for hippopotami. Courtesy of Barcelona Regional and Zoo de Barcelona.

For the construction of large aquarium windows, the most widely used material is acrylic (PMMA: polymethyl methacrylate). The availability of virtually unlimited sizes, the bonding capabilities and, especially, the excellent optical qualities of acrylic, make this material the best choice in the majority of applications. Following a typical approach, the window for the new hippopotamus installation would be constructed using monolithic slush cast acrylic sheets.

Although slush cast acrylic sheet production is highly industrialized and does not involve extremely costly processes, the scarcity of certified manufacturers leads to extended delivery times and a significant purchase cost. As replacement time and cost are among the design team's main concerns, material selection has not been restricted to the acrylics field. Looking closer at the project's individual characteristics, it has been noted that one of the factors which makes acrylic difficult to replace in aquarium applications, the optical performance, is not critical in this case study. Each hippopotamus generates 50 kg of excrements everyday so the water ends up cloudy if not muddy most of the time. This fact gives an opportunity to materials with inferior optical performances.

This paper describes the feasibility study which has been undertaken to evaluate the possibility of using laminated glass panes on Barcelona Zoo's new hippopotamus facilities.

2. Material overview and design criteria

2.1 Acrylic

Because of the scarcity of published technical data, the selection of design parameters for acrylic is not based on a precise analytical calculation but on empirically derived procedures based on experience.

Fortunately, the majority of published test data and past performance observations are related to applications with predominant flexural loading stress fields and a high level of commitment to the safety of people such as windows for submarines, aircrafts and hyperbaric chambers. As a consequence, the available data can be safely extrapolated to the field of aquariums.

These data altogether with the ASME PVHO-1 Safety Standard for Pressure Vessels for Human Occupancy [1] constitute a reasonably solid basis for dealing with the design and engineering of aquarium windows. According to these references, the most suitable grade in aquarium use is MIL-P-5425 (USA Government Qualified Acrylic Grade).

One of the most characteristic features of acrylic and the feature which most influences its design and calculation is its nonlinear response to applied loads. As acrylic elasticity depends on temperature and time, a different Young Modulus has to be considered in each working scenario. Under the specific working conditions of this study the effective modulus of elasticity value ranges from 1500 Mpa for long term loading scenarios to 4000 Mpa under short term loads.

In this specific case study, apart from temperature and loading rate and duration, two other factors have a major influence on the definition of working stress levels: notch sensitivity and weathering. The former is critical due to the high scratching capacity of hippopotami and its negative effect on the acrylic tensile and flexural strength can reach a severe 90%. The latter, which is mainly due to exposure to UV radiation, has an influence on stress reduction which is commonly quantified at 50%.

As is usual with monolithic acrylic panes, the design criteria adopted consists of using high safety factors, which means highly conservative allowable working stress levels. Considering the specific characteristics of this case study and using the test data and engineering recommendations [2] [3] published to date, working stress levels have been established within the range of 2.4 to 8.3 MPa, depending on the working scenario.

2.2 Laminated glass

In the case of glass, although abundant technical data and regulations are available, this information is mostly aimed at use in construction. As a consequence, it is of little use when transferred to the design of a window for underwater visibility. This situation leads to a design strategy based on redundancy and post-breakage stability. The approach suggested for this project is the use of soda-lime heat strengthened laminated glass [4] [5] [6].

When using lamination techniques, the mechanical performance of a glass pane is not so different from that of a pane made from acrylic. This is due to the viscoelastic or nearly viscoelastic behaviour of the material used as a interlayer.

Given the important structural demand of this case study, the design uses an ionoplast structural interlayer as it is the type of interlayer with the highest mechanical performance currently available.

As in the case of acrylic plastics, the modulus of elasticity to be considered varies, depending on the working scenario. The values used are provided by the industry [7] and range between 692 Mpa and 0.54 Mpa for load durations between 1 second and 10 years and temperatures within the range of 10ºC to 80ºC.

In the context of this feasibility study and as a first approximation accepted, considering the design strategy is not based on high safety factors but rather on redundancy and post-breakage stability, the allowable working stress levels adopted are those which are commonly accepted by the European industry; 20 Mpa for long term loads, 35 Mpa for short term loads and 120 Mpa for impact loads [8]

3. Preliminary design

3.1 Loads

Self weight (SW)
PMMA MIL-P-5425 density: 1190 ± 10 kg/m3 [1]
Soda-lime glass density: 2500 kg/m3 [4]

Hydrostatic pressure (HSP)
According to zoological ergonomic criteria, hippopotami feel comfortable in water which is between 1.5 and 2 m in depth. As the lower edge of the window pane is at a level of 0.4 m, in the worst case the water level will rise up to 1.6 m above the pane's lower edge. Assuming that the overflow devices have been carefully designed to ensure that this level will not be exceeded even in accidental scenarios, the following triangular load distribution has been considered: 15.7 kN/m2 at level 0 and 0 kN/m2 at level 1.6

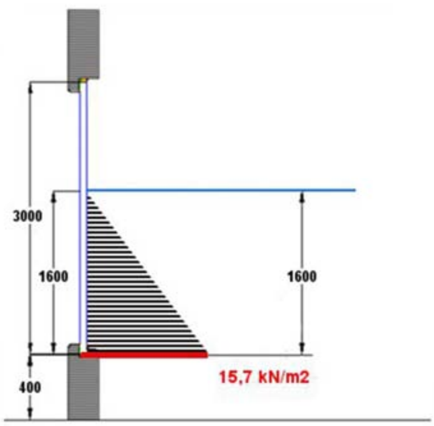

Figure 2: Hydrostatic pressure

Hydrodynamic pressure (HDP)
Among the many peculiarities of hippopotami, and one which is to be highlighted, is their predilection for entering the water abruptly. To obtain an estimation of the maximum load this generates, the US Army Corps of Engineers Shore Protection Manual [9] has been used. According to the indications given in this manual and considering non-breaking waves and a conservative wave height, the following equivalent hydrostatic pressure has been derived: 21.4 kN/m2 at level 0 and 0 kN/m2 at level 2.7

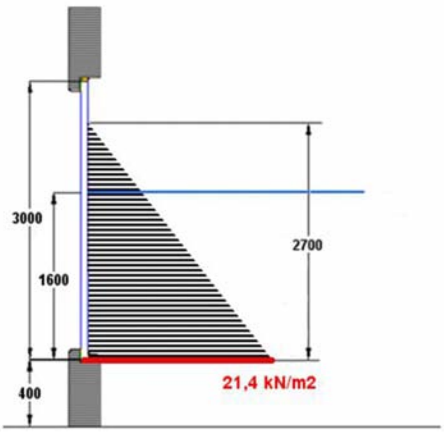

Figure 3: Equivalent hydrostatic pressure

Wind load (WL)
Wind load has been quantified in + 1.6 / -1.9 kN/m2 (positive value indicates pressure from wet side to dry side).

Static point loads (SPL)
As the estimation of this load is extremely difficult, a major effort has been made in order to define a set of design values with the planners of Barcelona Zoo which, realistically and safely cover all the expected point load cases.
Several approaches have been followed. Among them, the most remarkable is the typification of a representative specimen and its parametrization to analyze the most restrictive loads a hippopotamus can generate on the window pane, considering both, its mass and the buoyant force exerted by water on its body. The results obtained show that two load intensities have to be checked: 9700 N at level 0.6m and 11500 N at level 1.5 m (relative levels considering level 0 located at the pane's lower edge). The load application surface has been defined on an area of 200 mm x 200 mm.
Obviously the validity of these values depends entirely on the preventive measures taken at the facility's design in order to minimize the thrust capacity of the hippopotami and avoid unforeseen point loads (pool's floor grip minimization, the avoidance of load amplification through a lever effect using objects brought into the water by the animals, limiting the number of hippopotami to avoid unexpected loads caused by agglomeration, etc.)

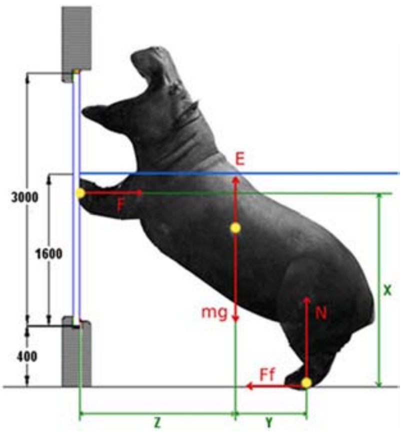

Figure 4: A hippopotamus exerting a point load on the window

Dynamic point loads (DPL)
As in the case of static point loads, dynamic point loads are not easily quantifiable. After studying several approaches, the dynamic point load to be considered on this preliminary design has been derived from the estimation of the maximum kinetic and potential energy which one hippopotamus can generate within the analyzed facilities. It has an energy of 15.7 kJ and can be expected at any point on the wet surface of the window.
In a similar way to static point loads, the atrezzo designed for the installation has to ensure that assumptions and hypothesis made to define dynamic point loads are valid even under unexpected scenarios. Considering that out of the water, a hippopotamus can achieve speeds of up to 50 km/h, the facilities must be set up in a way so that all trajectories approaching the window from land are removed.

Thermal loads (TL)
Thermal loads are especially intricate in this case study, where three different environments act simultaneously. Air in indoor conditions on the whole surface of dry side, air in outdoor conditions above the water level on the wet side and heated water on the lower part of wet side.

Outdoor conditions	
Air maximum temperature:	42 ºC [10]
Air minimum temperature:	-11 ºC [10]
Air annual mean temperature:	15.5 ºC [11]
Air summer mean temperature:	26.3 ºC [11]
Air film coefficient:	From 3 to 80 W/m^2K
Maximum solar radiation:	300 W/m^2 (1)
Water setpoint:	23 +2/-3 ºC
Water film coefficient:	From 20 to 1000 W/m^2K
(1) Controlled by means of passive shading devices	

Indoor conditions	
Air temperature:	Considering the dry side openings layout, indoor extreme values are assumed to be able to reach the ones in outdoor conditions although with a certain offset.
Air film coefficient:	From 3 to 25 W/m^2K

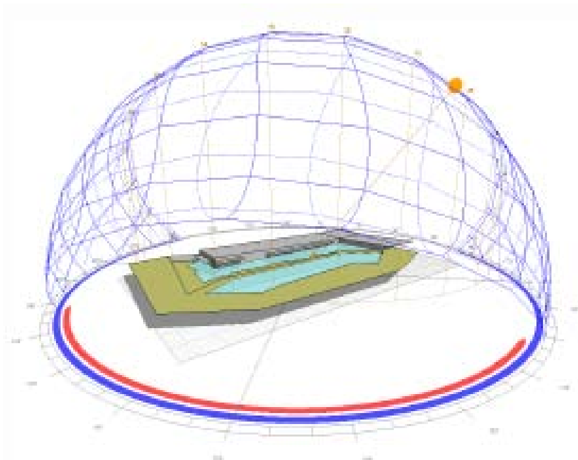

Figure 5: Solar analysis to quantify maximum solar radiation on underwater windows

From the environmental conditions above, FEM simulations have been carried out to derive critical temperature distributions on window panes. Among all the environmental scenarios investigated, four must be noted. The Long Term Scenario (LTTL), the Standard Summer Day Scenario (SSDTL) and the extreme scenarios (ETL) which are the Hottest Summer Day Scenario (HSDTL) and the Coldest Winter Night Scenario (CWNTL). Inside these thermal scenarios we can find: maximum surface temperatures of up to 69 ºC, minimum surface temperatures of up to -11 ºC, maximum temperature gradients of up to 35 ºC, positive and negative temperature gradients acting simultaneously and temperature differences of up to 49 ºC.

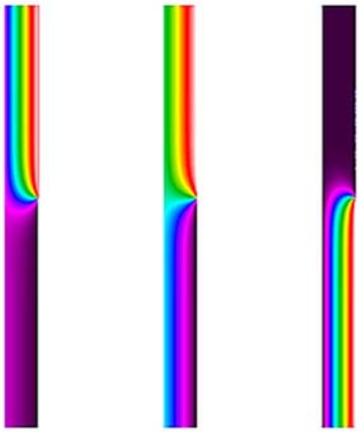

Figure 6: Temperature distribution for acrylic and glass under different environmental scenarios. Standard Summer Day, Hottest Summer Day and Coldest Winter Night

Other loads

Scratching on wet surfaces

The animal's ivory tusks have a hardness of 6-7 Mohs, which means that hippopotami can easily damage acrylic surfaces with a hardness of only 3.5 Mohs. Soda-lime glass, with a hardness of 6 Mohs offers a much higher resistance to damage caused by hippopotami.

Figure 7: Example of the high scratching capacity of hippopotami. Courtesy of Barcelona Regional and Zoo de Barcelona.

Scratching on dry surfaces

While vandalism cannot be totally eliminated, accidental scratching by visitors with rings, bracelets, belt buckles, baby strollers, electric carts, vacuum cleaners and floor polishers can be minimized by positioning a waist-high metal railing or acrylic or glass pane in front of the aquarium window.

Pane/frame manufacturing tolerances

Without a conscious framing system design the pane and frame manufacturing tolerances could introduce unexpected loads and stress concentrations which may lead to the window collapsing at loads far below design levels.

Frame differential settlements

As with manufacturing tolerances, this source of unexpected and uncontrolled loads must be eliminated through an adequate frame design.

Earthquakes and fire

Not critical issues in this case study.

3.2 Working scenarios

Five working scenarios have been analyzed. The definition of each working scenario consists in identifying the following parameters: type and magnitude of acting loads, material mechanical properties as a function of load type and environmental conditions and design stress.

Long Term Scenario: SW + HSP + LTTL
Hydrodynamic Pressure Scenario: SW + HSP + HDP + SSDTL
Static Point Load Scenario: SW + HSP + SPL + SSDTL
Dynamic Point Load Scenario: SW + HSP + DPL + SSDTL
Thermal Load Scenario: SW + HSP + ETL

3.3 Mechanical verification

Acrylic

The design criteria adopted for acrylic is based on the use of high safety factors. According to this strategy, the minimum thickness admissible is the one which provides a positive allowable stress / stress ratio for all work scenarios. After analysing all the work scenarios it was seen that the most restrictive is the Dynamic Point Load Scenario which results a minimum thickness of 230 mm for a monolithic pane in MIL-P-5425. For this thickness, the level of stress obtained under the Long Term Scenario is 4 times lower than the allowable working stress.

Laminated glass

Following a design strategy based on redundancy and post-breakage stability, the minimum composition admissible is that which satisfies the following conditions:

- Positive allowable stress / stress ratio for all working scenarios.
- Positive short term allowable stress / stress ratio for all working scenarios considering that the pane is made of n-2 plies of glass.1

As with acrylic, the Dynamic Point Load Scenario is the scenario which determines the pane composition. The minimum composition acceptable is a laminated (ionoplast interlayer) formed by 6 plies of 12 mm thick heat strengthened low iron glass. The level of stress obtained under the Long Term Scenario by the non-damaged glass plate (6x12 mm plies) is 3 times smaller than the allowable working stress. A damaged plate (4x12 mm plies) is able to resist all working scenarios during the time necessary for guaranteeing the safety of users of the installation.

It must be said that given that the objective of the study consists in generating an alternative to acrylic which is capable of improving its performance, especially in terms of cost and delivery times, the analysis of glass has been restricted to the maximum dimensions in which the ionoplast interlayer is commonly supplied. 5.6 m by 2.5 m.

freeminds Bellapart construction

3.4 Framing detail design

Even with slight variations, the framing systems required by glass and acrylic are equivalent in terms of complexity.
Details worth mentioning are: compensation of frame-panel manufacturing tolerances through non-shrink grout applied onsite, in-plane free translation through compressible fillings in jamb and lintel gaps, a footing device to ensure uniform self weight load distribution on the glass pane and, specifically for this case study where the hydrostatic pressure can not compensate the backward push generated in the event of impact, bidirectional resistant bracings not only on the sill, but also on the jambs and lintel.

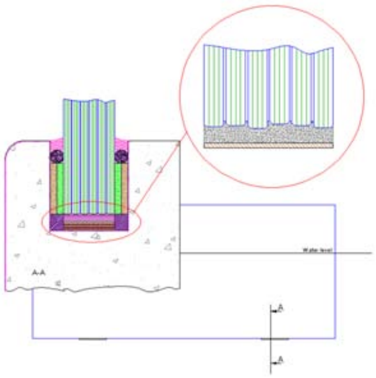

Figure 8: Detail of glass pane footing device to ensure uniform self weight load distribution

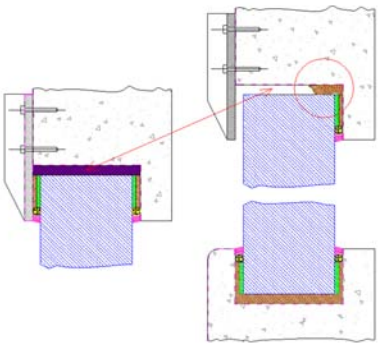

Figure 9: Jambs and lintel gap polyurethane foam filling to prevent from grout blocking in-plane movement

3.5 Acrylic / glass comparison

Purchase cost
The purchase cost for the glass version is expected to be one order of magnitude bellow the cost for the acrylic version.

Availability, transport and installation
At the time this work was done, acrylic panes had to be imported from Japan or USA with a delivery time of around 12 months, while the glass version could be produced in the majority of European countries with a delivery time of around 12 weeks.

Given that the weight of both solutions is within the same order of magnitude, the cost of land transportation and installation would be the same for glass than for acrylic.
To take full advantage of a design using glass, the pane should be smaller than 5.6 m by 2.5m. This would reduce delivery time avoiding delays due to interlayer special shipping and would minimize the finished product transport cost.

Maintenance
Acrylic has a low abrasion resistance but it can be repaired on-site. Glass possesses a much higher abrasion resistance but it cannot be repaired. The availability and cost of glass purchasing gives this alternative with clear advantages in the event of major damage and the need to replace panes.

Design life
10 years in both cases. In case of a fully indoor window the pane could be designed in acrylic for a design life of 20 years.

Safety
The design can be safely resolved in both materials; nevertheless, considering the uncertainty associated with loads existing on hippopotami facilities, a design criteria relying on post-breakage stability is much more preferable. From this point of view, and assuming that future tests on life-size prototypes will validate the assumptions made regarding the post-breakage mechanical performance of heat strengthened laminated glass, the design on laminated glass can be considered safer than the design on monolithic acrylic.

Optical performance
As far as the mock-up visual inspection has validated the optical performance of a 6x12 low iron glass pane for this particular application, both designs can be accepted. Nevertheless, it has to be stated that optical performances for acrylic are much better than those for a laminated glass pane, consequently from the optical point of view acrylic would be preferable.

4. Future works

Unlike acrylic, studies regarding the influence of water immersion on glass properties are scarce. Furthermore, existing studies are hardly applicable to aquarium windows and, far from pointing in a single direction, they conclude that the effect on the strength of soda-lime glass may be positive or negative depending on the characteristics of the immersion [12].
Nevertheless, the use of a laminated pane where the surfaces of the wet side ply remain mainly under compression, makes the conclusions obtained on this feasibility study valid even though there is an important lack of knowledge on this area.
Efforts should be made in the final design with respect to this topic in order to prove that the influence of water immersion on glass behavior does not threaten the final window design.

Even though optical performance is not a critical issue for this case study, we cannot forget that our concerns here lie with a window. Although the samples produced at the time of writing are encouraging from de point of view of local visual imperfections, it is very important to check light transmittance and image distortion on life-size prototypes under final working conditions. As the refractive index of acrylic is more similar to that of water compared to glass, the distortion of the image of the exhibit is expected to be considerably more noticeable for a glass window than for an acrylic window. Before entering the construction phase, Barcelona Zoo officials should verify that the optical performances obtained are satisfactory.

Figure 10: Sample of a heat strengthened laminated pane 500 mm x 500 mm consisting of 6 soda-lime low iron 12 mm thick plies laminated with 1.52 mm thick ionoplast film. Courtesy of Cristec

Considering the difficulties with respect to load definition, one of the key points of the proposed conceptual design is post-breakage stability. To fully validate a detail design, post-breakage load bearing capacity has to be checked using life-size prototypes tested under both static and dynamic loads.

5. Conclusions

For certain types of aquarium, the construction of underwater vision windows in heat strengthened low iron laminated glass is not only feasible but it can be considerably advantageous in terms of cost and availability. The improvement provided by glass in these two areas in comparison with acrylic is estimated to be one order of magnitude.

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