Door ir. F. Verbaas

Royal Huisman developed a glass cockpit for the half-raised bridge deck of the flybridge ketch Twizzle (picture Royal Huisman Shipyards)..

From Simple Window to Structural Material

Application of Glass on Board, an Update (Part 1)

In the architectural world, glass structures become more and more important. The sensation of open space and connecting the inside with the outside world has great appeal. Use of glass is no longer limited to facades and windows. It is also used to build stairs, parapets and floors in all sorts of buildings: hotels, museums, shops. Glass is not only used as a plate, but also as a supporting structure, such as constructions with glass floors supported by glass beams. It is not surprising a similar drive is found in the yacht industry.

Yachts are designed to let the guests on board experience the most beautiful spots on this planet. Spacious outside decks provide the best view, but the beauty of some places on this planet is better enjoyed from a comfortable inside position where the viewer is protected from wind, cold, heat or insects. Demand is therefore for accommodation with large transparent panels providing an alternative, as good as practicable, for being outdoors. As a bonus, glass can be made very attractive visually when seen from the outside. The second function of a yacht: being a thing of beauty giving tribute to its owner, can thus also be served by the application of glass. Last

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	Yield strength	Strength@break tensile/compr.	Elongation @break	Young's modulus	Strain to failure tensile
	MPa	MPa	%	GPa	mm/m
Steel Mild	235	410	22	200	1.18
Steel HTS	355	510	21	200	1.78
Aluminium 5083	125	275	12	69	1.82
Aluminium 5059	160	300	10	69	2.31
Thermally Toughened Glass (TTG)	-	120	-	70	1.71
Chemically Strengthened Glass (CSG)	-	150	-	70	2.15
CSG selected	-	220	-	70	3.43
Glass Reinforced Poly-ester (GRP) – traditional	-	190/147	-	15/14	12.7
GRP – UD	-	304/246	-	23	13.2
Carbon Composite	-	600/367	-	67	8.96

Table 1. Typical mechanical properties of glass compared with other structural materials.

but not least, glass is quite inert and it does not rust or otherwise corrode. Glass comes to the builder's site as ready-made panels that can be inspected before application on board. All areas covered by glass can be excluded from the expensive and all critical paintwork.

The marine industry traditionally knows glass as plates of fragile material necessarily permitted on board to provide view from the control station and to close the openings needed to provide daylight to the accommodation as required by labour regulations. What is it that architecture is embracing and the marine industry, with the noted exception of super yachts, is missing? An update on glass.

Problem Characteristics on Board

Modern glass is a structural material. The mechanical properties as observed in samples of practical size are not far off from many other materials used in marine construction. An in-depth description of glass and its characteristics is outside the scope of this article. Here, let it be sufficient to address the main problem characteristics for application on board:

1. The brittleness of glass is well known. Glass is frangible. It is perfectly linear-elastic. The stress-strain curve is a straight line, which ends at the point where it breaks with no plastic deformation. Fibre reinforced plastics, well established in marine construction, also show no plastic deformation on breakage, but glass pairs brittleness to a high stiffness. As a consequence, it breaks at a strain where the common metallic materials just reach the plastic deformation phase. It is obvious that permissible strain in glass constructions under design load will have to be chosen well below the strain at breakage. This aspect will drive the design of glass constructions.
2. The load bearing capacity of a glass structure reduces with time. The degree of loss of load bearing capacity due to "static fatigue", as this phenomenon is called, depends on the stress history. To get "infinite" lifetime, a maximum stress level for loads of long duration is to be observed. To a certain height and for practical applications, this static fatigue could be seen as a parallel of the "fatigue limit" as known for metallic materials. However, for glass this refers to static loads. The underlying mechanism is based in chemistry and totally different from the mechanisms at work in fatigue of metals.
3. Glass is more vulnerable to loss of strength after surface damage than other construction materials. A glass pane can be cut by making a simple scratch on the surface and a gentle tap of a small metal object in the right location. Edges, where two surfaces come together, are particularly vulnerable. This vulnerability to damage will also need to be catered for in the design.
4. Glass is also different from other materials used in marine construction because a crack, once it is generated, may develop in an almost instantaneous failure (brittle instantaneous breakage). Cracks caused by static fatigue may develop somewhat slower, but in either case, for practical applications failure can be taken as instantaneous. Because the material shows little elongation before break, there are no warning effects like increase of deflection. Failure comes without warning. When the glass is suitably strengthened by a residual stress distribution to "safety glass", it does not break into pieces, but into small particles and there is no residual structural integrity.
5. Along with the previous point comes the relatively large variation in breaking strength. Results from tests on otherwise identi-

Part 1

This is the first part of this article. The second part will be published in SWZ Maritime's March issue.

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Laminated CSG panel subjected to a pressure test. Note the large deflection before breakage (picture Tilse Industrie- und Schiffstechnik GmbH).

cal samples can easily vary by a factor two or more. To get a realistic idea about load bearing capacity, a large number of tests is required and the results statistically processed. The value commonly used for design is the Characteristic Failure Stress (CFS). This applies to quasi-static loading over a short time, for instance wind loading, and relates to a five per cent probability of breakage at the lower limit of the 90 per cent confidence interval and strength values obtained from four-point bending tests according to ISO 1288-3.

The application of glass on board therefore has to be done in a way that mitigates the above drawbacks. The methods that can be applied depend on the type of glass material used. The methods available will be discussed in the second part of this article.

Types of Glass Material

Glass for use on board and in buildings is typically soda lime silicate glass, produced in a float process technique and so named as float glass. This is the material commonly used in window panes for houses and buildings. The compressive strength of float glass is very high, about 900 MPa, but the CFS, tensile breaking strength, is only about 40 MPa. To make it more suited for application in areas where there is a need for a high load bearing capacity, the float glass is processed to increase breaking strength. This is done by introducing a residual stress profile in the glass pane cross section with compressive stresses in the surface to provide a margin to counteract tensile stresses and tensile stress in the core of the pane. The tensile strength in the core of the material is quite large. Breakage on tension is triggered mainly by defects in the surface [1].

There are two types of strengthening processes available. There is a chemical process, leading to Chemically Strengthened Glass (CSG) and a thermal process. Depending on the intensity of the thermal treatment, the product will be Thermally Toughened Glass (TTG) [2] or Heat Strengthened Glass (HSG).

To produce CSG, the glass panes, cut to size with polished edges, are immersed in a bath of molten potassium salt. Potassium ions diffuse into the glass surface driving out sodium ions and wedge themselves into their place. Because potassium ions are larger than sodium ions, this creates a compressive stress of 600 to 700 MPa in the near surface layer of the material. The diffusion depth is not very large. Inside the material, the compression rapidly decreases to become negligible at some 30-50 µm below the surface and then develops to the inner tensile stress. This compressive stress neutralises the existing surface flaws to develop critical cracks under an external tensile stress and thereby effectively increases the load bearing capacity of the panel. However, the compression is shallow and any scratch or damage with similar depth has its stress concentration at the tip in the area where there is no compressive stress or, at worse, a tensile stress is present. A scratched panel may fail under the same load as an untreated panel. The advantage of CSG is the very high surface quality that can be attained. When CSG breaks, it forms large sharp shards similar to float glass. The CSG process can be used for glass panes of any shape or curvature. The breaking strength depends on the process parameters. The "generally used value" for CFS of CSG as given in EN12337-1 is 150 MPa. This represents the industry base standard. With careful processing and selected base materials CFS values of 220 MPa are well achievable.

Thermally Toughened Glass

To produce TTG, float glass panes cut to size with polished edges are heated in an oven to make them expand thermally. Immediately after leaving the oven, the surface is quenched in cold air. The quenched surface "freezes" its expanded state, but the core of the pane cools down and shrinks. This results in a compressive stress in the surface when the panel is fully cooled down. The transition to zero stress is at a much greater depth below the surface than in CSG and it can be roughly considered to be one fifth of the thickness of the glass. The CFS of TTG as given in EN 12150-1 is 120 MPa. This represents the industry standard.

The system of a thick compressive layer balanced by a significant tensile stress in the centre part of a cross section results in a large amount of energy stored in the glass. This energy is released when the glass breaks and causes the glass panel to be shattered to small pieces. This is considered a safety feature, because the small pieces of TTG are considered less harmful than the large shards that may be formed by float glass or CSG when it is broken. The high energy content does have some drawbacks. The thermally prestressed glass pane essentially is a self-destruction mechanism which can be set off by a relatively small incident that is not necessarily related to the loads considered in design. A tick of a "safety hammer", mandatory to be carried in cars, is an example of such an incident. The system can also become unstable. If, from any source, the glass was contaminated with sulphur (from fuel used for heating the oven) and nickel (from tooling prior to processing) nickel-sulphide may form which, through its particular reaction to the TTG production process, could set off spontaneous breakage at some time, which may be many years later.

TTG is the default glass for marine applications. The surface quality traditionally was much less than that of float glass or CSG, but with new computer controlled production plants this is improving. The process is practically suitable only for panes of flat glass. Developable surfaces with sufficiently large radius of curvature can be made by "cold bending". This is usually done by laminating plies of glass in a curved mould. In the laminate, the glass plies are kept in a bended shape and this introduces an internal stress distribution. This distribution of course affects the load bearing capacity of the laminated pane.

Heat Strengthened Glass

HSG has undergone a similar treatment as TTG, but to a lesser extent. The result is a glass material that has a marked increase in strength relative to float glass, but does not have the dramatic disintegration of TTG. The breaking pattern is more comparable to that of float glass. This lower fragmentation can be important when residual strength is important. The minimal CFS of HSG as given in EN 1863-1 is 70 MPa.

Inversely, the thermal process can also be applied more intensely than for TTG to get glass with higher surface compression and higher breaking strength. Theoretical analysis indicates that the number of fragments into which a piece of heat-treated glass disintegrates is proportional with the surface compression stress to the fourth power [3]. Where fragments of TTG typically have two "faces" of the original glass surface, fragments of higher strengthened glass will be smaller than the thickness of the original pane and will show only one face corresponding with the original surface.

Glass Chemical Compositions and Laminated Glass

Recently, other glass chemical compositions like sodium-alumino-silicate glass, specifically designed for chemical glass strengthening by ion exchange, have been proposed and have found use for the display of smartphones, other consumer electronic displays and, very recently, automotive glazing. Such glasses have the potential to achieve very high strength properties with significant depths of compression layers consistently. It not so unlikely to foresee, in a near future, glazing based on this new product on board of a vessel [4].

Laminated glass is built from two or more plies of the above glass types, bonded together by an interlayer material. This interlayer usually is a thermoplastic material or a resin cured in situ, with properties chosen for optimal combination of performance and cost of the laminated panel. A laminated pane can consist of any practical combination and number of glass types and interlayer types.

Applications on Board

The potential for applications of glass on board is very large. Practical applications as proposed up to now include:

- windows in outside bulkheads of deckhouses and superstructures,
- deck hatches,
- glass decks,
- glass roofs and awnings,
- glass doors,
- windscreens,
- bulwarks,
- glazed openings in the side shell and transom ("portholes"),
- viewing ports under the waterline,
- ornamental stairs,
- swimming pools, and
- viewing ports in watertight bulkheads.

CSG test sample subjected to four-point flexural test according to ISO 1288-3 (picture Tilse Industrie- und Schiffstechnik GmbH).

Relation to Maritime Regulations, Standards, Equivalency

Most of these applications relate to one or more of the risks the maritime regulations aim to mitigate:

- water entering the vessel,
- falling overboard,
- spread of fire, and
- hazard to persons on board.

Maritime regulations are based on the 1966 Load Line Convention and SOLAS. The provisions in these conventions for small windows and portholes are a reference to prescriptive product based standards developed in the 1970s [5]. All other traditional means of risk mitigation in the regulations are based on steel or at least metal construction.

The only recent international standard for glazing in the maritime environment is ISO 11336-1:2012. The scope of this standard is large yachts up to 3000 GT not carrying more than twelve passengers. These limits were chosen specifically to stay clear of the higher statutory requirements for vessels of 3000 GT and over. It covers "traditional" glazed openings, but contrary to traditional maritime standards, it does support mounting by bonding, laminated glazing, and use of glazing materials other than glass. Part 2 of this standard, which at the time of writing this article is in an advanced stage of development, will deal specifically with glazing bonded to the structure. Part 3, dealing with manufacturing and production control and installation and inspection on board is also in an advanced stage of development. In December 2015, the ISO community approved the development of Parts 4 and 5 covering advanced design techniques and glass bulwarks/parapets respectively.

Larger yachts and yachts with more passengers are currently served by existing maritime standards and the extensive and prescriptive requirements in the Passenger Yacht Code (PYC). It is possible that in time, a new part of the standard will be developed covering passenger yachts and referred to from the PYC.

To apply glass in critical applications as listed above, alternative solutions must be found that will ensure equivalence with the requirements in the regulations.

Most seagoing vessels, including yachts today, are assigned a Load Line. A Load Line is assigned on the basis of the Load Line Convention. Flag states can use equivalent national regulations. The Large Commercial Yacht Code, now in its third revision, is an example of such a national equivalent. If a vessel is assigned a Load Line, statutory requirements prevail over Class Rules [6]. Any equivalency, therefore, should be approved by the flag authority according to their relevant procedures.

Glazing is no longer just "a piece of transparent material" used to close openings in shell or bulkheads against the ingress of water, but has become an integral part of the construction of the ship. It would therefore be preferable to bring glazing into the scope of classification and let it no longer be a statutory aspect.

Joining the Big Boys

According to Glass for Europe, a group of leading glass manufacturers, in 2014 the European glass production plants produced 8.5 million tonnes of glass [7]. This volume would be sufficient to cover about 400 km^2 with a roof of 8 mm glass. Of this massive production, eighty per cent is intended for use in buildings and fifteen per cent in cars and utility vehicles. The maritime industry does not even appear in the statistics. It is part of 0.75 per cent of the production used for “transport non-automotive” applications, meaning vehicles for rail traffic and all marine industry. Worldwide production, according to the same source, is estimated at 65 million tonnes. It shall be obvious the efforts for research and development are devoted to satisfy the needs of the main markets of the building and automotive industry. The maritime industry is too small to have its own material standards. Glass manufacturers are not interested in the minute product volume the maritime industry can possibly absorb and certainly will not be inclined to run separate production or separate quality schemes for the maritime sector. The maritime sector will have to join in with the big boys.

The glass parts manufactured for the automotive industry are typically vehicle specific. Like the cars they are intended for, products are manufactured in large series of near identical products. Products are of moderate size. The maritime applications of glass much more resemble the architectural applications.

Adopting Architectural Technology and Design Methods

The operational profile of yachts and cruise ships has a very large component of providing “hotel” functions, like cabins, restaurants, bars, casinos, lounging areas, theatres where application of glass can play a key role in the experience, but that are not covered by the maritime regulations like ICLL and SOLAS. There is, however, no justification for the safety standards of these hotel facilities on a vessel, be they used in port or at sea, to be below the standards of similar facilities on land. The function and hazard of a glass balcony on a yacht in port or on easy cruising are no different from function and hazard of a glass balcony on a hotel. Failing to meet at least the adopted land based standards as a baseline minimum would put the owner and operator of the vessel in risk of litigation in case of any accident.

In view of the above, the needs for glass applications for the maritime industry are best served by adopting the technology and design methods used in architecture while applying due consideration to the specific conditions that may be encountered in the maritime environment where the vessel operates.

Buildings happen to be situated in a country, so building codes are national legislation, which may vary widely from country to country. The European Union, faithful to its call, has decided to bring more uniformity by bringing unified building codes and unified product certification.

The unified building codes are also known as the EuroCodes [8]. This is a series of European standards. Standards which cover design methodology, (land based) load determination, risk based assessment and determination of load bearing capacity. The system allows for “National Annexes” in which EU member states can provide their national exemptions or additions when considered necessary. Standards relevant to glass construction have had a long gestation period, but now are in an advanced stage of maturity. PrEN16612 will give methods to determine the load bearing capacity of glass constructions. PrEN16613 will give methods to determine the efficiency of interlayers for use with laminated glass.

The EU “Construction Products Regulation” adopted in 2011 adds mandatory CE certification for building materials brought on the EU market. Where the use of CE marked products may not be mandatory for seagoing vessels it is anticipated that with time, the majority of the glass products available to builders will have the CE mark anyway. Subcontractors with a background in architecture will have less problems understanding what is expected from them.

In absence of a suitable marine alternative or evidence that the architectural product standards are not adequate for the maritime industry, the best option for the maritime industry to satisfy its need for regulation of applications of glass on board is to embrace the Eurocodes system and use that as far as practicable for all applications not directly and mandatorily regulated elsewhere. This will ensure the safety regulations that apply on land are implemented as a baseline. Specific additions for the marine environment can be developed in a kind of National Annex for the maritime environment.

Fire Safety Poses a Challenge

Fire safety in the maritime industry is regulated through SOLAS and the FTP Code. ICLL and SOLAS call for compliance with national or international standards. Fire safety is regulated by prescriptive requirements in the text of the Convention and Code. The performance criteria for isolation and protection in marine and land based codes have the same aim, but are defined differently and the methods to demonstrate compliance are different. This is a noted area of potential collision between maritime and land based standards. This aspect will require further investigation, in particular for passenger yachts and passenger vessels, and will be a significant challenge.

References

[1] Griffith, A.A. (1921), “The Phenomena of Rupture and Flow in Solids”, Philosophical Transactions of the Royal Society of London, A 221: 163–198.

[2] The naming TTG used in this article is based on the naming used in the system of European and international product standards. TTG is often, and technically more correct, also referred to as TSG, standing for “Thermally Strengthened Glass”. Some sources use this acronym as standing for “Toughened Safety Glass”.

[3] “Frangibility of Tempered Soda-Lime Glass Sheet”, by S.T. Gulati; Glass Processing Days ’97, ISBN 952-90-8959-7.

[4] Aluminosilicate glass is now available up to 2 mm thickness only.

[5] Standard for ship’s windows; BS MA 25 was introduced in 1973. The standard covers windows up to 800 x 1100 mm in size. The corresponding ISO standards originate from the mid 1980s.

[6] See Lloyd’s Register SSC Rules, Pt 4, Ch 1, 1.1.4.

[7] www.glassforeurope.com/ on 15 January 2016.

[8] http://eurocodes.jrc.ec.europa.eu/showpage.php?id=332.