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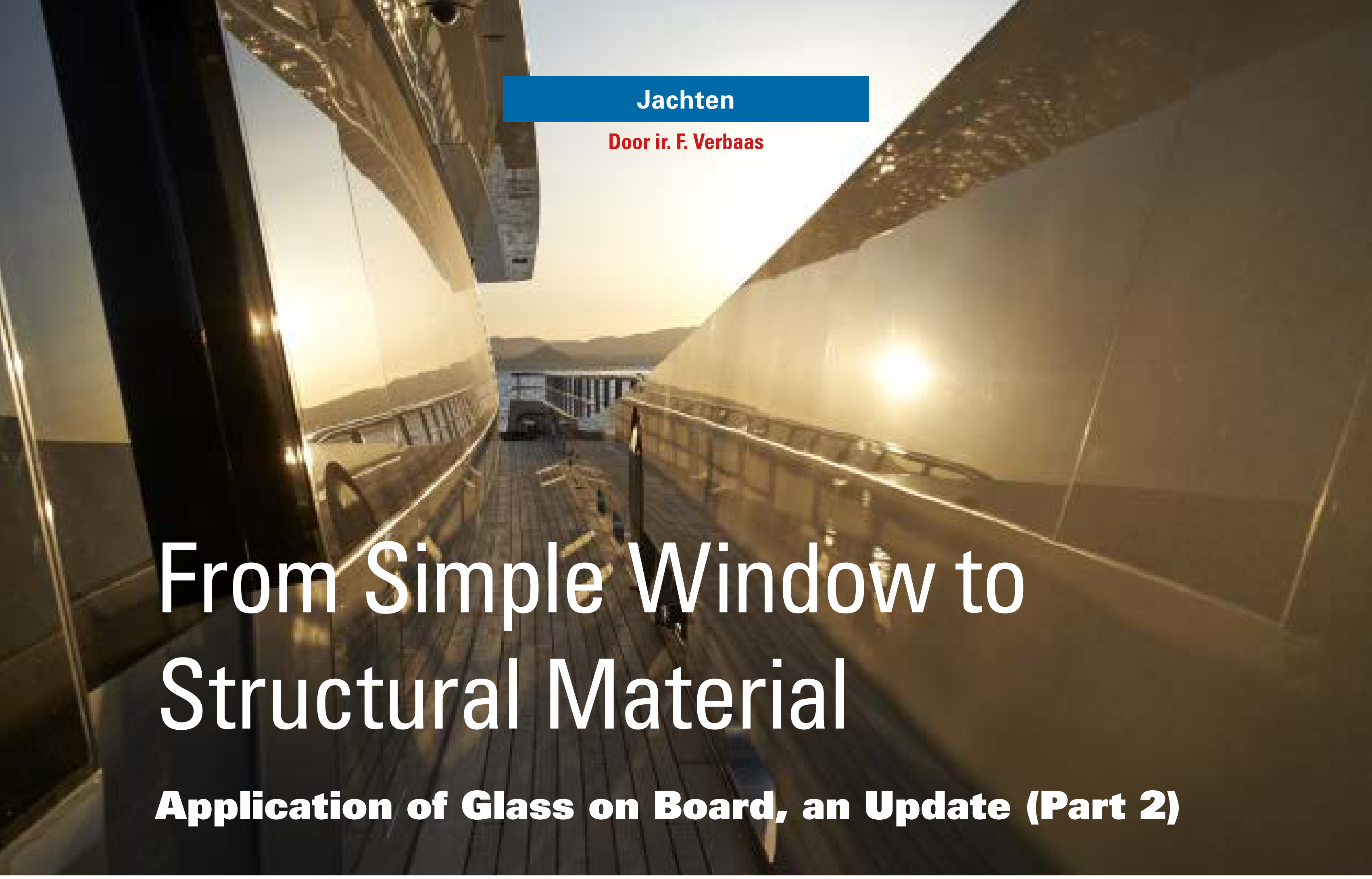
From Simple Window to Structural Material

Application of Glass on Board, an Update (Part 2)



Feadship built yacht Como has unprecedentedly large windows in the hull and there is a great deal of glass in the superstructure: the latter is placed on top of the metal rather than being set into it, creating a continuous glass surface (picture Feadship).

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.

In the first part of this article, a few problems with glass as a structural material were mentioned. These will now be discussed one by one.

Part 2

This is the second part of this article. The first part was published in SWZ Maritime's February yacht special.

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Dealing with Low Deformation Before Breakage

The breakage at low deformation can be counteracted by fitting and holding the glass in such a way that the deformation of the supporting structure (the vessel) is not transferred to the glass. In ship construction, most attention usually goes to strength and stiffness is largely ignored. For yachts with large openings, knowing and managing the deformation of the hull in a seaway is a key parameter for success. Then, with the deformations known, the method of mounting can be designed to ensure the glass stays in place, is not unduly loaded, and keeps the required weathertight integrity.
Of course the size of the panel is important here. Unless the glass is used as a part of the ship's main construction, the fitting must be designed to deal with the combination of strain, racking and warp deformation of the opening, bending of the edges, the difference in thermal expansion and the contraction and rotation of the edges of

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the glass pane under load. The effect of all these parameters depends on the size and aspect ratio of the panel. If the panel is divided into segments, the magnitude of the relative displacement around the panel reduces and the mounting's design becomes easier.

The relative movement to be taken into account when designing the attachment method comes from the combination of various effects. These include the ship's global and local deflections, differences in thermal expansion between the glass and the structure, and the rotation and contraction of the edges of the panels under load. Glass reacts very unfavourably to edge constraints and should be mounted "free floating" as far as practicable. Constructions where a single glass panel is applied to cover multiple openings usually show bad performance in load bearing capacity.

Loads to Consider

The loads to be taken into account comprise wind and sea loads, own weight, acceleration due to ship movements, effects of angle of heel, loads following from other functions, and accidental loads. Wind load is derived from the combination of pressure and suction. Load duration must also be accounted for. A large glass deck will be subjected to the load of its own weight permanently.

The marine industry traditionally bases design on the "the severest sea load" the vessel is expected to encounter during its lifetime. This load is assumed to act only a short time, but all other load cases are considered to be less demanding than this single maximum load case. Where effects of fatigue during the rest of the ship's lifetime are considered relevant, this is commonly wrapped into the factor giving the permissible design stress as fraction of the failure stress.

For glass, and for laminated structure in particular, the effect of load duration on load bearing capacity is much more pronounced than for metal or marine composite construction. The requirement from a relatively small, but permanent load may be higher than the requirement from the combination of that small permanent load and a much higher short term load.

Bonding

Bonding with a single component polyurethane adhesive is commonly used for mounting glass panels up to about 2.5 m edge length. Bonding will provide fixation, elastic support and water/weathertight integration. The thickness of the bead of adhesive is to be chosen to suit the required freedom of motion, the width of the bead to attain the required holding capability. Guidelines for the design of bonding of glass into the structure for yachts are given in Class Rules. An ISO standard for glass directly bonded to the structure is under development: ISO 11336-2.

For larger panes or where there is large deformation in the supporting structure, different systems may be required to provide holding, elastic support and tightness. The integration of the mounting process with the ship's outfitting and completion work may need special attention.

Static Fatigue

Traditionally, maritime applications of glass are vertical or close to vertical. This means lateral load components are small and the aspect of static fatigue can be considered not significant. For large horizontal panels this is different. The static load component becomes much larger and in the end may drive the design more than other load components.

Dealing with the Vulnerability to Surface Damage

The vulnerability to loss of strength after surface damage can be overcome by general careful handling, protection of edges and by adding protective layers or foils. The prime method to deal with the vulnerability to damage is protection. This protection can be physical or procedural. Exposed edges are of course extremely vulnerable and shall typically be protected. For vertical edges on glass doors, this protection can take the form of a foil or coating. For glass decks that people can walk on, a protective ply of glass can be provided. Procedural protection can take the form of precautions during cleaning and regular inspection on surface damage.

Glass Bulwarks and Stairs

Glass bulwarks and stairs deserve a separate discussion. Of all glass structures mentioned above, these two constructions are primarily intended for interaction with humans. There is a high probability failure occurs when a human is using it or at least is in close distance and failure could put these people at risk. Protection of the structural core therefore is essential. On bulwarks, a separate handrail helps to ensure users can have a safe grip. Some flag authorities insist that the edge of a glass panel cannot be used as a handrail. A handrail also avoids a lot of cleaning work to remove prints left by fingers.

13 m long glass balustrade, cold bent, laminated, leaves the production hall at Sedak, Gersthofen, Germany.

Dealing with the Rapid "Unstoppable" Growth of Cracks

When a crack begins to develop in a pane of glass, it continues until it hits the edge of the panel. When the tip of the crack extends, it may encounter surface defects, which cause new cracks to branch off. Consequently, the development of a crack at some point in a piece of glass could lead to the loss of the whole pane. There are no practical methods to avoid this, so the only way to avoid loss of the whole structure, is to split the structure into separate sub-structures that work in parallel to meet the design load. The practical way to do this is lamination. The structural plies of glass are bonded together by an interlayer. Breakage occurring in one ply will in generally not pass through the interlayer into other plies. Provided there is reserve load bearing capacity, the loss of load bearing capacity of one ply can be accommodated by the other plies. The pieces of broken glass will remain adhered to the interlayer. This is a method to limit the risk for the environment. Glass types that break in large shards can be used on board in (and only in) laminates and they shall never be used in monolithic form.

If the failed ply is broken into large shards, which remain attached to the interlayer, they still contribute to the load bearing capacity. Consequently, residual strength of a laminate of Chemically Strengthened Glass (CSG) that is broken will be larger than the residual of a laminate of Thermally Strengthened Glass (TSG) that is broken. CSG on the other hand, has a larger vulnerability to loss of strength due to surface damage. This is a trade-off between probability and effect, which must be made during design and brings it into the realm of risk analysis.

In windows and other openings, the ply most likely to fail, of course, is the one on the non-exposed side, typically the ply on the inside, because that is the ply in tension when the window pane is subjected to a load from the outside. If the glass pane is attached by adhesive bonding, and the inside ply is of a glass type that breaks into very small particles, the remaining intact plies may become detached from the structure and the advantage of laminated construction is lost. If the glass pane is fitted in a conventional frame, it will come loose and may pop out of the frame in its entirety, likewise removing any remaining integrity. For this reason, one should be careful with using Thermally Toughened Glass (TTG) with a higher pre-stress than the industry standard 120 MPa in a laminate.

Polymer Laminates

The load bearing capacity of a laminate depends on the stack of glass plies used and on the properties of the interlayers. The available interlayer materials are polymers and hence will show the typical behaviour of polymers including, to some extent, being hygroscopic, be subject to aging, be open to chemical reactions and show a variation in mechanical properties depending on temperature and load duration. The polymers used as interlayers surely are developed with a view to meet the demands of the application, but the resulting properties need attention in the design. Performance of the glazing after breakage may be leading. Cured-in-situ epoxy interlayers developed for high stiffness, for example, can show brittle fracture and should be combined with a softer, but more plastic interlayer to get the reliability expected from a laminate. Discussion of the theory and practice of lamination is beyond the scope of this article.

The Probabilistic Nature of Breaking Strength

Flexural strength tests of glass, even when made on samples of the same production, can lead to results that have a standard deviation of twenty per cent of the average. As a consequence, results can easily vary by a factor two. The load at which failure can be expected, therefore, is highly stochastic. The breaking strength of a single specimen in a test says very little about the breaking strength that can be expected from the next specimen. All testing with the aim of determining a breaking strength should be done on a suitably large number of samples to level out individual variance.

The design of glass structures is usually based on the Characteristic Failure Stress (CFS), representing five per cent probability of breakage. This level indicates that the load level is such that failure is a possibility and depending on the probability of occurrence of the load back-up systems may need to be provided.

This probabilistic nature of breaking strength also means that a physical test of a glass structure can be useful for validation of the computational model used for the design. If the test piece under a representative test load deflects as predicted by the computation

The glazed side panels of the Como provide uninterrupted views (picture Feadship).

model, the computation model can be accepted as valid and the expected failure load can be derived from the stress response of the model and the CFS. Destructive testing is interesting and spectacular but, with the uncertainty about the presence of defects in the critical parts of the structure, it does not bring much added value. It is carried out sometimes to satisfy curiosity and to be able to say it was tested.

Some Examples of Glass Structures on Board

The Large Yacht Code 3 (LY3), in the clause 4.5 on windows, gives a good example of backup systems. Windows in the main deck need not have storm shutters if the panes are laminated and can be shown to withstand a test pressure of 4.0 times the design pressure [9], [10]. If the laminate has two identical plies with an interlayer providing full collaboration and one of the two plies happens to fail, the remaining intact ply can be expected to be able to withstand a pressure of about one quarter of the pressure the laminate was shown to withstand, that is ¼ * 4.0 = 1.0 times the design pressure. If the interlayer provides less than full collaboration, the residual load bearing capacity will be more than ¼ of the demonstrated value, so will be in excess of the design load. The probability that both plies belong to the five per cent "bad" panels is 0.052 = 0.0025; a probability of failure well acceptable to be left to the remaining backup system on board: The residual weathertight integrity provided by the interlayer and attached shards of glazing limiting ingress of water until the crew has applied the emergency shutters the ship is required to carry on board.

Adaptation of the Architectural Code for Bulwarks

Glass bulwarks, known in architectural circles as "parapets", as indicated are more directly involved with safety of people on board than the other structures built from glass mentioned. People will stay away from a glass bulwark with a broken panel (assumed they can see it is broken), but, as discussed, failure can occur instantaneously and strength assessments should be made on the basis that the most effective ply of the construction has just failed. The load to be assumed on a parapet is different for each application. A glass parapet protecting falling off a terrace of a potentially crowded onboard bar could see a larger personnel load than would need to be assumed on a balcony of a passenger cabin. The architectural building codes give guidelines. What they do not cater for, is that the ship can be a moving platform with potential large horizontal accelerations tipping people off their feet and falling against the parapet or seeking support from the handrail. For maritime application, the load from the architectural code is to be suitably adapted for this effect.

Good Engineering Is Key

The disadvantages of glass as a structural material can be overcome with good engineering. Appreciation of the material and its properties is a requirement.
The best option for the maritime industry to bring applications of glass on board to technology of today is to use the technology, standards and the materials of the building industry, with adaptations as necessary to cater for the conditions at sea. For successful application of glass on board it is preferred that glazing becomes part of Classification.

References

[9] Full collaboration means the plies of the laminate act together as one monolithic ply with a thickness equal to the sum of the thicknesses of the plies and the interlayers. No collaboration means the plies each take a share of the load, but they do not act together. Consequently, for the same load bearing capacity, a laminate of non-collaborating plies needs to have greater thickness than a laminate of collaborating plies.
The traditional approach to laminates in the marine industry is to ignore the effect of the collaboration.

[10] As a rule of thumb, the capacity of a panel to resist lateral loads can be taken as proportional to the square of the thickness. Consequently, if one ply of a two-ply laminate fails and is considered no longer contributing to strength, the load bearing capacity is reduced to ½ * ½ = ¼ of the original value.