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Foundations for a code for Maritime Structural Design of Glass Components

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SUMMARY
This paper explores some parallels and differences between the architectural approach and the marine approach to glass construction. It identifies parallels and identifies areas that could be used in a Code for Maritime Structural Design of Glass Components.

1 INTRODUCTION

Glass is considered inherently unsafe as a construction material because of its proverbial brittle failure mode and because failure can be triggered in many ways, some of which in magnitude have no relation whatsoever with the load the structure was designed to withstand. Yet, the trend in yacht design is to use 'transparent structure' in an increasing amount. The knowledge about the material and its applications however is scarce. The knowledge of engineering of glass constructions is centred in the architectural world, where glass applications have become a discipline in its own right.

The glass materials available for use on board are the same materials as used in buildings. The methods to calculate load bearing capacity are framed on first principles and not different for marine or land based constructions. The dimensions and variety of glass elements proposed for use on board are identical to those used in buildings, and, like in buildings, the glass elements are part of the human living environment. Consequently, the author concluded in an earlier publication (Verbaas, 2016), the best way for the marine industry to come to par is to look closely at the developments and regulations in use in the architectural world and to borrow what could be useful.

2 SOURCES

Construction of buildings and bridges in Europe is governed by the Eurocodes. For most common construction materials, like steel, concrete and even aluminium unified design codes exist and are implemented in the legislation of the EU member states. For glass constructions in buildings however no agreement on a common European code has been reached yet. The member states are using their own national regulations. An excellent overview of these national codes of EU member states and an outlook to a Eurocode for glass construction was given by Feldmann and Kasper in the 2014 'Guidance for European Structural Design of Glass Components' (JRC, 2014). This source was used extensively when writing this paper.

As can be expected, the national codes in general all have the same aim but there is a huge variation in the national implementations.

Based on the information provided in the overview in the JRC Guidance (JRC, 2014), the design codes for the Netherlands (NEN 2608, (Normcommissie Vlakglas, 2014)) and Italy (CNR-DT 210/2013, (CNR, 2013)) were selected for further reference since they were the most modern, most developed and both explicitly link in with the Eurocodes system.

The audience of this paper is the yachting industry so the reference codes for the marine side are the well-known BS MA 25 (BS MA 25, 1973) with restrictions as laid out in the Large Commercial Yacht Code (LY3), and the Passenger Yacht Code (PYC), and ISO 11336-1: 2012 (ISO 11336-1, 2012). These standards refer to windows only. There are no specific marine standards covering other applications of glass on board.

3 BASIS OF ARCHITECTURAL CODES FOR GLASS CONSTRUCTIONS

The basis of structural design in the architectural glass codes is given in EN1990 (EN 1990:, 2002) clause 2.1:
'A structure shall be designed and executed in such a way that it will, during its intended lifetime, with appropriate degrees of reliability and in an economical way:
- sustain all actions and influences likely to occur during execution and use, and

[1] *Note: This article is provided by the author in a private capacity. The author wishes to express his thanks to his employer Lloyd's Register EMEA for providing the support in writing this article. It is emphasized this article expresses the author's personal view on the matter and does not necessarily reflect the position and opinion of Lloyd's Register.*

- meet the specified serviceability requirements for a structure or a structural element.'
and then adds clauses in the same vein about durability, fire resistance, resistance to impact, etc. This is a very broad description, reflecting the wide scope Eurocodes are covering.

The Netherlands Code (Normcommissie Vlakglas, 2014) makes this more specific for glass constructions. Local failure is permitted as long as it does not lead to people or objects falling from height. Accidental loads are to be covered and residual strength is to be evaluated. The risk of injury as a result of the failure is to be investigated. The 'economical way' requirement is catered for by an assessment of the risk associated with failure of the construction or the component, so the requirements the glass construction or the glass element has to fulfil can be differentiated appropriately. In this way, effort and cost for execution can be put to the areas where they make a difference and less stringent criteria can be applied where the consequence of failure is low.

3.1 Fracture of material

Whether a glass element is intact or broken should not be a point for discussion. There is no plastic phase in the failure mechanism that may cause confusion. Breakage is manifest. To determine the load a piece of glass can resist however is much more complicated. The reason for this is the wide spread in results of strength tests that can occur. The Italian code (CNR, 2013, p. 56) gives an example shown here in Figure 1. The results presented are of a series of strength tests performed on 200 samples of 6 mm annealed float glass from same batch production. 100 samples were tested with air side of the glass in tension, the other 100 samples with tin side in tension. Float glass is made by pouring molten glass on a surface of molten tin to let it solidify. The lower side is in contact with the tin and is called the 'tin' side. From the other side is in contact with air and therefore called the 'air side. Note the difference in range and the difference at the 50% probability level: 57 MPa for the tin side in tension and 79 MPa for the air side in tension. It goes without saying that if panes are not mounted with the tin side facing the expected dominant load, the probability of failure during the life of the component is increased.

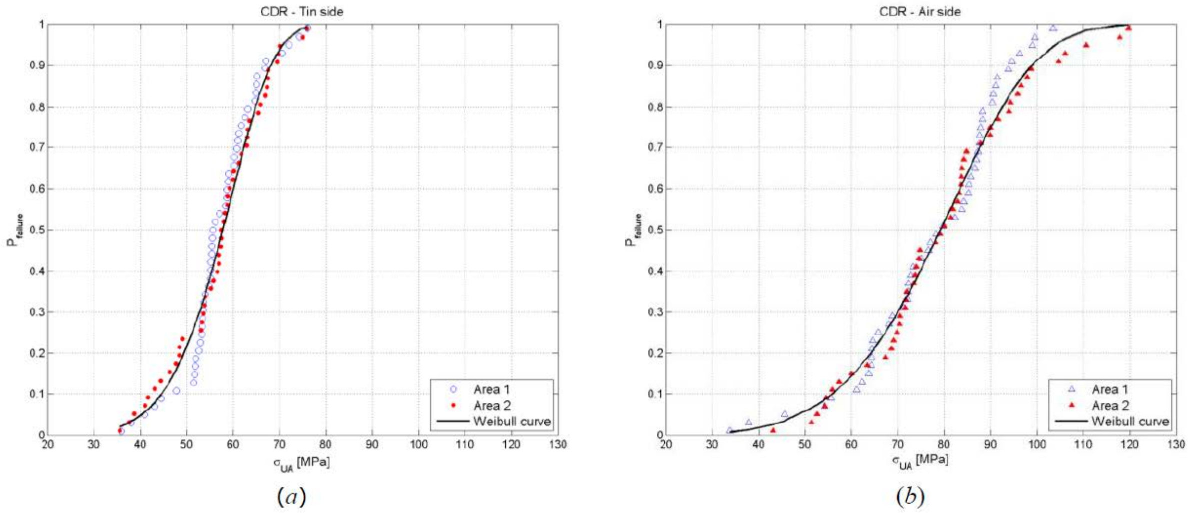


Figure 1 Cumulative probability of fracture as function of surface tensile stress. 6 mm annealed glass, from (CNR, 2013)

The method to determine the stress used in design calculations is very different between the national codes, with different parameters being used. The JRC guidance (JRC, 2014, p. 61) concludes that '*The Eurocode should harmonize the different views on the safety concepts and residual load bearing capacity among Europe in a consistent manner, e.g. using different classes*'.

The concept of 'classes' the JRC Guidance refers to is illustrated in Figure 2. Both the load (E) and the load resistance (R) are considered stochastic variables, made non-dimensional by dividing them by their respective standard deviation. The dash-dotted lines represent the average values of load and load resistance. The concentric circles around the intersection represent contours of equal probability of a combination of load and resistance occurring, with greater radius β representing lower probability. Where action *E* exceeds resistance *R* failure would occur, so design point *P* must be chosen as shown, respecting a minimal distance β from the point where the lines representing the averages intersect. The 'classes' would be represented by the circles with different radius β.

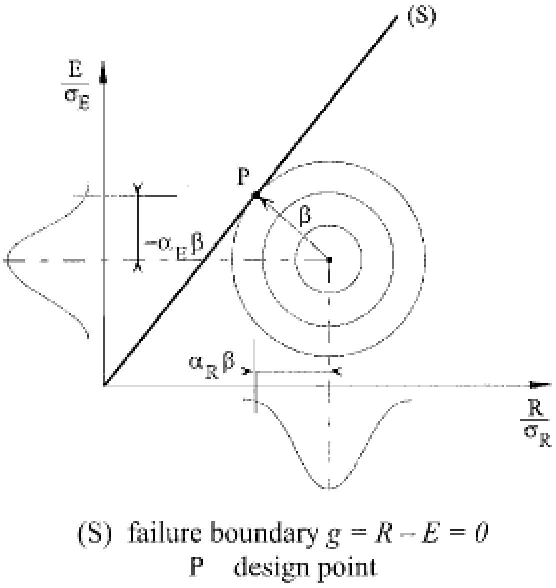


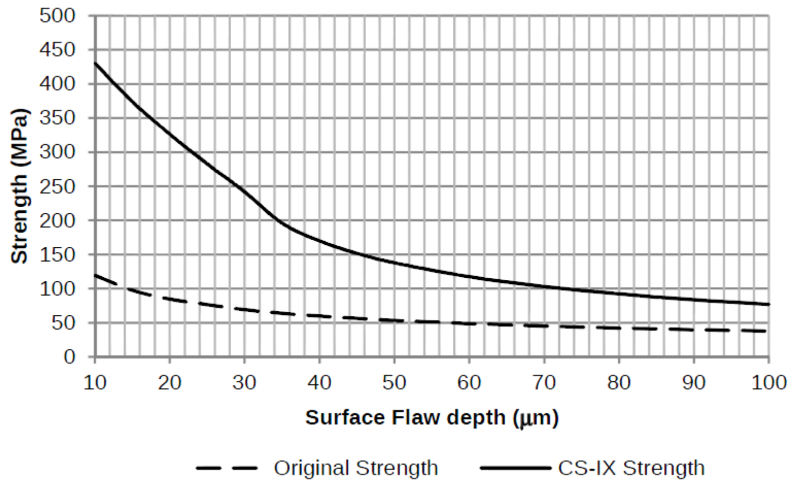
Figure 2 Principle of classes (EN 1990:, 2002, p. 96)

The formulation used in prEN16612 can be used to get an idea about the permissible design stress levels. For 60 seconds load duration (this is one of the parameters in the calculation) the permissible design stress for monolithic Toughened Safety Glass (TSG) processed in a modern production plant where the glass is processed in a horizontal position under the code would be around 75 MPa. For glass processed in vertical position, held by thongs, the permissible design stress is reduced to 50 MPa. The vertical toughening process is now as good as vanished but it was state of the art in the 1970’s time when BS MA25 was developed. BS MA 25 uses a design stress of 40 MPa.

As will be described below, the difference between the two approaches would line up with the potentially higher consequences of failure of a glass pane on board a ship may have. Whether advances in production techniques of TSG since the 1970’s have resulted in an increase of strength of the material over the basis of BS MA 25 could be a subject of investigation. On the other hand the expectations people have of safety and reliability have developed in the mean while also. A code for the application of glass elements on board would need to reflect both developments.

For chemically strengthened glass (CSG) ISO 13316 uses the same permissible design stress of 40 MPa. Most architectural codes do not cover the material because the scatter in breaking strength is considered too high:‘*The design of chemically prestressed glass should not be considered in the Eurocode if it is not possible to define characteristic values for the different types of qualities and ensure quality management*’ (JRC, 2014, p. 51; outlook No. 14). Macrelli and Poli (Macrelli & Poli, 2014) present a prediction method of strength of the end product based on characteristic flaw size of the base material. Figure 3 shows an example, also showing the huge influence of the surface flaw depth on the end strength.

Glass for application on yachts is selected for high optical quality which usually means the surface flaws are shallow. This may explain the good experience with CSG on yachts. Nevertheless the concerns of the architectural world must not be taken lightly. CSG needs to be treated with care and when damaged even only superficially the strength may already be impaired. Depending on the location of the pane in the vessel and the location of the damage on the pane, it may need to be replaced.



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- **Figure 3: Strength as function of critical surface flaw depth for original not strengthened glass (dotted line) and CSG-IX (continuous line); case depth 35 um, surface compression 380 MPa. From: (Macrelli, 2016)**

3.2 Structural response calculations.

There is general consensus that the structural response of glass structures can be assessed computationally using first principles carried out to 'the art of the applied mechanics' ((Normcommissie Vlakglas, 2014), clause 8.1.) Non-linear large displacement FEM is the preferred solution. The Italian code (CNR, 2013) gives examples and in annex 6.6 also a 'quick and dirty' algebraic method covering non-linear behaviour. The method is a little conservative and can easily be programmed in a spreadsheet.

The behaviour of laminated panes and interlayers in laminated glass today is both well established and documented. Stiffness and load bearing capacity of glass beams, shear panels, cantilevers and columns can be predicted with sufficient accuracy. (JRC, 2014), Ch. 7.

It is concluded the calculation techniques for glass used in buildings can be applied in naval architecture and could be the foundations for a maritime design code for glass structures. The influence of load duration and temperature on the structural response will be new aspects for the naval architect to deal with.

4 ACTIONS AND INFLUENCES

Any adoption of land-based technology to shipboard application must be done taking due care of the differences between the two environments. A ship is essentially a thin plate lightweight metal construction, and therefore more elastic than a building. When a ship is in its sea environment the hull and everything that is on it will be moving and flexing with the waves. When the vessel is caught in a storm even glass elements located on a sun deck, well above the level where sea loading is significant, will be confronted not only with the wind load but at the same time also with accelerations due to roll, sway and yaw, with a magnitude not very different from peak ground level accelerations as can be experienced in a severe earthquake. Architectural methods do recognize exceptional wind loads and earthquakes and guidance on the loads involved from both phenomena, in isolation, is provided. The sea environment however brings the induced accelerations as a direct consequence of and simultaneously with the wind. When adapting architectural codes for marine use this must be taken into account in a rational way.

For the positons closer to the waterline, the loads from the sea environment will dominate the design. Loads there can be derived from Class Rules.

5 FURTHER CONSIDERATIONS IN CLASSING GLASS ELEMENTS IN CONSEQUENCE CLASSES

Safety measures, or rather the possibility to take safety measures in case something fails, also is quite different between on-board and land based constructions. A building can be expected to be surrounded by or be at least adjacent to safe space people can be evacuated to. A ship, when it is at sea, only has the sea around it and possibilities for safe evacuation are much more limited. Evacuation of the ship in itself brings many hazards and must be seen as the very last resort. The aim is to have the ship itself provide the place of refuge in case of incidents. This means that elements with a low consequence class may become more important after an incident.

The consequences of failure of local components are different between the two regimes. For example: In the safety study of a building, the event of breakage of a small window to a storage space in the sub-terrain floor will not get any ranking in the list of hazards. The consequences of the failure itself are negligible. From the outside, the glass is so close to the ground that in case of failure the falling shards of glass will not be a hazard to anyone. On the inside, the vertical height of the glass above the floor may be large, so high falling shards could be hazardous, but since the space is usually un-occupied, the probability that someone will be hurt by shards of falling glass is very small. In either case the risk of injury is very small and simple monolithic annealed glass can be applied. In a safety study of a ship on the other hand, failure of a portlight close to the waterline in a space that is similarly un-attended should have top ranking. The space being un-attended will mean the defect may not be detected until water is found in places where it should not be and the stability may be impaired.

There is a difference in scope: Architectural building codes recognize two risks people may be exposed to when glass elements fail:

a) Injury to people from shards or pieces glass elements when they fail
b) People falling from height because of failure of a glass element intended to hold them (floor, parapet, wall).

Loads considered are own weight, weather loads (wind, snow, etc.), and loads from people, either walking or falling. Application of glass as a ‘primary member’, that is, responsible for the stability of parts of the structure other than the element itself in general is not (yet) covered by architectural codes for glass construction.

The approach in naval architecture is to ensure the safety of the people on board by giving requirements to ensure that:

1) the ship itself is safe (stable, watertight, weathertight) and
2) people are not separated from the ship involuntarily by falling overboard, and
3) the risk of injury is limited by prescriptive rules for arrangements and limitation of the materials that can be used on board.

Requirements 1) and 2) are covered by the 1966 International Convention on Load Lines, (ICLL). Requirement 3) is covered by SOLAS. For yachts in most cases a national equivalent is used, such as the Large Yacht Code or Passenger Yacht Code.

A maritime code for glass structures clearly could source tools from the architectural codes to cover the ‘marine’ requirements 2) and 3) for elements made from glass. Obviously some tuning may need to be done. The aspects covered traditionally get little attention in the marine industry but they are quite essential. There is no excuse for letting someone using a glass balcony on a yacht be exposed to a greater risk than when using a similar glass balcony in a building. On the ship, for example, the balustrade will be subjected to load from people falling against it more often, and be more severe, because people may lose balance more easily on the moving ship. To adapt for this in a rational way the risk analysis underlying the requirements needs to be investigated. This may also give material to cover marine requirement 1) concerning safety of the ship for glass elements.

5.1 Considerations for the assignment of a consequence class to glass elements

The Eurocodes system in EN 1990 defines ‘Consequence Classes’ (CC’s) for buildings and objects (EN 1990:, 2002).

Consequence Class	Description	Examples
CC1	**Low** consequences for loss of human life, *and* economic, social or environmental consequences **small** or **negligible**.	Agricultural buildings where people do not normally enter (e.g. storage buildings), greenhouses
CC2	**Medium** consequence for loss of human life, economic, social or environmental consequences **considerable**	Residential and office buildings, public buildings where consequences of failure are Medium (e.g. an office building)
CC3	**High** consequence for loss of human life or economic, social or environmental consequences **very great**	Grandstands, public buildings where consequences of failure are high (e.g. a concert Hall)

Table 1 Definition of Consequence Classes in EN 1990 annex B

The examples are the broad scale picture covering the full range of buildings and civil construction works. To make a rough mapping to the full scale of the marine industry: unmanned barges would be in CC1, yachts would be somewhere in CC2 along with cargo ships. Large passenger ships and (chemical) tankers would be CC3.

A glass element likewise can be assigned a Consequence Class based on the severity of the consequences if the element fails.

Ultimate Limit State Failure Consequences	Consequence Class/ Reliability Class	Probability of Failure		
		1 year	25 years*	50 years
Small	CC1/RC1	10^{-5}	$2.5*10^{-4}$	$5*10^{-3}$
Medium	CC2/RC2	10^{-6}	$2.5*10^{-5}$	10^{-4}
High	CC3/RC3	10^{-7}	$2.5*10^{-6}$	10^{-5}
*) The 25 years figures are not in EN1990 but were added to represent typical design service life of maritime structures				

Table 2 Consequence Classes EN 1990 (Annex B, C) and associated risk of failure

Note this is the risk of failure. Not every failure will result in injuries or loss of life, so the probability of injury or loss of life will be less than the probability of failure.

The Italian code for design of structural glass items (CNR, 2013) and the EU-JRC guidance (JRC, 2014) for glass constructions propose a refinement and to split CC1 in 2 levels: CC0 and CC1 to account for a difference in the risk of injury. This leads to consequence classes for components as given in Table 3 . :

	Responsible for Stability of	Personal Loading	Consequence of failure	Example on board, (based on description)
CC0	Self only	No	Low	Windscreen on top of bulwark; infill panel in metal railing <380 mm
CC1	Self only	Yes	Rather low	Glass balustrade; glass panel in floor of balcony or upper deck
CC2	Self and children	Yes	Medium	Glass beam supporting deck; glass web frame in 'Wintergarten'
CC3	All of or Significant part of structure		Serious	Glass column ('pillar') supporting upper tiers; Glass shear bulkheads preventing collapse of deckhouse Glass parts of hull structure

Table 3 Consequence Classes for Structural Glass; 'injury to people' side.

A similar mapping could be made for glass elements on board from a stability/load line perspective:

- Failure of glass elements in the hull, failure of which would affect the watertight integrity of the hull directly with, potentially, major consequences, obviously would be CC3.
- Glazing in openings in ICLL Positions 1 and 2, where breakage does not necessarily lead to immediate danger of flooding and where it can be expected feasible for the crew to take countermeasures to water ingress, even in bad weather, would be CC2
- Glazing in tiers above Position 1 and 2 would be CC1 or CC0. Failure of these panes is undesirable from a usage point of view but when it happens it is considered not to lead to a risk for the vessel.

Based on the Consequence Class of the vessel and the Consequence Class of the glass element on board a Reliability Class could be assigned.

The Reliability Class in turn would give the appropriate 'design margins' and the level of quality control and inspection during manufacture and lifetime for that element.

A Code for Maritime Structural Design of Glass Components will need to describe this mapping of classes and criteria in further detail.

6 THE ROLE OF RESIDUAL STRANGTH

The consequences of failure of a glass element are strongly dependent on the degree to which the element can still fulfil its role after failure. If in a glass beam made of parallel plies of glass loaded in-plane one ply fails and the others can take the load, the consequences could be limited to replacing the beam. Therefore, the consequence class for an element with sufficient residual strength can be lower than the consequence class of elements having no residual strength after failure.

The perception of consequences of failure of a glass element in the marine industry is driven by the behaviour of TSG material: On breakage, the glass pane ceases to exist and turns into gravel. Laminated glass is estimated to have some mechanical properties after failure of one ply, typically assessed by ignoring the broken ply in the calculation. On a case by case basis robustness of hull glazing was demonstrated in a practical way by successful testing of a full scale sample by subjecting it to a combination of 3 impacts by steel balls of 4.11 kg dropped from a height of 9 m. This requirement was copied from *EN 356:2000 Glass in building. Security glazing; Testing and classification of resistance against manual attack)* followed by hydrostatic pressure tests. There is, however, no formalized procedure covering this.

The Netherlands and Italian codes both recognize the benefit of post-failure integrity and require it is investigated as part of the design.
The Netherlands code NEN 2608((Normcommissie Vlakglas, 2014)) features a form of risk analysis, but it is not related to the probabilities in Table 2. The Italian code (CNR, 2013) in chapter 6.5 introduces a calculation model in which the contribution of broken plies in the remaining load resistance can be accounted for.

For the residual strength of a laminate the properties of the interlayer material are even more important than they are for the properties in the intact case. The influence of load duration and temperature therefore has to be taken duly into account.

What happens after failure can be laid down in a ‘scenario’. The situation with the element in the ‘as failed’ condition is considered as a new design that should be acceptable for the period needed for countermeasures or repair. In the architectural world this is referred to as ‘consequential engineering’, as described by F. Bos and F. Veer in (Bos & Veer, 2007).

A Code for Maritime Structural Design of Glass Components will need to consider failure scenarios in the assignment of Consequence Classes.

7 CONCLUSION

The architectural codes for glass construction contain a lot of material that could be combined with existing descriptions of the marine environment to develop a Code for Maritime Structural Design of Glass Components. Such Code could provide a rational and defendable basis for decisions on acceptability of application of glass material, for the design of glass structures, and for determining the survey regime during manufacturing and lifetime. It would also assist in making decisions about maintenance and repair.

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