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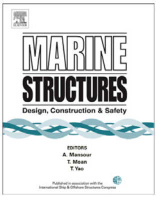

Experimental and numerical investigation of the behavior of ship windows subjected to quasi-static pressure loads

B. Gerlach*, W. Fricke

Hamburg University of Technology (TUHH), Institute for Ship Structural Design and Analysis, Am Schwarzenberg-Campus 4, D-21073 Hamburg, Germany

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ABSTRACT

High load-carrying capacity of ship windows is important for ship safety. This aspect has recently become significant after several incidents with broken windows in superstructures had occurred. In order to get more insight into the failure behavior and into the interaction between glass windows and surrounding wall structure, experiments and numerical investigations of windows subjected to quasi-static as well as impact loads were performed. In this paper quasi-static ultimate load tests with full-scale test models, each containing a clamped or bonded laminated safety glass window, are described. Finite element modeling of the steel structure, laminated glass, and elastomer bonding or gasket is outlined in detail. Material data are based on small-scale tests of steel and glass specimens, and on published data. Afterwards a method to calculate failure probabilities of glass panes under pressure loads is presented. Failure probabilities for the glass panes in the tests are determined and failure mechanisms are clarified. Finally, hints for designing safe windows and for improving window designs are given.

1. Introduction

Loads on ship windows can be quasi-static when windows immerse slowly into water during capsizing, or highly dynamic in the case of a wave impact. During recent years several incidents have

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* Corresponding author.
E-mail address: bjarne.gerlach@tuhh.de (B. Gerlach).

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highlighted the importance of windows for ship safety. For example, after the capsizing of the *Estonia* in 1994 the question was raised, at which time the windows failed leading to a massive inflow of water [1]. The sinking process was extremely fast; time for rescue measures was too short. Well-known examples of ships where window failure occurred due to wave impacts are the cruise vessels *Bremen* (2001), *Caledonian Star* (2001), *Grand Voyager* (2005), *Norwegian Dawn* (2005), *Pont Aven* (2006), *Louis Majesty* (2010) and *Marco Polo* (2014) [2]. In order to better understand the failure behavior and to improve the design criteria and procedures for ship windows, their load carrying behavior was investigated at TUHH in two projects. The quasi-static load carrying behavior, which is described in the present paper, was investigated in the project *"Structural Behavior of Large Windows aboard Ships"* [3]. The behavior of windows subjected to wave impacts was investigated in a separate project, published in Refs. [4,5].

Large ship windows are currently designed according to the rules of classification societies, e.g. in Ref. [6], defining a design pressure for superstructure walls and bulkheads which is applicable to the steel or aluminum structure as well as to the windows. In addition, reference is made to the standard ISO 5779 [7], where quite similar equations for window design pressures are provided. Finally, the greater value has to be considered as design pressure p_d in kPa. The required thickness t_r in mm of single safety glass panes is then determined using Equation (1) given in Ref. [6] which is based on linear plate theory, assuming a limit bending stress of 160 N/mm^2 and a safety factor of four. In this numerical-value equation b is the length of the smaller window edge in mm and β is a factor considering the aspect ratio.

$$t_\mathrm{r} = \frac{b}{200}\sqrt{\beta \cdot p_\mathrm{d}} \tag{1}$$

The strength of glass is a random parameter with a relatively large scatter. Basis for the mentioned limit stress are experimental data gained from extensive tests with glass specimens. Set-up and procedure of such tests are specified in standards, e.g. Refs. [8,9]. Comprehensive information on glass strength is given by Haldimann et al. [10].

Often, laminated safety glass (LSG) consisting of multiple panes with thicknesses t_1 to t_n with interlayers of polyvinyl butyral (PVB) is used where an equivalent thickness is calculated as follows [6].

$$t_\mathrm{e} = \sqrt{t_1^2 + t_2^2 + \ldots + t_\mathrm{n}^2} \geq t_\mathrm{r} \tag{2}$$

This thickness is equivalent in respect of the section modulus and thus the bending strength, presuming that the panes are equally thick, the interlayer is not active and linear theory can be applied. However, this equation is also used for different pane thicknesses as an approximation. In fact, depending on the interlayer stiffness, interlayers are more or less effective concerning the load carrying of LSG. Many researchers worked on this topic, e.g. Refs. [11,12]. In a design procedure that is provided in the recently adopted standard ISO 11336-1 [13] for megayacht windows, the effect of different pane thicknesses in LSG is included and the effect of interlayers can be considered.

Specifications for the framing of the windows, e.g. materials and minimum overlaps of pane and frame, are given in Ref. [14] for windows with maximum size of 1100 mm × 800 mm; larger windows are not covered. Individual classification societies have recently requested minimum overlaps, e.g. b/75 in Ref. [6]. In ISO 11336-1 [13], for whose elaboration the presented test results were provided, overlaps of 12 mm are required for yacht windows with an area of less than 1 m^2 and 15 mm for areas up to 2.5 m^2. But, still smaller overlaps of about 10 mm are common.

In this paper the test rig, test procedure and the results of the quasi-static ultimate load tests are described in Section 2. Afterwards, in Section 3, finite element (FE) modeling of ship windows, including the clamping or bonding of the glass panes and the surrounding wall structure, is explained in detail. Material data are gained from small-scale specimen tests as well as from relevant publications. For the analysis of the test results and later the assessment of window design improvements, failure probabilities of the pressurized glass panes are valuable. Thus, a method to determine the failure probability of glass panes as post-processing of the FE simulation is presented. The failure probabilities