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Testing and modelling of annealed float glass under quasi-static and dynamic loading

Karoline Osnes*, Tore Børvik, Odd Sture Hopperstad

Structural Impact Laboratory (SIMLab), Department of Structural Engineering, NTNU, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

Centre for Advanced Structural Analysis (CASA), NTNU, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

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ABSTRACT

In recent years, a considerable number of studies has been carried out to analyse the behaviour of laminated glass plates under blast loading by the use of the finite element method. This has proven to be quite challenging, as the response of the laminated glass is complex. The fracture strength of the glass layers govern much of the total response; however, a limited effort is often made to selecting this value in the analyses. The current work aims to identify the probabilistic fracture strength of the glass alone as a function of its geometry, boundary conditions and loading situation by the use of a newly proposed strength prediction model. It should be noted that the current study focuses on the initiation of fracture in glass plates, and no effort has been put into the description of crack propagation. To facilitate the validation of the model, three different experimental test series were carried out on annealed float glass. This included quasi-static four point bending tests on relatively small glass specimens, and quasi-static and blast pressure tests on larger glass plates. The experimental work demonstrated that the fracture strength of glass exhibits a large scatter within the same test setup. It also revealed that the fracture strength and its scatter were dependent on the geometry, and the boundary and loading conditions. The strength prediction model was able to successfully capture many of the trends observed in the quasi-static tests. Regarding the blast tests, the model was able to reproduce the experimental results reasonably well.

1. Introduction

Annealed float glass is widely used in window systems, but is a brittle material that offers little resistance to the intense blast waves produced by explosions. If the window fails, it breaks into numerous sharp fragments that can potentially cause major damage [1]. Laminated glass has been found to be effective at mitigating these risks and is now frequently used to increase the protection level by retaining the fragments on a polymer interlayer upon fracture. The polymer interlayer also provides additional resistance to the blast loading even after the glass layers have fractured [2–5]. Lately, much effort has been made to model laminated glass subjected to blast loading by the use of the Finite Element Method (FEM) [3–6]. This has proven to be challenging, as the behaviour of laminated glass is quite complex and dependent on many factors. These include the modelling of the supports, the material properties and failure criteria of both the glass and the polymer interlayer, and the delamination process between the glass and the polymer.

* Corresponding author at: Structural Impact Laboratory (SIMLab), Department of Structural Engineering, NTNU, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway.
E-mail address: karoline.osnes@ntnu.no (K. Osnes).

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Nomenclature

α	in-plane flaw orientation
δ	centre displacement in beam
η	distribution parameter
λ_s	surface flaw correction factor
μ	mean of the normal distribution
ν	Poisson's ratio
ϕ	angle of point on flaw
ρ	density
ρ_{flaw}	flaw density
σ	remote normal tensile stress
σ_n	in-plane normal stresses
σ_x	normal stresses in x direction
σ_y	normal stresses in y direction
σ_{fmax}	maximum tensile stress at failure
σ_{fmean}	mean tensile stress at failure
σ_{fmin}	minimum tensile stress at failure
σ_f	tensile stress at failure
τ	incubation time
τ_{xy}	in-plane shear stress
a	flaw depth
a/c	flaw shape
a_i	depth of flaw i
A_{jumbo}	area of jumbo plate
a_{max}	maximum flaw depth
b	decay coefficient
c	flaw half-length
D_{max}	maximum centre displacement
E	Young's modulus
F	applied load
$f(\phi)$	angular flaw function
F_f	failure load
h	thickness
i_+	impulse of positive pressure phase
K_{IC}	fracture toughness
K_I	stress intensity factor for mode I loading
L	length
L_l	length of loading span
L_s	length of support span
N, c_i, w_i	normalized histogram parameters
N_0	number of flaws on glass surface
N_i	number of flaws with $a \geqslant a_i$
P_0	atmospheric pressure
P_{max}	peak reflected overpressure
$P_{r,max}$	peak reflected pressure
$P_r(t)$	reflected pressure
P_s	negative overpressure
Q	flaw shape parameter
R_1, R_2	random variable from 0 to 1
s	standard deviation of normal distribution
t	time
t_a	arrival time of reflected pressure
t_c	time of failure frame in model
t_{frac}	time of fracture initiation
w	width
Y	geometric flaw shape factor

The identification of the glass plates' fracture strength is not straight forward, and is therefore frequently modelled as deterministic using a fixed fracture stress or strain [3,5]. This value is often based on a limited number of experimental tests, or simply adjusted to fit a representative experiment. It is widely known that the fracture strength of glass plates is probabilistic due to the presence of micro-structural surface flaws [7]. Fracture initiation in glass plates normally depends on the combination of the properties of the flaws and the applied normal stress. Consequently, the fracture may not occur at the point of maximum applied stress. Additionally, the glass strength will also be dependent on both the geometry of the plate and the boundary and loading conditions [8].

In most commercial Finite Element (FE) codes, the failure modelling is based on a deterministic approach. In other words, the given fracture strength applies to the entire glass plate. If this approach is to be used in a design process of glass, the fracture strength must be carefully chosen. It would naturally be advantageous to know the likelihood of the fracture strength specified in the FE model. The current study aims to obtain the probabilistic fracture strength of any glass plate as a function of its geometry, confinement and loading. This will hopefully make the identification of the fracture strength in an FE model more attainable. Note that no effort has been made to model the crack propagation in this work, and the modelling applies only to the initial fracture strength.

Traditionally, the probabilistic strength of brittle materials is described by the Weibull distribution [9], which requires calibration from experimental data. However, Nurhuda et al. [10] found that experimental tests involving glass plates with different test setups lead to different Weibull parameters. This suggests that the Weibull parameters are not material constants, but are dependent on both the dimension and the loading conditions of the glass specimens. Nevertheless, effort has been made to re-scale these parameters to fit different experiments than the ones from which the parameters were extracted, as in the work by Przybilla et al. [11]. The method proved suitable to convert the fracture stress distribution from a four-point to a three-point bending test series. The potential shortcoming is, however, the need for experimental tests with a sufficiently large population. Otherwise, an accurate description of the statistical distribution is not possible.

Recently, a strength prediction model of annealed glass plates was proposed by Yankelevsky [12], which aims to predict the glass strength without the need of material tests. The model is based on the existence of microscopic surface flaws in glass, and uses Monte Carlo simulations to determine the fracture strength for glass plates under certain loading conditions. It can also predict the origin of failure, and captures that this does not necessarily occur at the point of maximum applied stress. The resulting fracture strength provided by the model showed good correspondence with experimental four-point bending tests. In a further development of the model [13], both fracture strength and origin of fracture proved to be well predicted, when compared to a larger series of four-point bending tests.

The current work proposes a further development of this approach, and includes additional features and adjustments to the original model. In addition, experimental tests on annealed float glass have been carried out to facilitate validation of the strength prediction model. This includes quasi-static four-point bending tests on relatively small glass specimens, and quasi-static and dynamic