ARTICLE IN PRESS

Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Numerical analysis of fragmentation in tempered glass with parallel dynamic insertion of cohesive elements

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ARTICLE INFO

Article history:
Received 9 November 2016
Received in revised form 13 September 2017
Accepted 14 September 2017
Available online xxxx

Keywords:
Thermally tempered glass
Dynamic fragmentation
Finite-element method
Cohesive elements
High performance computing

ABSTRACT

Tempered glass panes are subjected to high eigenstresses that induce a state of compression along the surfaces and a state of tension in the inner part. Whenever a crack reaches the tensile region, it rapidly propagates and branches in all directions driven by the eigenstress. These mechanisms induce dynamic fragmentation. The present work contains a numerical investigation of this phenomenon on panes with different thicknesses, using massively parallel simulation based on FEM with the dynamic insertion of cohesive elements. Simulations are first validated by comparing the obtained number of fragments with experimental data. Then, the resulting energy fields are examined and they show that the dissipated energy is significantly underestimated by the existing analytical models. Finally, an extended analytical model that includes the influence of the plate thickness is proposed to correctly estimate the number of fragments for high eigenstresses.

1. Introduction

When tempered glasses break they may shatter into many pieces. This is a direct consequence of the large amount of potential energy that is stored inside the material due to the temper process. Two alternative procedures can be used to introduce residual stresses in glass: the thermal and the chemical temper. In the first case, the profile of the residual stresses through the thickness of the pane can be approximated with a parabola having a negative value (compression) on the free surface twice the central tension [1]. In the second case, the stress profile depends on the duration of the ion-exchange process [2]. In general, the depth of the compressed region is much smaller than that of the tensile one and, therefore, the maximum compression stress is much higher than the central tension. The shape of the stress profile and the value of the stresses through the plate thickness can be derived from well-established experimental techniques such as, for instance, the scattered light method [3,4]. The present work refers only to thermally tempered glasses.

Since the pioneering work of Acloque [1], the problem of fracture and fragmentation in glasses has been largely investigated from the experimental point of view [1,5–8]. The standard fragmentation test is prescribed by the European Norm EN 12150-1 [9]. The typical specimen for this test is a plate having a size of $360 \times 1100\ \text{mm}^2$, as shown in Fig. 1. Following the prescriptions of the Standard, the fragmentation is triggered by striking a sharp steel tool in the point A. No prescriptions are given for the impact velocity. After fragmentation, the number of fragments is counted within a small region having a surface

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https://doi.org/10.1016/j.engfracmech.2017.09.015
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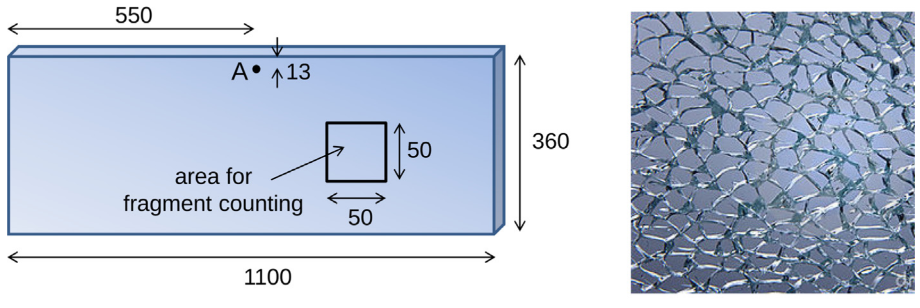
Please cite this article in press as: Vocialta M et al. Numerical analysis of fragmentation in tempered glass with parallel dynamic insertion of cohesive elements. Engng Fract Mech (2017), https://doi.org/10.1016/j.engfracmech.2017.09.015

Nomenclature

$\mathbf{a}$	acceleration vector
c	P-wave velocity
D	damage parameter of the cohesive law
E	Young modulus
E_{diss}	energy dissipated by the fragmentation process
E_{kin}	kinetic energy
E_{pot}	potential energy stored in a glass plate after the temper
E^{+}_{pot}	potential energy given by the portion of plate subjected to tensile stresses
E^{-}_{pot}	potential energy given by the portion of plate subjected to compression stresses
G	shear modulus
G_{c}	fracture energy
h_{el}	size of the finite element
K	stiffness of the cohesive law
K_{Ic}	mode I fracture toughness
l	length of the cohesive zone
m	mass of a fragment
m_{aver}	average fragment mass
$\mathbf{n}$	vector normal to the crack surface
N_{frag}	number of fragments after fragmentation
S	area of the glass plate
t	thickness of the glass plate
$\mathbf{t}$	vector tangent to the crack surface
x	length of the edge of a square fragment
β	ratio between the shear and the normal strength of the cohesive law
δ	effective crack opening
δ_{c}	critical opening displacement
δ_{max}	maximum effective opening over time
$\boldsymbol{\Delta}$	crack opening displacement vector
Δ_{n}	norm of the component of the crack opening normal to the crack plane
Δ_{t}	norm of the component of the crack opening tangent to the crack plane
Δt_{crit}	time step for the explicit dynamic simulations
μ	best-fitting parameter
ν	Poisson ratio
ρ	mass density
$\boldsymbol{\sigma}$	stress tensor
σ_{c}	tensile strength
σ_{CT}	maximum tensile stress in the stress profile produced by the temper process
σ_{eff}	effective stress acting on the facets of the finite elements
σ_{n}	stress component normal to the facets of the finite elements
τ	stress component tangent to the facets of the finite elements
ϕ	best-fitting parameter
CDF	cumulative distribution function
FEM	finite element method



(a) (b)

Fig. 1. (a) Set up of the fragmentation test prescribed by the Standard EN 12150-1 [9] (Dimensions are in mm). Point A is the location of impact. (b) Example of a real crack pattern obtained in the 50 × 50 mm^2 reference area where the number of fragments is counted.

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